TENTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES (IWTC-10)

Topic 6.3: Tropical Cyclones and Climate Change

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Abstract

A substantial number of studies have been published since the IWTC-9 in 2018, improving our understanding of the effect of climate change on tropical cyclones (TCs) and associated hazards and risks. They reinforced the robustness of increases in TC intensity and associated TC hazards and risks due to anthropogenic climate change. New modeling and observational studies suggested the potential influence of anthropogenic climate forcings, including greenhouse gases and aerosols, on global and regional TC activity at the decadal and century time scale. However, there is still substantial uncertainty owing to model uncertainty in simulating historical TC decadal variability in the Atlantic and owing to limitations of observed TC records. The projected future change in the global number of TCs has become more uncertain since IWTC-9 due to projected increases in TC frequency by a few climate models. A new paradigm, TC seeds, has been proposed, and there is currently a debate on whether seeds can help explain the physical

mechanism behind the projected changes in global TC frequency. New studies also highlighted the importance of large-scale environmental fields on TC activity, such as snow cover and air-sea interactions. Future projections on TC translation speed and Medicanes are new additional focus topics in our report. Recommendations and future research are proposed relevant to the remaining scientific questions and assisting policymakers.

6.3.1 Introduction

The effect of anthropogenic climate change on tropical cyclone (TC) activity is of great interest and is an important topic for the science community and the public. Many new studies have been published since the previous IWTC meeting, IWTC-9, held in December 2018, providing new understanding of TC climate in the past, current, and potential future projections. Here we provide an overall review of new research since IWTC-9, specifically paleohurricanes; historical TCs; TC detection and attribution; TC future projections; and a few emerging topics, followed by recommendations and future research.

6.3.2 Tropical Cyclone Observations

a) Paleotempestology

Paleohurricane archives (e.g., sediment deposits (Rodysill et al. 2020), tree rings (Altman et al. 2021), etc.) constrain how TC properties like frequency and rainfall have varied over the past few hundred to thousand years. These archives give a context to recent changes and future projections of TC properties against a pre-industrial baseline. For example, Maxwell et al. (2021) used tree ring width records from the US to show that recent increases in TC rainfall extremes are exceptional compared to the past few hundred years. Recent efforts have expanded the coverage of paleohurricane sites into the western North Pacific (WNP) (Bramante et al. 2020; Tao et al. 2021; Yang et al. 2020; Zhou et al. 2019), southwest Indian Ocean (Green et al. 2022) and Caribbean Sea (Schmitt et al. 2020; Wallace et al. 2019, 2021a,c; Winkler et al. 2020). Many of these new records have high temporal resolution (e.g., annual - Winkler et al. (2022) and indicate multi-decadal or longer variability in TC frequency over the past two thousand years. However, these low-frequency variations in single paleohurricane records do not necessarily reflect regional or basin-scale TC climate changes. In fact, pseudo paleohurricane records created using synthetic TCs demonstrate that multi-decadal shifts in TC frequency captured in sediment reconstructions from the Bahamas arise predominantly from random variability, not climate (Wallace et al. 2020). Compilations of paleohurricane records can theoretically constrain basin-scale changes in NA TC frequency (Wallace et al. 2021b). Still, more work is needed to increase site density in the Atlantic and to integrate different reconstruction types (Burn 2021). Combining millennial-scale simulations of TCs with paleohurricane proxies offers a productive avenue for increasing the applicability of these paleoclimate archives.

b) Historical and Satellite Data - Global

Historical global records of TCs typically comprise the “best-track” dataset from the 19th century onwards when ship-based observations became more routine. However, before geostationary weather satellite monitoring in the 1970s, TC records were prone to discontinuities and sampling issues. TC observations improved substantially during the satellite era, but changes in satellite technologies and monitoring practices throughout the first two decades of satellite coverage imply that global records became more reliable since the 1990s, a period marked by relatively consistent observational platforms.

A recent study by Klotzbach et al. (2022) analyzed TCs from an observationally consistent period (i.e., 1990–2021) and showed decreasing global trends in metrics like annual hurricane numbers and ACE, but an increasing trend in Cat. 4–5 hurricanes. They also noted that the overall number of short-lived named storms (i.e., those lasting <= 2 days) had increased over the period, primarily linked to technological improvements, suggesting the need for globally consistent historical records for long-term trend analysis.

To circumvent data heterogeneity issues for trend analysis, Kossin et al. (2020) used the HURSAT homogenized records of TC intensities from satellite imagery data for the period 1979–2017 to show a significant increase in the global exceedance probability and the proportion (Cat. 3–5 relative to Cat. 1–5) of major hurricanes, as well as an increase in global TC intensity (Fig. 6.3.1A–C). A subsequent study by Jewson and Lewis (2020) demonstrated that the increase in the proportion of major TCs (Cat. 3–5) compared to all TCs with Cat. 1–5 is mainly driven by a decrease in the number of Cat. 1–5 TCs and, to a small extent, by a slight increase in the number of Cat. 3–5. Based on a potential intensity (PI) metric derived from the ERA5 dataset for the period 1979–2018, Emanuel (2020) also supported the notion of an increase in major TC wind speeds. Using multiple-century reanalyses and models, Chand et al. (2022) found a declining trend in global TC frequency over the twentieth century.

Studies have also examined changes in other metrics of global TCs over the historical period. For example, Dai et al. (2022) found no long-term trend in TC days over the period 1965–2020. Wang et al. (2020b) noted a significant decrease in the duration of time TCs spend at intensities larger than Cat. 1. Recently, Wang and Toumi (2021) showed that the annual-mean distance of the locations of LMI to the nearest land had decreased at a rate of ~30 kilometers per decade (Fig. 6.3.1D–F). Wang and Toumi (2022) also found a significant positive trend in the global number of landfalling TCs and major storms that made landfall during the 1970–2020 period, but no significant trend by basin due to large inter-basin variability.

Tu et al. (2021) showed that the TC rain rate had increased globally during the period 1999–2018, primarily due to an overall increase in the outer band of TCs, as opposed to in the inner band where the rain rate had decreased considerably. A similar finding was reported by Guzman and Jiang (2021). Traxl et al. (2021) reported that relatively simple thermodynamic mechanisms, like Clausius-Clapeyron scaling, may be too simple to explain the response of TC precipitation to climate warming, and that dynamical processes will also need to be carefully considered for reliable projections. From their perspective, the expected response of TC-related precipitation to future warming in the tropics may deviate strongly from simple Clausius-Clapeyron scaling and, upon also considering the dynamical influences, may be less sensitive than suggested by thermodynamic changes alone.

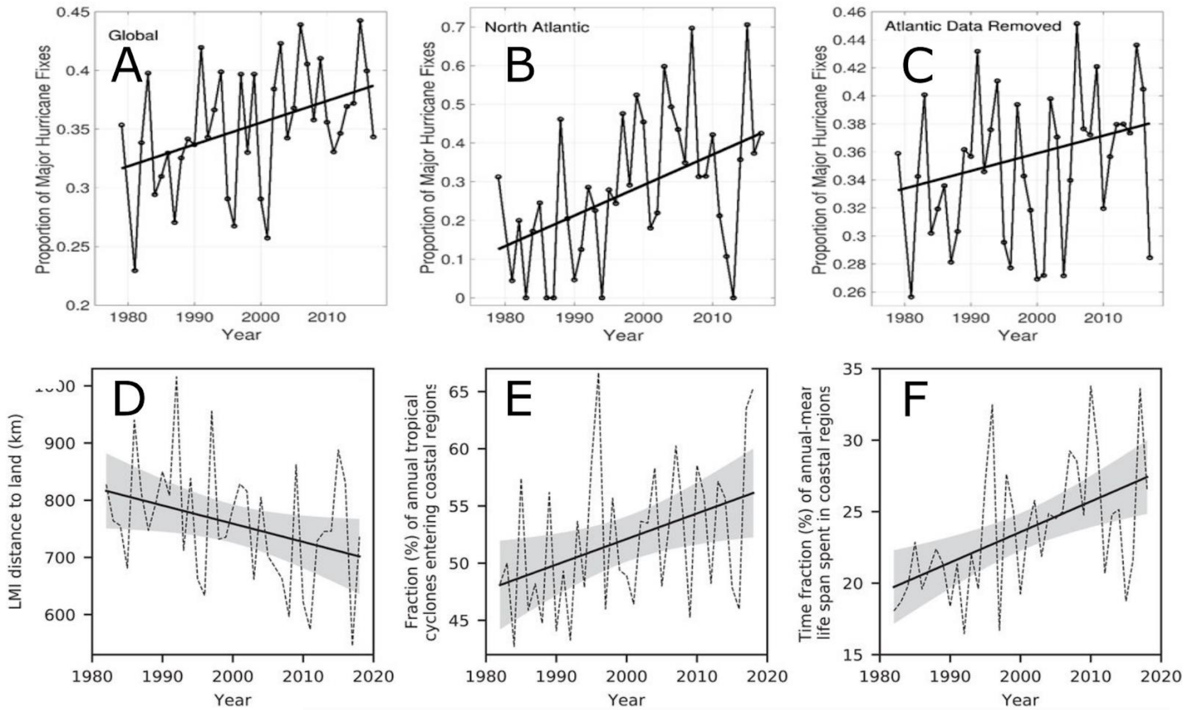

Figure 6.3.1: (A–C) Observed trends in the proportion of major hurricane frequency. (D–F) Observed trends in “land-ward” migration of global TCs in terms of (D) annual-mean distance to land of the locations of lifetime maximum intensity (LMI); (E) the fraction of annual TCs entering the coastal regions, defined as the offshore area with a distance to the nearest land less than 200 km; and (F) the time fraction of annual-mean lifespan spent in coastal regions. Adapted from Kossin et al. (2020) and Wang and Toumi (2021).

c) Historical and Satellite Data - Basins

New studies have examined observed trends in TC metrics over the past decades and centuries for each basin. Significant trends depend on the TC metrics, period, regions, and calibration method. Table 6.3.1 provides a summary of these findings. Detailed descriptions for each basin are available in Appendix 1. Generally, the increasing trend in TC intensity is more robust than the changes in the number of storms among the ocean basins.

