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An update on the influence of natural climate variability and anthropogenic climate change on tropical cyclones

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Abstract

A substantial number of studies have been published since the Ninth International Workshop on Tropical Cyclones (IWTC-9) in 2018, improving our understanding of the effect of climate change on tropical cyclones (TCs) and associated hazards and risks. These studies have 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 scales. However, there are still substantial uncertainties owing to model uncertainty in simulating historical TC decadal variability in the Atlantic, and the limitations of observed TC records. The projected future change in the global

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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.
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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. A review of the knowledge on TCs and climate was produced for the 9th International Workshop on Tropical Cyclones (IWTC-9) held in December of 2018 in Hawaii and published in Walsh et al. 2019. In December 2022, the 10th International Workshop on Tropical Cyclones (IWTC-10) was held in Bali, Indonesia. In preparation for that workshop, 20 working groups prepared reports on the progress in topics associated with tropical cyclones in the last 4 years. This review paper was prepared by an international working group team prior to the IWTC-10, was then presented at the workshop, where it was also discussed in breakout groups. More information about IWTC-10 can be found here: https://community.wmo.int/en/meetings/tenth-international-workshop-tropical-cyclones-iwtc-10. Many studies appeared in the period 2019–2022, which provided new understanding of TCs climate in the past, current, and potential future projections and will be discussed below.

A few review papers on tropical cyclones appeared since the publication of Walsh et al. 2019, in particular the companion papers Knutson et al. 2019; Knutson et al. 2020, focusing on TC trends and projections, respectively. TCs' trends and projections were included in the latest IPCC chapter on extreme events (Seneviratne et al. 2021), while Cha et al. 2020; Lee et al. 2020b focused on TC trends and projections in the western North Pacific only (i.e., typhoons), Sobel et al. 2021 discussed the uncertainty of TC frequency projections and the pathways forward and Lin et al. 2020 summarized the relationship between the El Niño-Southern Oscillation (ENSO) and TCs in the past, current and future climates.

Here we present a review written by an international group of experts for IWTC-10, which was held in December 2022 in Bali. The focus of the review is the new research that appeared since IWTC-9 in a variety of topics, specifically paleohurricanes; historical TCs; TC detection and attribution; TC future projections; as well as a few emerging topics, such as TC risk. We conclude with the recommendations that were presented at the workshop, and a discussion of future research topics.

2. Observations

2.1. 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.

2.2. 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. 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 20th 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 km per decade (Fig. 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

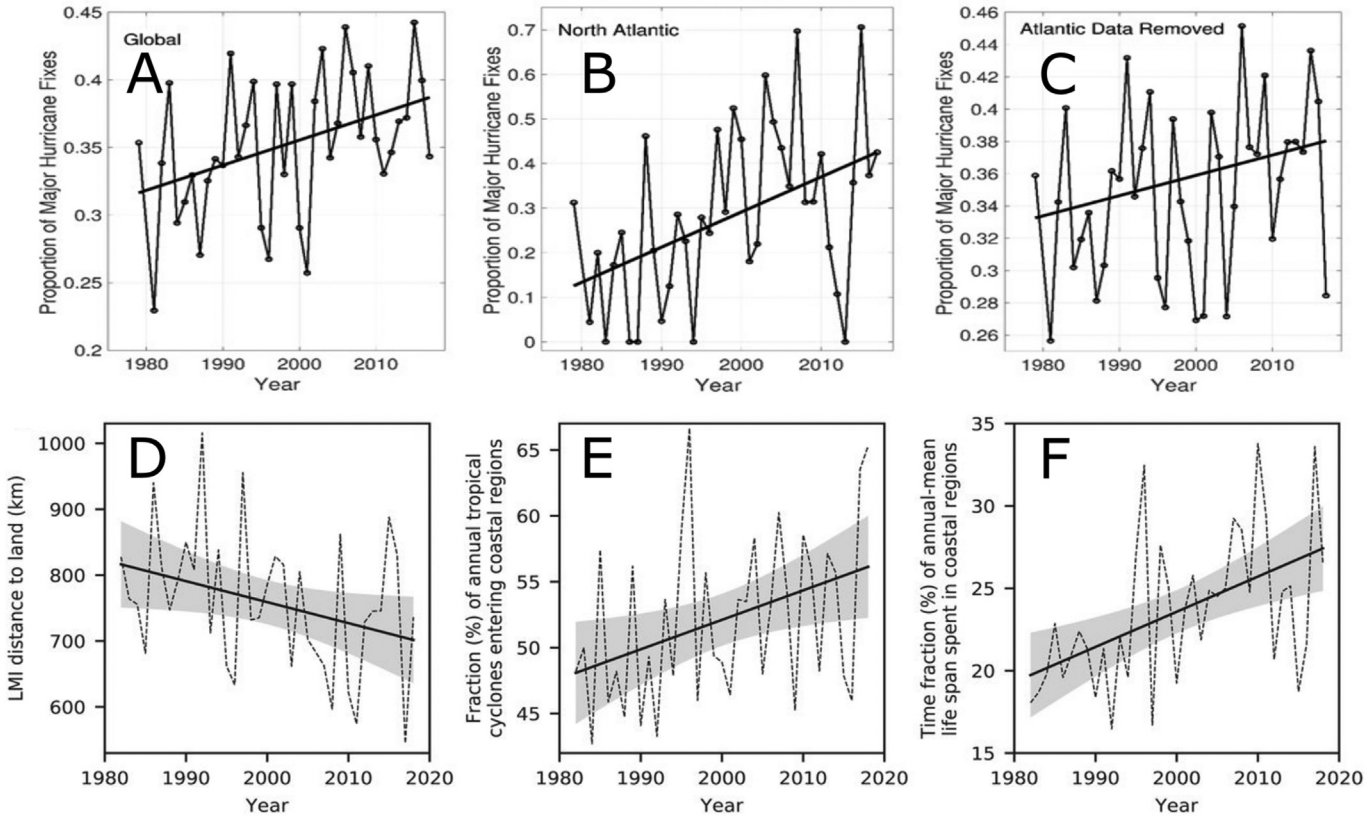

Fig. 1. (a–c) Observed trends in the proportion of major hurricane frequency to all hurricane estimates for the period 1979–2017 for (a) global, (b) North Atlantic, and (c) global, but with the North Atlantic data removed. (d–f) Observed trends in "land-ward" migration of global TCs for the period 1982–2018 in terms of (d) annual-mean distance to land of the locations of lifetime maximum intensity (LMI, km); (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 (%). The lines show linear trends. Figure adapted from Kossin et al. (2020) (licensed under CC BY-NC-ND 4.0) and Wang and Toumi (2021) (@Science). Used with permission.

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.

2.3. 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 1 provides a summary of these findings. Detailed descriptions for each basin are given below. Generally, the increasing trend in TC intensity is more robust than the changes in the number of storms among the ocean basins.

2.3.1. 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 basin wide 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

Table 1
Summary of observed trends in TC metrics for each ocean basin.

	Number	Intensity	Other 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	• Increase in 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)	• Increase in 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) • Increase in 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; Kranthi et al., 2022)	
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

hurricanes or major hurricanes (Vecchi et al. 2021, Fig. 2). 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 (Kossin 2018, see discussion on section 3