Table 6.3.1 Summary of observed trends in TC metrics for each ocean basin.

	Total number of storms	Mean TC intensity	Other TC metrics
North Atlantic	·Increasing trend in total storms observed since 1990 and simulated since 1900 (Klotzbach et al. 2022; Emanuel 2021a), in particular, the northeastern portion (Lima et al. 2021) ·No change in U.S. landfalling or basinwide adjusted major hurricanes (Vecchi et al. 2021) or basinwide modeled total storms (Chan et al. 2021) since the early 20th century	·Increased TC wind speeds over the past four decades (Kossin et al. 2020; Emanuel 2020; Elsner 2020)	·Slower translation speed over the U.S. since 1900 (Kossin 2018) ·Increasing trend in precipitation of landfalling hurricanes (Touma et al. 2019) ·Slower decay rate of landfalling hurricanes (Li and Chakraborty 2020)
Western North Pacific	·Decreasing trend in total storms since 1990 (Klotzbach et al. 2022) ·No change in total storms since the mid-twenties century (Emanuel 2021a)	·Increased mean wind speed for TCs and severe TCs (Kossin et al. 2020) ·Increasing trend in rapid intensification (Song et al. 2020)	·Northward shift in landfalling TC tracks (Chen et al. 2022b) ·Increasing trend in the duration of landfalling storms (Liu et al. 2020a; Chen et al. 2021a) . Increasing trend in the distance traveled by TCs over land (Chen et al. 2021a) ·Increased TC heavy rainfall since 1961 for East Asia (Utsumi and Kim 2022)

North Indian Ocean	·Increasing trend in severe storms since 1990 (Swapna et al. 2022) ·Increasing number of storms in the Arabian Sea relative to the Bay of Bengal (Deshpande et al. 2021; Liu et al. 2021)	·Increasing trend in LMI in the Arabian Sea over the period 1982–2019 (Deshpande et al. 2021)	
South Indian and South Pacific	·Slight increase in severe TCs since 1990 (Klotzbach et al. 2022) ·Slight decrease in total storms in the South Pacific since 1981 (Chand et al. 2019)		· Slight decrease in landfalling TCs around the Australian coast (Chand et al. 2019)

6.3.3 Tropical Cyclones Detection and Attribution

a) Event attribution for tropical cyclones

A relatively new subfield of detection and attribution of climate change is that of event attribution, where the influence of anthropogenic climate change on the probability of occurrence or magnitude of an event (e.g., a TC) is explored, typically through a combination of models and observations.

Since the previous IWTC report (Walsh et al. 2019), two assessment reports have addressed this topic in the context of TCs: a WMO task team-based assessment (Knutson et al. 2019) and the IPCC AR6. Chapter 11 on Extreme Events in the IPCC AR6 report (Seneviratne et al. 2021) concludes the following about TC event attribution: “Event attribution studies of specific strong tropical cyclones provide limited evidence for anthropogenic effects on tropical cyclone intensifications so far, but high confidence for increase in precipitation. There is high confidence that anthropogenic climate change contributed to extreme rainfall amounts during Hurricane Harvey (2017) and other intense tropical cyclones.”

Patricola and Wehner (2018) used regional model simulations to estimate that extreme rainfall during Hurricanes Katrina, Irma, and Maria had been made worse by anthropogenic climate change, whereas no significant influence on their intensities was found. Reed et al. (2020, 2021, 2022) used models to estimate that anthropogenic climate change increased rainfall (e.g., 3 hourly extreme rainfall, total accumulated rainfall) in Hurricanes Florence (2018), Dorian (2019), and for Atlantic hurricanes in general during the 2020 season. Wang et al. (2018) and Kawase et al. (2021) analyzed Hurricane Harvey (2017) and Typhoon Hagibis (2019), respectively, in terms of the influence of observed historical SST and atmospheric temperature changes over the past roughly 40 years. However, these studies did not address the issue of attribution to anthropogenic forcing. Strauss et al. (2021) estimated that for Hurricane Sandy (2012) approximately $8.1B ($4.7B–$14.0B, 5th–95th percentiles) of the storm's damages were attributable to anthropogenic sea level rise. Frame et al. (2020) estimated that the economic costs of Hurricane Harvey attributable to climate change ranged from ~$67B to ~$21B based on bottom up vs top down estimate techniques, respectively.

A few studies explored how anthropogenic climate change might have affected a particular TC active season. Murakami et al. (2018) reported that the active 2017 hurricane season in the NA might have been influenced by anthropogenic warming. Meanwhile, Qian et al. (2019) concluded that it is uncertain if the active 2018 TC season in the WNP was influenced by anthropogenic climate change.

b) Detection and Attribution of Trends in Tropical Cyclone Activity

Analysis of long-term trends and multidecadal variations in observations and model simulations of TC activity can be used to possibly attribute observed changes to specific causes (e.g., anthropogenic forcing by GHG or aerosols) and as a way to test models for skill at reproducing past observed trend-like behavior, both of which can be useful for evaluating the likely reliability of future projections of TC activity.

Murakami et al. (2020) found a detectable influence of external climate forcing (anthropogenic plus natural) on the pattern of TC frequency change in the period 1980–2018 (Fig. 6.3.2). They examined spatial shifts in TC frequency of occurrence on a global scale. They found a distinct spatial pattern of the trends that has implications on the basin-wide distribution of TCs: substantial decreases in the SIO and WNP and increases in the NA and central Pacific. Furthermore, the increase in NA TC frequency over this period was found to be largely due to reduced aerosol forcing, while the models' long-term GHG-induced trend in that region (and most of the global tropics) was negative. This result agrees with the analysis of the impact of aerosols on PI (Sobel et al. 2016, 2019a; Ting et al. 2015), which is more sensitive to aerosols than GHG and can be used as a proxy for TC intensity. Murakami (2022) further showed that aerosols also induce remote effects on TC activity through influences on the atmospheric circulation.

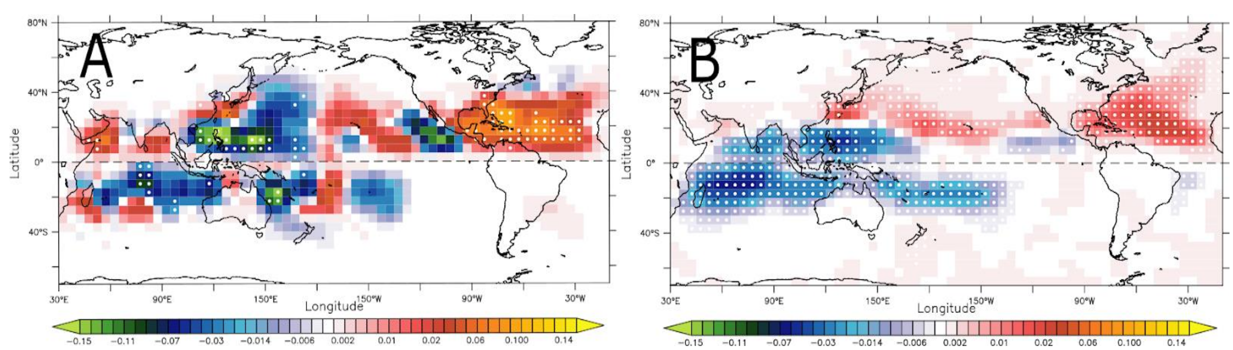

Figure 6.3.2: (A) Observed and (B) simulated trends in TC density during 1980–2018 (units: number per year). The similarity indicates a substantial effect of anthropogenic forcing. Adapted from (Murakami et al. 2020).

Bhatia et al. (2019) found an increase in the proportion of TCs going through rapid intensification in the NA, interpreted as possibly an emerging detectable anthropogenic signal based on comparison with model simulations of natural variability and responses to idealized anthropogenic forcing. As mentioned above, based on HURSAT, Kossin et al. (2020) found that the fraction of major TCs has increased, which Seneviratne et al. (2021) in IPCC AR6 concluded was a change distinct from natural variability (with medium confidence).

Levin and Murakami (2019) estimated that US major hurricane "droughts" were becoming less common with anthropogenic warming according to one climate model. Loehle and Staehling (2020) argued that trend detection for hurricanes is very difficult in the NA, because relatively short (multi-decadal) data series are inherently likely to yield spurious trends in the basin. Pfleiderer et al. (2022) estimated that the externally forced warming trend in NA SST (1982–2020) has doubled the probability of extremely active TC seasons over that time period. However, they did not clearly separate the aerosol and GHG influences which could have strong implications for future changes, since only the GHG forcing is expected to continue to markedly increase in future decades.

Idealized studies of dust influence on TCs by Strong et al. (2015, 2018) showed that dust may be an important forcing for explaining past TC changes, though the quantitative influence was not estimated. Reed et al. (2019) estimated that a large idealized decrease in dust led to more frequent (27%) and longer-lived (13%) NA TCs, but only slightly stronger storms (3%). They also found a 57% increase in ACE per hurricane season.

Ting et al. (2019) concluded that recent favorable vertical wind shear conditions over the main development region (and less-favorable conditions near the U.S. East Coast) had been dominated by modulation by the Atlantic Multidecadal Variability, though without identifying the specific mechanisms responsible for these variations (e.g., natural variability, aerosols). Changes in WNP TC precipitation observed by Utsumi and Kim (2022) were unusual compared to simulated natural forcing changes implying the possible detection of an attributable anthropogenic signal. Murakami et al. (2022) concluded that the increasing events of extreme precipitation in Japan since 1977 was attributable to increasing anthropogenic forcing via an increase in the frequency of intense typhoons near Japan. The decrease in translation speed over the WNP midlatitudes in the last 40 years (Yamaguchi and Maeda 2020a) was attributed to the trend in observed SSTs, but not directly to anthropogenic forcing.

6.3.4 Tropical Cyclone Projections

a) Tropical Cyclone Frequency Projections - Global

TC frequency is one of the most debated issues of future TC projections, since our knowledge of the potential mechanisms associated with TC frequency are not as robust as those associated with TC intensity and TC precipitation. Projected changes in global TC frequency from various studies have been recently summarized by Knutson et al. (2020; Fig. 6.3.3), indicating that the majority of studies (22 out of 27 studies) project a decrease in global TC frequency of ~13% for 2^{o}C of global warming (median value). Results from future multi-model simulations up to the middle of the current century following a high emission scenario, based on high-resolution fully coupled general circulation models (Roberts et al. 2020a), confirmed the tendency towards a reduction of TC frequency in the SH, but they found no systematic changes in the NH by 2050 (Roberts et al. 2020b). However, a few studies also show an increasing number of global TCs in the future (Vecchi et al. 2019; Emanuel 2021b; Bloemendaal et al. 2022). Lee et al. (2020) showed that TC frequency projections using a statistical-dynamical downscaling model could increase or decrease depending on the environmental variable used to describe humidity in the GPI used as a weight to determine the rate of seeding the storms in that model. The potential importance of seeds (weak pre-storm vortices) in modulating TC frequency has been recently highlighted (Vecchi et al. 2019), suggesting that their number tends to increase due to warming, but to decrease due to higher CO_2 concentration.

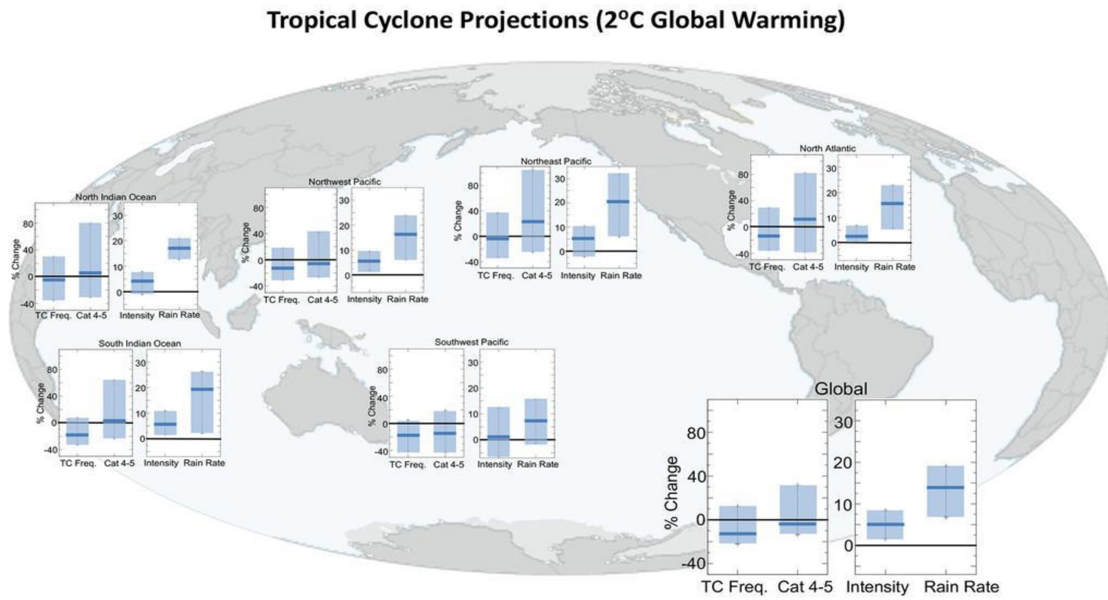

Figure 6.3.3: Summary of TC projections for a 2°C global anthropogenic warming. Shown for each basin and the globe are median and percentile ranges for projected percentage changes in TC frequency, Cat. 4–5 TC frequency, TC intensity, and TC near-storm rain rate. For TC frequency, the 5th–95th-percentile range across published estimates is shown. For Cat. 4–5, TC frequency, TC intensity, and TC near-storm rain rates the 10th–90th-percentile range is shown. Adapted from Knutson et al. (2020).

Future projections have also examined changes in the characteristics in extratropical transition (Michaelis and Lackmann 2019; Liu et al. 2020b; Bieli et al. 2020; Jung and Lackmann 2019, 2021), as well as in post-TC risk at higher latitudes (Sainsbury et al. 2020; Haarsma 2021). Most of these studies focused on the NA basin. In most studies, future extratropical transitions led to events with greater intensity, heavier precipitation and stronger downstream midlatitude development, though not all of the characteristics are statistically significant or present in all of the models analyzed.

b) Tropical Cyclone Frequency Projections - Basins

The uncertainties in future projections of global TC frequency are further enhanced when assessing basin-scale regional changes. Regional SST patterns (e.g., relative warming in the eastern Pacific), large-scale circulations changes (e.g., Hadley Cell changes), and ocean warming (either surface enhanced or deeper) all produce uncertainty on the large-scale drivers of regional TC frequency, in addition to any changes in genesis processes and TC seeds. The following results are based on future projections at 2100 under strong forcing (e.g., RCP8.5/SSP585) unless otherwise stated.

There is general agreement in modeling studies that TC frequency in the SH will decline and/or shift polewards. For the SIO and SP regions, model projections (Knutson et al. 2020; Bell et al. 2019b; Cattiaux et al. 2020; Chang et al. 2020a; Roberts et al. 2020b) suggested a decrease in frequency, while Wehner et al. (2018) and Murakami (2022) indicated a poleward shift in TC activity in the SH. In contrast, Bhatia et al. (2018) showed a slight increase in the SP and Australian region using the HiFLOR model. Emanuel (2021b) showed a poleward enhancement using statistical-dynamical downscaling. Examining the components of a GPI, Bell et al. (2019b) suggested that all of the GPI environmental variables are less favorable in the SI under warming conditions, with cyclonic relative vorticity being a significant factor. In the SP, reduced low-level convergence and increased vertical wind shear are the most important factors. Results using the dynamic GPI of Murakami and Wang (2022) found reduced vertical velocity at 500 hPa is a key factor for future TC frequency reduction.

Future TC projections are generally much more uncertain and basin-dependent in the NH (Fig. 6.3.3), though Bhatia et al. (2018) and Emanuel (2021b) found slight increases in most basins in line with their global results. In the WNP, Bacmeister et al. (2018) and Hong et al. (2021) found an overall reduction in TC frequency, while Bell et al. (2019a) did not find robust changes across models. Using a high-resolution coupled model, Chang et al. (2020a) noted reduced activity in the southern part of the WNP basin, but a poleward increase, similarly to the HighResMIP models (Roberts et al. 2020b). In the ENP, while Bacmeister et al. (2018) and Chang et al. (2020a) found a decrease in TC frequency, the results from Roberts et al. (2020b) suggested both a northward and a westward shift in TC activity bringing more TCs towards Hawaii, with the western shift also present in Murakami et al. (2020) and Bell et al. (2019c). In the NA, Wehner et al. (2018) found an increase in TCs in both 1.5°C and 2.0°C warming scenarios primarily near the basin boundaries. In contrast, Bacmeister et al. (2018), Chauvin et al. (2020) and Murakami et al. (2020) obtained reduced TC frequencies in that basin. While the HighResMIP coupled simulations showed little change in TC frequency in the NA, there was an increase in the atmosphere-only simulations (Roberts et al. 2020b). In the NIO, Bacmeister et al. (2018) and Roberts et al. (2020b) suggested reduced TC frequency, while other models found no significant changes. In the Atlantic, Knutson et al. (2022) projected an increase in U.S. landfalling Cat. 4-5 hurricanes despite a decrease in NA basinwide TC frequency, due to weaker westerly steering flow leading to a greater fraction of TCs making U.S. landfall, while Bloemendaal et al. (2022) project an increase in TC activity in the central and eastern NA.

c) Tropical Cyclone Intensity Projections

There is a general consensus from theory and climate modeling that the strongest TCs will get stronger in the future and will at least become a larger fraction of total TC frequency. These results are also supported by observational studies (e.g. Kossin et al. 2020). Knutson et al. (2020) noticed that under 2˚C warming, there is a ~13% increase in the proportion of intense TCs (Cat. 4–5). Lee et al. (2020)'s statistical-dynamical downscaling led to a relative increase in intense TCs, with an increased fraction undergoing rapid intensification in both genesis scenarios used. Roberts et al.

(2020b) reported small increases in intensity in HighResMIP simulations by 2050, but with mixed results across models. Similarly, Chang et al. (2020a) reported a shift to higher wind speeds in their high-resolution coupled simulation. Sugi et al. (2020)'s simulations showed only small changes in the more intense TCs, consistent with a balance between dynamic (weak vortices from a reduction in upward mass flux) and thermodynamic factors (increases in PI). The CMIP6 downscaling results of Emanuel (2021b) showed a large increase in intensification rate in the future, in particular, > 20% increase at higher intensity regimes, similarly to Bhatia et al. (2018). Analyzing multiple individual storm cases Patricola and Wehner (2018) also obtained increases in TC intensity in all future scenarios.

Results from individual basins are less certain. For the NA basin, Chauvin et al. (2020) reported an increase in intensity for very strong TCs, though ACE values in the future were similar to the present. Cattiaux et al. (2020) noticed an increase in the mean intensity in the future in SIO, but the number of intense TCs remained constant. For the WNP, Cha et al. (2020) reported that under a 2˚C warming, the median, 10th and 90th percentiles for TC intensity increased by +5%; +2%; +9%, respectively, while the proportion of Cat. 4 and 5 TCs increased by +10%; −2%, +29% for each of these percentiles. Chen et al. (2022a) found a ~10% of storm intensity increase in the South China Sea.

d) Tropical Cyclone Storm Surge Projections

TC storm surge height is, amongst other factors, strongly influenced by TC intensity, size, and track, and can be further amplified by a shallow coastline and local bathymetry (Ramos-Valle et al. 2020; Bloemendaal et al. 2019). Recently published global databases on present-climate storm surge reconstructions (Tadesse and Wahl 2021) and storm surge return periods (Dullaart et al. 2020) can support trend and risk analyses of TC storm surge heights. Tide gauge observations revealed that sea level rise has been the primary contributor to changes in total water levels over the past decades, and will likely continue to be an important contributor in the future (Fox-Kemper et al. 2021). Similar results on the global scale were also found by Muis et al. (2020), who showed that towards the end of the century and under the RCP4.5 scenario, 10-year water levels would increase by approximately 0.5m in the global tropics. This change is predominantly driven by future sea level rise. Furthermore, an increase in TC intensity is expected to directly contribute to further increased storm surge heights (Knutson et al. 2020). Mori et al. (2019) found that future changes in TC activity will increase storm surge heights by 10 – 30% around 15° – 35°N, with increases of 0.3 – 0.45m near Japan, while Chen et al. (2022a) obtained an increase of ~ 8.5% in storm surge heights over the Pearl River Delta, towards the end of the century (RCP8.5). For the US, end-of-the-century estimates of the 100-year flood level at the RCP8.5 forcing scenario were found to occur approximately every 1–30 years (Marsooli et al. 2019; Mayo and Lin 2022).

6.3.5 Environmental factors influencing TC activity

a) Relationship between Tropical Cyclones and ENSO - Past, Present and Future

ENSO drives year-to-year variability of TC activity around the globe either directly through local effects or remotely via teleconnections (see Lin et al. 2020 for a review). New studies increase our understanding of the interannual and decadal variation of TCs related to ENSO variability (Appendix 2). However, observed variations in global TC frequency are driven in part, but not entirely, by ENSO (Patricola et al. 2022). Whether this ENSO-TC relationship has changed over the past decades as a result of anthropogenic global warming, or how it may change in the future under enhanced warming, is not very clear. Inconsistent long-term observational TC records (e.g., Knutson et al. 2019) and challenges in climate model simulations of ENSO (e.g., Tang et al. 2021) are among the key factors that may contribute to our lack of understanding of how the ENSO-TC relationship may evolve under a warming climate. Model biases in simulating the tropical Pacific mean climate and trends (e.g. Seager et al. 2019; L'Heureux et al. 2022) can have large implications for future ENSO simulations, including an exaggerated Pacific warming and a high frequency of extreme El Niño events (Tang et al. 2021). Removing these biases leads to a more La Niña-like, rather than an El Niño-like future climate. Feedbacks of TCs themselves on ENSO can further complicate the ENSO-TC relationship (e.g., Lian et al. 2019; Wang and Li 2022a,b,c; Wang et al. 2019). Regardless, theoretical studies and model experiments have shown that the underlying processes and the associated key characteristics of ENSO are likely to change due to greenhouse warming (Cai et al. 2020). Therefore, there is an expectation that changes in ENSO characteristics may influence its relationship with TCs in the future.

b) Other factors influencing TC activity

The influence of land surface conditions on TC activity has also been explored. For instance, Cai et al. (2022) proposed a plausible SST footprint mechanism of Tibetan Plateau snow depth affecting rapidly intensifying WNP TCs (Fig. 6.3.4). Additionally, Cao et al. (2021) suggested that spring North America snow cover substantially impacts the following summer's WNP TC genesis via changes of the tropical central-eastern Pacific SST anomalies.

The variability of the TC-relevant large-scale circulation over the WNP basin has also been explored. The monsoon trough, the western Pacific subtropical high, the South Asian high and upper tropospheric trough show significant interannual-to-inter-decadal variability associated with SST anomalies that affect WNP TCs (Zhao et al. 2019a; Wang and Wang 2019, 2021; Feng and Wu 2022). Changes in the monsoon trough, and the upper tropospheric trough are accompanied by a significant decrease in TCs over the southeastern WNP basin and a west-northward shift of both the latitude of WNP TC formation and the LMI location (Feng and Wu 2022). These changes

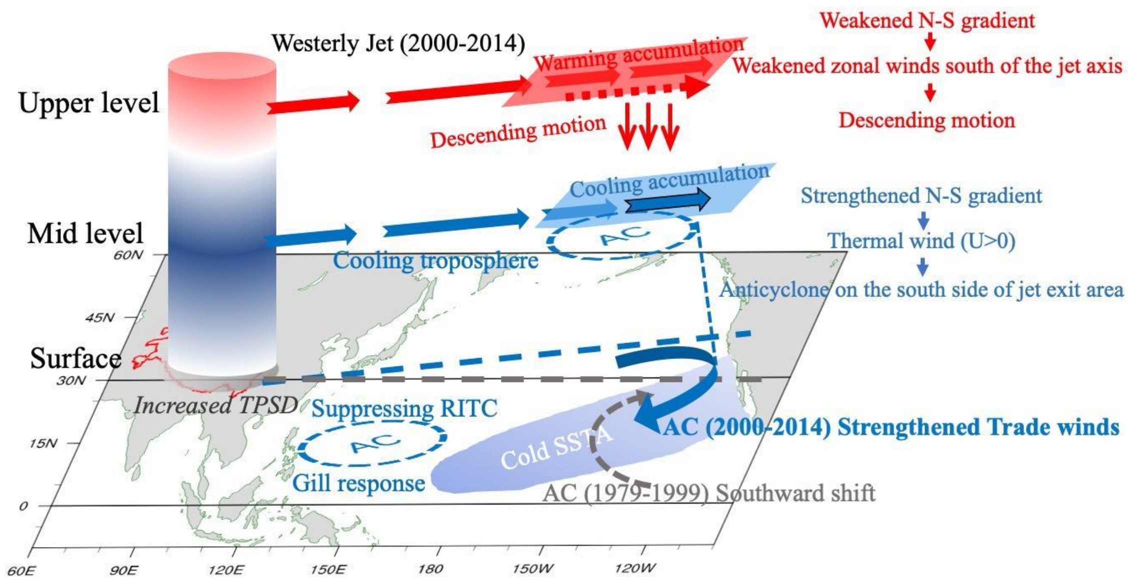

Figure 6.3.4: Schematic diagram of the potential relationship between January–March Tibetan Plateau snow depth with July–November rapidly intensifying TCs over the WNP during 2000–2014. Adapted from Cai et al. (2022).

were associated with trans-basin SST anomalies mainly via changes in large-scale circulation systems (Chen et al. 2021b,c; Wang and Wang 2019), while the observed poleward shift of TC formation and LMI were attributed to the combined effect of natural variability and global warming (Chaluvadi et al. 2021; Wang and Wu 2019).

c) Air-sea interaction: Tropical cyclones in climate models

Several advances have been made in recent years in our understanding of local-scale TC-ocean interactions, focusing on both upper-ocean temperature and salinity. Regarding upper-ocean temperature, TC winds often induce SST cooling behind the path of TCs, called SST cold wakes. SST cold wakes can influence subsequent TCs in observations and climate model simulations by reducing the occurrence of weak to moderate Atlantic TCs and by increasing the occurrence of strong Atlantic TCs (Karnauskas et al. 2021). In addition, SST cold wakes can influence the local-scale atmospheric environment, including rainfall, cloud cover, winds, and air-sea fluxes, in the weeks following TC passage (Ma et al. 2020; Pasquero et al. 2021). Considering salinity effects, upper-ocean freshening associated with precipitation can reduce the magnitude of SST cold wakes by increasing upper-ocean stratification and reducing ocean mixing (Balaguru et al. 2022). Furthermore, reduced salinity tends to favor TC rapid intensification in the eastern Caribbean and western tropical Atlantic (Balaguru et al. 2020). The inclusion of ocean coupling in global climate models can have a substantial influence on simulated global TC frequency, intensity, and geographical distribution (Li and Sriver 2019). In addition, ocean coupling tends to decrease simulated TC precipitation, with contributions from both large-scale SST biases and local-scale TC cold wakes (Huang et al. 2021). Future TC precipitation projections tend to increase in most regions; however, the magnitude can vary substantially depending on ocean coupling (Huang et al. 2021). Coastal TC-ocean interaction and the associated possibility of rapid intensification just prior to landfall (Pun et al. 2019) is another aspect that deserves attention. Biases in the ocean are a crucial issue for simulating TCs. Chassignet et al. (2020) assessed this issue by comparing the low-resolution and high-resolution counterparts in the Ocean Model Intercomparison Project phase 2 (OMIP-2) framework. They found significant improvement in capturing ocean features (e.g., western boundary currents). However, the temperature and salinity fields are still inconsistent among the different model families. Ocean thermocline biases in the tropical North Pacific in the CMIP6 models were investigated by Zhu et al. (2021).

6.3.6 Special Topics

a) Trends in Tropical Cyclone Translation Speed

Kossin (2018) noticed that tropical-cyclone translation speed (TCTS) has decreased globally by 10% over the period 1949–2016 and argued that this is consistent with expected changes in the atmospheric circulation forced by anthropogenic warming. However, a substantial part of this trend could be due to data artifacts and inhomogeneity related to temporal changes in satellite data quality/availability and TC detection techniques (Moon et al. 2019; Lanzante 2019; Chan 2019). Hall and Kossin (2019) documented a slowing trend in TCTS over the continental U.S. since 1900 (Fig. A2) – a relatively long available observational record compared to other studies. In historical simulations from a high-resolution large ensemble, the slowdown trend of global-mean TCTS was absent, with an increase in global-mean TCTS in a warmer climate, despite the slowdown of TCTS at high latitudes. This was due to an increase in the relative frequency of TCs at higher latitudes with faster TCTS (Yamaguchi et al. 2020). In contrast, analyzing the same simulations, Zhang et al. (2020) concluded that future anthropogenic warming can lead to a robust slowing of TC motion, particularly in the midlatitudes, related to a poleward shift of the midlatitude westerlies. Kim et al. (2020b) observed that the global-mean TCTS increased by 0.31 km h^{-1} per decade over the last 36 years (1982–2016, the most reliable data period), but the steering flow controlling the local TCTS decreased by –0.24 km h^{-1} per decade in the major TC passage regions. The inconsistency between these two related variables (TCTS and steering flows) was caused by the relative TC frequency changes by basin and latitude. At the regional scale, Yamaguchi and Maeda (2020b) reported that TCTS in the WNP mid-latitudes has decreased significantly during September over the last 40 years. Wang et al. (2020a) suggested that there is a seasonality dependence on the factors influencing interannual variability in the WNP TCTS, while Sun et al. (2021) found a relationship between WNP TCTS and TC intensity. Gong et al. (2022) also suggested that the increasing trend of WNP TC intensity had a significant influence on the trends of the WNP TCTS. Hassanzadeh et al. (2020) projected an increase in the likelihood of faster-moving landfalling Texas TC in the late 21st century based on multi-model datasets. Lai et al. (2020) showed a significant slowdown of TCs in both observations (11%) and simulations (11%) in China, associated with increasing flood risks along the Chinese coastline. Therefore, current TCTS observed trends vary according to the analysis period and region. In particular, the meridional regional variability of TC tracks plays a crucial role in the observed mean TCTS trend. In future projections, most studies predict that the TCTS will be slower locally (especially in mid-to-high latitudes), but the global-mean values will increase due to a poleward shift of TC tracks.

Another important topic is the possible influence of the ocean on TCTS. An interesting question is as translation speed changes, how TC intensity can be affected via air-sea interaction. As TCTS increases, TC-induced ocean cooling is reduced, leading to increased air-sea fluxes available for

TC intensification. Chang et al. (2020b) reported that TCTS in the South China Sea increased by ~ 43% in the past two decades, while TC intensity over the region also increased. They suggested that the increase in TCTS is a contributor to the TC intensity increase. Similarly, the importance of TCTS changes on TC intensity was noted in the case of STY Hagibis (2019). A slowdown of TCTS and an increase in size hindered Hagibis's intensification (Lin et al. 2021).

b) TC frequency and Climate Change: Environment and Seeds

In recent years there has been substantial effort toward understanding the controls on global annual TC frequency, which is relatively constant in the present climate (Knutson et al. 2019). Global TC frequency is marked by considerable uncertainty in future climate projections. Possible factors that have been investigated include large-scale environmental favorability (e.g. potential intensity, vertical wind shear, ventilation index) and low-pressure disturbances that serve as seeds for TCs. Several studies have suggested that TC seeds are important in determining TC frequency (e.g., Vecchi et al. 2019; Hsieh et al. 2020; Yamada et al. 2021; Yang et al. 2021), with a recent review on the topic presented in Sobel et al. (2021). Vecchi et al. (2019) proposed that both TC seeds and the efficiency with which TCs develop from seeds (related to the thermodynamic environment) are important for global TC frequency. In a follow-up study, Yang et al. (2021) showed that the annual cycle of Atlantic TCs can be reproduced by using a framework that accounts for TC seeds and the probability of TC genesis from the seeds. Hsieh et al. (2020) and Yamada et al. (2021) found a positive correlation between the number of TCs and TC seeds. They also found that the efficiency with which TC seeds develop into TCs, which is related to large-scale factors, also have an important role in determining TC frequency. Furthermore, the efficiency of seeds developing into TCs tends to be less efficient in a warm climate due to a nonlinear relation between temperature and specific humidity (Vecchi et al. 2019; Hsieh et al. 2020; Sugi et al. 2020). These results reinforced the hypothesis that in addition to the larger-scale environmental modulation of TC genesis, these pre-storm vortices may exert an independent influence on TC frequency under warming conditions (Sobel et al. 2021). In particular, recent studies suggested that the changes in the frequency of seeds might be the root of the inter-model differences in TC frequency sensitivity to warming (Yamada et al. 2021; Hsieh et al. 2022). This framework is also able to explain changes in TC frequency across different climates (Hsieh et al. 2022). A future decrease in the number of TC seeds, determined by counting vortices, has been projected by some climate models (Sugi et al. 2020).

Other studies found that the frequency of TC seeds plays a lesser role in maintaining the climatological TC number. In particular, regional climate model simulations that either prescribe or suppress the most common type of Atlantic TC seed, African easterly waves, through the lateral boundary conditions produced no change in seasonal Atlantic TC frequency (Patricola et al. 2018). These experiments unravel the causality among co-variability in TCs, TC seeds, and the large-scale environment, suggesting that the environment drives variability in TCs, TC seeds and types of seeds, rather than the environment and TC seeds driving TCs. Similarly, Emanuel (2022) argued that TC frequency is controlled primarily by environmental favorability, and that there is still no definitive evidence that low amplitude weather noise is able to control TC frequency. Emanuel's (2021b) TC downscaling framework applied to CMIP6 models assumes no change in seeding rate with climate change, for example. Although frameworks based on TC seeds and the large-scale environment can simulate TC frequency, the definition of a TC seed has a strong influence on the probability that the seed will develop into a TC. It is also possible that feedbacks between TCs and the climate may play a role in determining global TC frequency (Emanuel 2022). Hoogewind et al. (2020) suggested that the spatiotemporal distribution of environmental conditions, although important, does not constrain the annual global TC number. They found that the maximum potential TC genesis rate – estimated using the geography of environmental favorability (i.e., PI and ventilation) and various spatial densities of TCs based on a range of TC separation distances – is an order of magnitude greater than the observed TC frequency.

c) Tropical Cyclone Risk: Present and Future

Socioeconomic impacts related to TC passages are increasing worldwide due to a rise in coastal physical infrastructure value and population living in coastal regions (Klotzbach et al. 2022). TC activity close to coastlines and TCs penetrating further inland after making landfall are projected to increase under future climate change (Bruyère et al. 2019; Li and Chakraborty 2020; Wang and Toumi 2021; Camargo and Wing 2021). These projected changes in combination with the destructive impacts of TC wind, storm surge, and precipitation hazard negatively affects TC risk under climate change worldwide. For TC wind risk, recently two new global-scale academic TC wind hazard models were published. Lee et al. (2018) and Bloemendaal et al. (2020) generated present-climate global wind speed return period maps, and both studies demonstrated that the probabilities for severe TCs are highest in the North Pacific basins. Lee et al. (2020), Emanuel (2021b) and Bloemendaal et al. (2022) also analyzed TC future risk. Lee et al. (2020) and Bloemendaal et al. (2022) provided future-climate return period maps for high emission scenarios. Both studies showed that large parts of the world face an increase in wind hazard under climate change, particularly for severe TCs. Bakkensen and Mendelsohn (2016) found that in 2100 and under the RCP4.5 scenario, TC wind risk would increase global damages from $60 to $90 billion/year, of which 84% of all damages will be in the US.

Local-scale, present-climate studies on TC wind risk include Loizou et al. (2022), who found that 10-year wind losses in Bermuda range between US $3.2 - 3.7 billion, and 100-year losses range between US$ 4.8 - 5.5 billion. Sobel et al. (2019b) and Bloemendaal et al. (2020) found that the return period range for a Cat. 1 TC in the vicinity of Mumbai, India lies between 49-97 years, and a Cat. 3 100-500 years. Local-scale studies on TC wind risk under climate change generally show an increase in wind hazard, for instance, for New York state (Lee et al. 2022) or the Small Island Developing States (Bloemendaal and Koks 2022). Smiley et al. (2022) showed how social inequalities led to differences in climate change impacts in the case of Hurricane Harvey.

Dullaart et al. (2020) presented global-scale present-climate TC-induced extreme water level return periods and estimated that 114 million people are exposed to a 1000-yr TC flooding event. On a local scale, Ruiz-Salcines et al. (2021) concluded that for Manzanillo, Mexico, a very high risk for storm surge occurred for urban areas beside a lagoon and that the return period for TC winds will diminish in the future. Akter and Dayem (2021) found that 10% and 36% of the study area around Cox' Bazar, Bangladesh are at very high risk of flooding at the 50- and 100-yr return period, respectively. By 2050, these percentages will increase to 31% and 50%, respectively. For the US Northeast coast, Mayo and Lin (2022) reported that by the end of the century, the current 100-year water level height could become up to seven times as likely due to sea-level rise. These probabilities increase further by up to a factor of two, when including changes in TC characteristics. A cyclone on the scale of Amphan-scale could cause over 200% more people to be exposed to the most severe flooding in India under future scenarios, compared to increases of 0-20% in Bangladesh (Mitchell et al. 2022). Most of these changes are due to sea-level rise rather than changes in exposure.

Studies about TC risk associated with extreme rainfall generally focus on regional scales. In the Middle Americas, Dominguez et al. (2021) found that TC risk is highly modulated by changes in TC activity over the North Atlantic ocean related to ENSO phases and high social vulnerability. In this sense, structural, economic and social vulnerabilities are an important factor for TC risk assessments (Wilson et al. 2022). Other studies combine TC rainfall with wind speed or storm surge for present and future projections. For instance, Harr et al. (2022) analyzed changes in a joint TC hazard composed of wind and precipitation over the NA under the SSP5-8.5 scenario and found that the return period in 2050 is shorter than in 2020. Gori et al. (2022) analyzed a composed hazard of TC rainfall and storm surge over the southeastern and eastern coasts of US under the SSP5-8.5 scenario and concluded that increasing TC intensity and decreasing translation speed will lead to an increase in rainfall and storm surge by 25% for the 2070-2100 period.

Recent studies aggregated exposure, various indicators of vulnerabilities (e.g., land use changes, elevation, proximity to coastlines, GPD, among others), mitigation capacity (e.g., public health capacity, proximity to hospitals, educational and assistance level, emergency shelters), with TC hazards (i.e., storm surge, TC intensity, TC rainfall, TC frequency) into spatial TC risk maps which are extremely useful for disaster risk management (Hoque et al. 2019; Zhou et al. 2021).

d) Medicanes

Within the class of Mediterranean cyclones, there is a subgroup of hybrid and shallow warm-core cyclones with extratropical cyclogenesis. The so-called MEDIterranean hurriCANES (medicanes) (Rasmussen and Zick 1987; Reale and Atlas 2001; Emanuel 2005) are mesoscale maritime extratropical cyclones that can physically emulate TCs at a certain point in their lifecycle (Emanuel 2005; Miglietta 2019; Miglietta and Rotunno 2019). Most of these cyclonic formations could be considered as hybrid cyclones, but some of them can acquire a hurricane structure, although they rarely attain hurricane intensity (e.g. Miglietta and Rotunno 2019). These cyclones can pose serious societal and ecological threats to the affected islands and coastal regions, as well as open seas-related activities. The historical record of these systems has limited reliability and sample size, given their maritime characteristics, small size and infrequent occurrence. Thus, it has not been possible to derive an objective reliable climatology of these systems so far. A few studies of medicanes based on ERA5 reanalysis have been published (de la Vara et al. 2021; Zhang et al. 2021), but the ERA5 horizontal resolution is not fine enough to study some of the processes occurring in these systems. An important issue is that the identification of medicanes is subjective, mixing hybrid and warm-core cyclones (Tous and Romero 2013; Miglietta et al. 2013; Nastos et al. 2018). An alternative approach to build a climatology is to perform a dynamical downscaling from reanalysis as done by (Cavicchia et al. 2014a). In that case, no statistically significant trend was found. However, this method also has limitations, as shown when applied to an ensemble of regional models (Gaertner et al. 2018).

Projections for a decrease in frequency and an increase in intensity of medicanes due to the impact of anthropogenic climate change are robust among various studies (e.g. Gaertner et al. 2007; Walsh et al. 2014; Cavicchia et al. 2014b). Romera et al. (2017) obtained similar trends to previous studies, analyzing multi-decadal simulations of a large ensemble of RCMs. Tous et al. (2016) supported these results using a high-resolution atmospheric-only global climate model. However, as medicanes could be impacted by air-sea interactions, coupled ocean-atmosphere models should be considered (Gaertner et al. 2018). González-Alemán et al. (2019) used a coupled global climate model to study medicanes and in addition to trends, explored new metrics such as destructiveness, medicane-associated rainfall and the occurrence of a hurricane-like structure: all of these characteristics occurred more often in future scenarios. Gutiérrez-Fernández et al. (2021) analyzed future characteristics of medicanes using a fully coupled RCM model and despite the potential negative feedback due to the SST cooling effect in response to strong winds, the future trends of medicanes remained the same. Results from the application of a statistical-deterministic downscaling method to medicanes were in line with the increasing intensity trend (Romero and Emanuel 2013, 2017) even though in this methodology medicanes were considered TCs, which is not the case for all storms. The future increase in the intensity of medicanes has been largely attributed to an increase in SST in the Mediterranean basin. Higher SSTs would enhance convection, while in a warmer climate, the atmospheric stability would increase. These competing effects were investigated by Koseki et al. (2021), applying a pseudo-global warming approach to medicane Rolf (2011). Their results are consistent with other studies, but these competing effects led to a limited increase in the intensity of this medicane.

6.3.7. Future Research

The role of TC seeds in future projections should be further explored, given that there are two current views on this issue in the community.

Climate model biases in SST trends in the tropical Pacific, versus observed trends, could have potentially important consequences for TC projections. In particular, if current projections for ENSO or mean tropical Pacific conditions are incorrect, that could lead to changes in some of the regional patterns of future TC projections.

Other cases in which there is potentially a difference between observations in the recent decades and the climate model historical simulations should be analyzed. For example, in the WNP, Wang and Toumi (2021) observed a recent migration of TCs toward the coast (Fig. 6.3.1D–F). In contrast, Chand et al. (2017) project an oceanward shift of TCs in that region (Fig. 6.3.5). These are very different scenarios, especially from a disaster mitigation perspective. Whether the current observations in the recent migration towards the coast are due to anthropogenic forcing or natural variability, or the projected ocean-ward shift of the WNP TCs may be influenced by model biases (probably related to ENSO) requires further investigation.

Event attribution of TCs is another field to be further explored, in particular related to rapid intensification. For example, STY Hagibis (2019) set a new rapid intensification record in the WNP and the observed ocean pre-condition was also one of the warmest on record (Lin et al. 2014, 2021). To what extent anthropogenic warming may have contributed to this extraordinary event deserves further investigation.

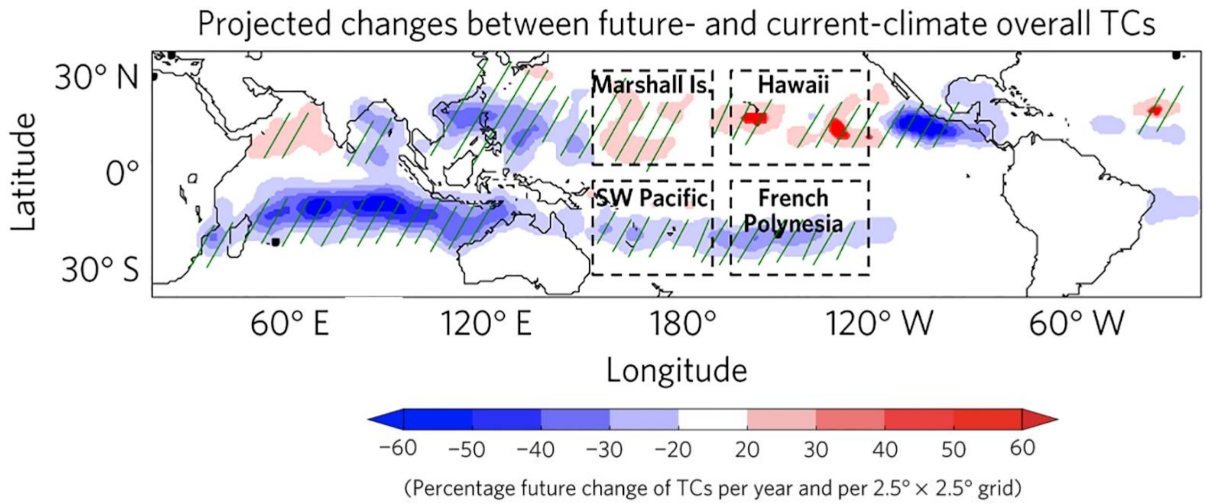

Figure 6.3.5: Projected future changes in TC density showing "ocean-ward" migration. Adapted from (Chand et al. 2017**).**

6.3.8 Recommendations

1. Efforts should continue to develop and maintain observed climate data sets related to TCs and medicanes as well as quantify uncertainty in the datasets, in particular in the satellite era.
2. To assist policymakers, it is recommended to provide more information on future changes in TC activity at a regional scale rather than global and/or basin-scale changes in TC activity in cases where the projections are robust enough.
3. It is recommended to elucidate if anthropogenic climate change might have already affected a specific region in the world in the last 10–15 years beyond the influence of natural variability and if the change would continue in the future.
4. The physical mechanisms behind the number of global TCs should be further refined in the future studies. The relationship among TC formation, seeds, and the large-scale environment should be further clarified in both observations and modeling studies.
5. It is important for the community to reach a commonly accepted definition for medicanes and maybe have one single forecast center responsible for these systems, particularly as their impacts are expected to increase in the future.
6. It is important to have an accepted definition on what constitutes a TC seed, which would help the progress in understanding changes of TC frequency in the future.

Acronyms used in the report

ACE	Accumulated Cyclone Energy
Cat.	Category or Categories on the Saffir-Simpson scale
CMIP6	Coupled Model Intercomparison Project 6th phase
CP	Central Pacific
ENP	Eastern North Pacific
ENSO	El Niño - Southern Oscillation
ERA5	European Centre for Medium-Range Weather Forecasts Reanalysis 5
GDP	Gross Domestic Product
GHG	greenhouse gases
GPI	Genesis Potential Index
HiFLOR	High-resolution Forecast-oriented Low Ocean Resolution
HighResMIP	High Resolution Model Intercomparison Project
HURSAT	Hurricane Satellite
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
IWTC	International Workshop on Tropical Cyclones
LMI	Life-time Maximum Intensity
NA	North Atlantic
NH	Northern Hemisphere
NIO	North Indian Ocean
PI	potential intensity
RCM	regional climate model
RCP4.5	Representative Concentration Pathway 4.5
RCP8.5	Representative Concentration Pathway 8.5
SH	Southern Hemisphere
SIO	South Indian Ocean
SP	South Pacific
SSP585	Shared Socioeconomic Pathways 5-8.5
SST	sea surface temperature
TC	tropical cyclone
TCTS	tropical cyclone translation speed
US	United States
WMO	World Meteorological Organization
WNP	Western North Pacific

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Appendix 1 - Historical and Satellite Data - Basins

a) North Atlantic

TCs in the NA basin are influenced by multiple internal and external forcings such as multidecadal climate variability and localized aerosol effects, often leading to conflicting conclusions on causes and robustness of historical trends. For example, increasing trends are noticed in most basinwide TC metrics (such as number of named storms, hurricanes and major hurricanes) over the past three decades (Klotzbach et al. 2022) and over the 20th century in raw (unadjusted) data, but no significant trend is found when an extended period of reconstructed (adjusted for ship-track density) observational data since the mid-twentieth century is considered for hurricanes or major hurricanes (Vecchi et al. 2021, Fig A1). The notion of “no significant century-scale trend” was also supported by Chan et al. (2021), who used bias-corrected SST to simulate TC trends for the basin with a global atmospheric model. Unadjusted U.S. landfalling hurricane and major hurricane frequency since the late 1800s also indicate no significant long-term trend (e.g., Vecchi et al. 2021). An increase in the frequency of TCs in the northeastern Atlantic sector was also observed (Lima et al. 2021).

In contrast, Emanuel (2021a) inferred increasing trends in several NA TC metrics over the past century using a statistical/dynamical approach to derive a global reconstruction of TCs from climate reanalyses, but those trends were reanalysis-dependent, and a pronounced increasing trend was only found in the NA. While there are notable inconsistencies in time-dependent trends of metrics like the number of NA hurricanes and major hurricanes, both observational and theoretical studies have shown that the overall mean intensity of TC wind speeds (Kossin et al. 2020; Emanuel 2020), and in particular the wind speeds of the strongest TCs (Elsner 2020), have increased considerably over the past four decades. Limitations of observed datasets currently do not allow for a confident determination of trends in observed intensity at the century scale. The occurrence of slower translational speeds over the continental U.S. since 1900 mentioned above (Kossin 2018) is linked to the increasing likelihood for TCs to “stall” near the NA coasts since the mid 20th century (Hall and Kossin 2019). These changes, coupled with an increase in TC-related rain rate (Tu et al. 2021), an increasing trend in precipitation of landfalling Atlantic major hurricanes (Touma et al. 2019), and a slower decay rate of landfalling hurricanes (Li and Chakraborty 2020), could potentially be contributing towards greater TC damages.

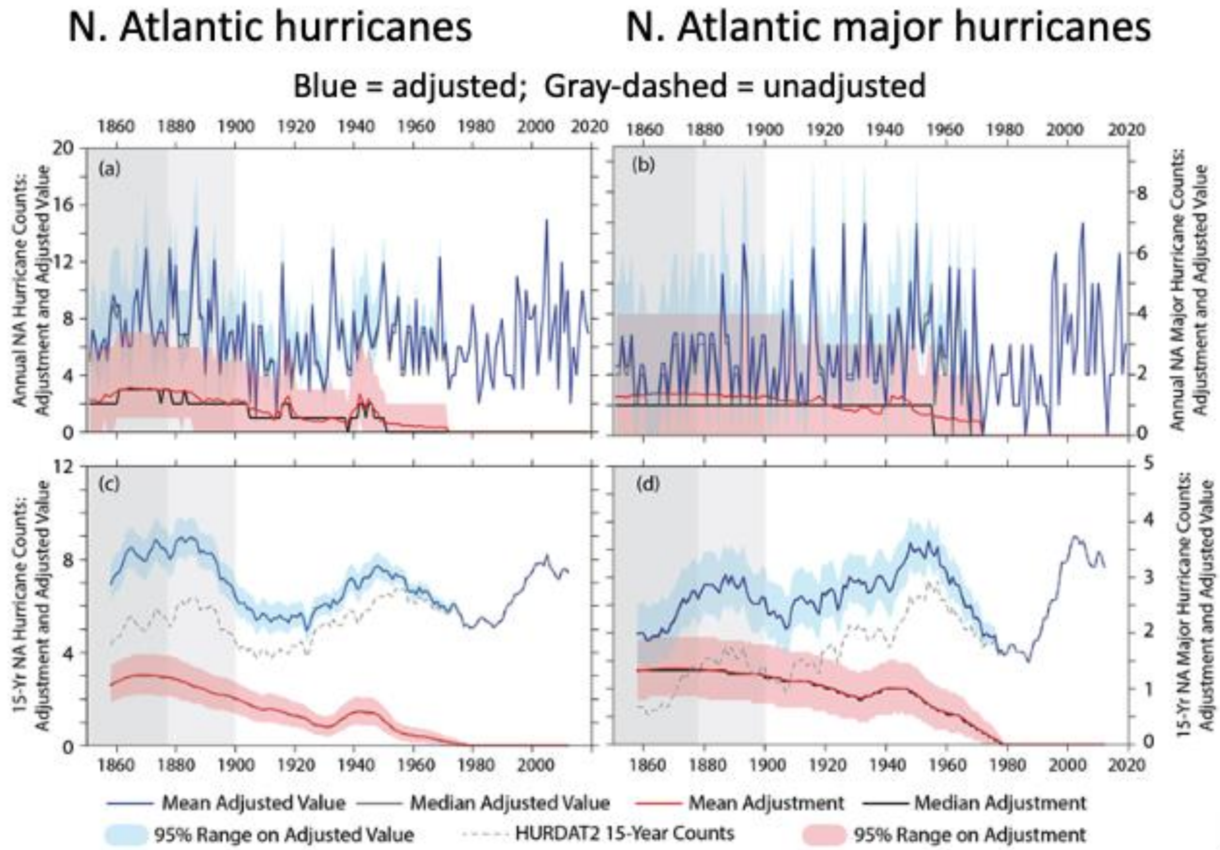

Figure A1 Number of North Atlantic hurricanes (left) and major hurricanes (right) after adjustment for ship track density changes (blue) and no adjustment (gray). Adapted from Vecchi et al. (2021).

b) Western North Pacific

The frequency of WNP TCs has decreased significantly in recent decades (e.g., Klotzbach et al. 2022), though only a weak, insignificant trend is simulated in the reanalyses-based reconstruction of TC frequency since the mid-twentieth century (Emanuel 2021a). There is also no trend in the proportion of major typhoons (Cat. 3–5 relative to Cat. 1–5) since 1980 (Kossin et al. 2020; Jewson and Lewis 2020), but the mean wind speed probabilities of TCs and severe TCs have increased considerably over the period (Kossin et al. 2020; Knutson et al. 2020; Elsner 2020). The landfall locations of TCs in the WNP have shifted northward during the last four decades, primarily due to the shift of landfalling TC tracks (Chen et al. 2022b; Tran et al. 2022). The northward displacement of WNP TC tracks, together with an increasing trend in the rapid intensification of TCs (Song et al. 2020), has resulted in an increasing trend in the annual number of rapidly intensifying landfalling TCs along the coast of East Asia (e.g. Liu and Chan 2022). A

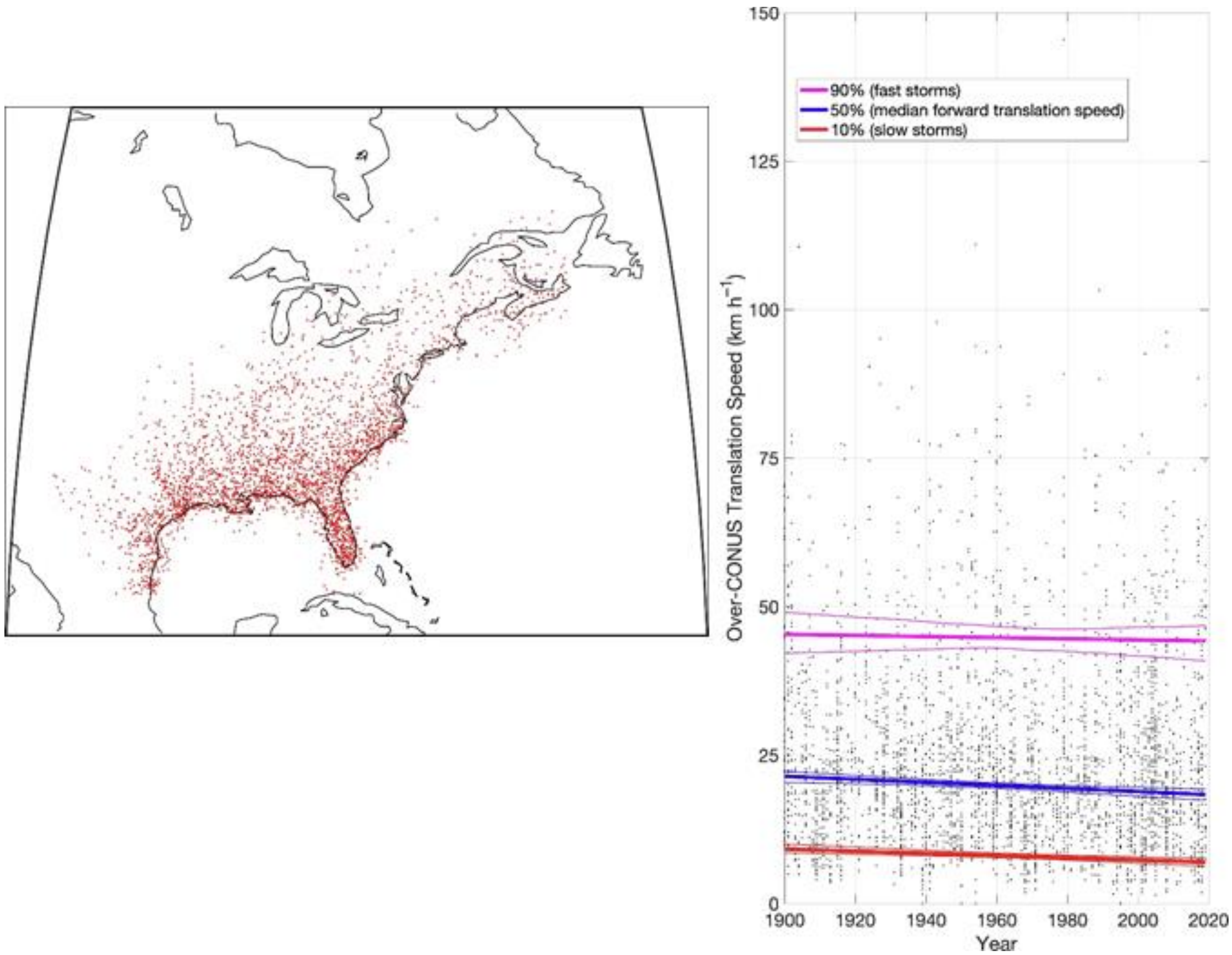

Figure A2 Slowdown of TC translation speed over the contiguous US since 1900. There has been a 14% slowdown in median and a 24% slowdown of the 10th percentile. Adapted from (Kossin 2018, 2019).

few studies reported increasing trends of the mean duration of TCs over land, and TC intensity at landfall over the east coast of China since 1980.

These increasing trends are due to a decrease in the weakening rate of TC intensity after landfall as well as the northward shift of landfalling TC tracks (Liu et al. 2020a; Chen et al. 2021a). Tian et al. (2022) found that for typhoons over China (1960–2018) the frequency and extreme intensity of heavy precipitation events has been increasing, with possible roles for changes in translation speed and shifts in tracks. Furthermore, an increase in the precipitation associated with landfalling typhoons in China using a different methodology was noted (Niu et al. 2022). Utsumi and Kim (2022) found that TC-related heavy rainfall has increased since 1961 for coastal East Asia, and decreased over the southern part of the WNP. Liu and Wang (2020) found a significant positive trend in the rainfall produced by weak TCs and strong TCs over southeastern and southern China, respectively.

c) North Indian Ocean

While no significant trend in overall TC numbers is found for the NIO basin since 1990s (Klotzbach et al. 2022), there is strong evidence that the number of severe and extremely severe cyclonic events (with lifetime maximum wind speed > 46 m s^{-1}) has increased over the period (Swapna et al. 2022). When separated into two subdomains, the Bay of Bengal and the Arabian Sea, distinct patterns of TC variability and trends can also be found. Climatologically, the Bay of Bengal region has more TCs than the Arabian Sea. But in recent years, a greater number of TCs are observed in the Arabian Sea compared with the Bay of Bengal (Deshpande et al. 2021; Liu et al. 2021). Deshpande et al. (2021) also showed increasing trends in most other TC metrics – such as in TC frequency and duration of cyclonic storms and very severe cyclonic storms, as well as in TC lifetime maximum intensity and accumulated cyclone energy – over the Arabian Sea during the period 1982-2019. These trends are absent for the Bay of Bengal.

d) South Indian and South Pacific Ocean

There is no clear trend in the annual number of TCs in the SIO and SP basins over the past three decades. However, there is some indication that the number of severe TCs (i.e., Categories 4–5) may have increased slightly (Klotzbach et al. 2022). In contrast, Chand et al. (2020) found weak but statistically insignificant, declining trends in the total numbers of TCs and in the frequency of severe TCs for the entire SP (i.e., east of 145°E) over the period 1981–2016. Similarly, for the Australian region (0–30°S; 90–160°E), Chand et al. (2019) found a decreasing trend in the frequency of TCs and severe TCs over the period 1981–2018. A slight decrease in landfalling TCs over the entire Australian coast was also noted.

Appendix 2 - ENSO and TC relationship

Changes in large-scale atmospheric and oceanic environmental variables affect TC activity (e.g., Chung et al. 2019; Kim et al. 2020a; Yamaguchi and Maeda 2020a; Feng et al. 2021; Basconcillo and Moon 2022; Lee et al. 2021; Utsumi and Kim 2022). In particular, Zhao and Wang (2019) suggested that more frequent CP ENSO-like events since the late 1990s increased the interannual relationship between ENSO and WNP TCs through the influence of mid-level moisture and vertical wind shear. In response to mean state changes, Zhao et al. (2019c) recently found an increased co-variability of tropical cyclogenesis latitude and longitude over the WNP basin which could be related to the Hadley and Walker circulations (Fig. A3). Their combined variation could be a plausible avenue for understanding global TC changes. Additionally, there is a close association between TC season onset date and major El Niño events via tropical western Pacific equatorial easterly anomalies and a Gill-type response, with major El Niño events consistently causing extremely late TC season onset date (Zhao et al. 2019b). Bell et al. (2020) examined ENSO's influence on TC track variability globally using CMIP5 models under a high emission climate scenario (RCP8.5) and showed that some models can simulate the ENSO and TC track relationship reasonably well. In some regions, they found regional changes in how ENSO will affect TC tracks, such as the SIO, which will become more La Niña-like, due to a decrease in the occurrence of TCs in El Niño events.

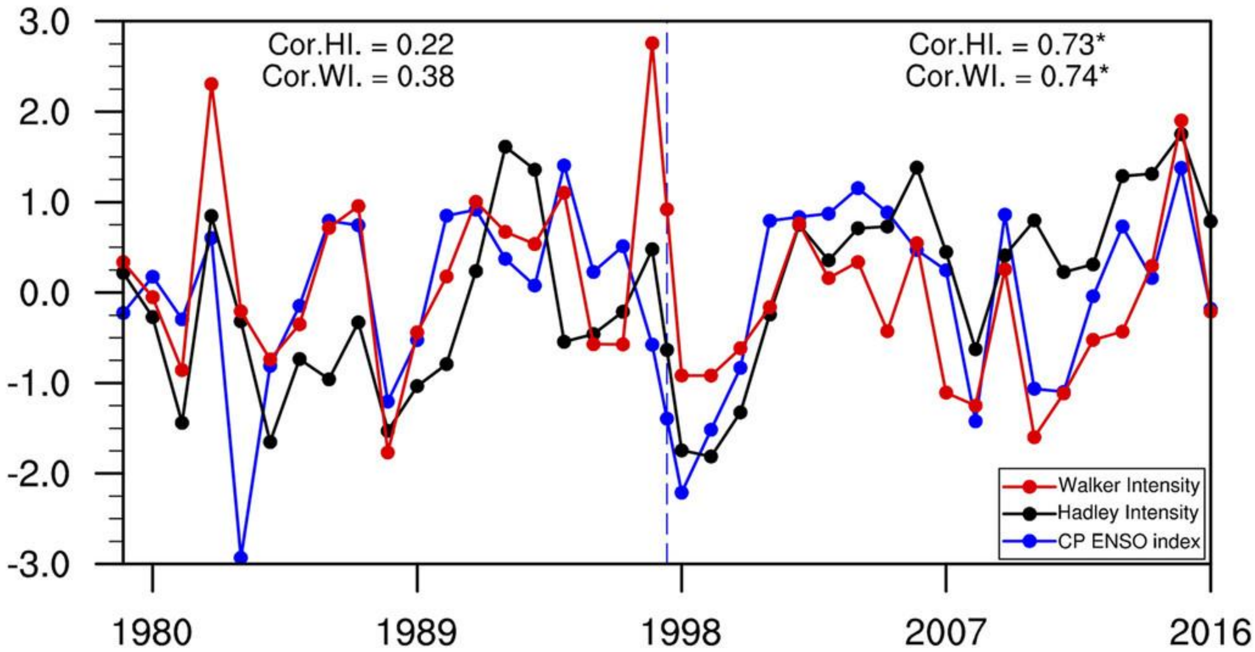

Figure A3 Normalized time series of Walker circulation intensity (WI), Hadley circulation intensity (HI), and the CP ENSO index. Correlations between the HI or WI and CP ENSO index during 1979–97 and 1998–2016 are also denoted. An asterisk indicates that the correlation is significant at a 95% confidence level. Adapted from Zhao et al. (2019c).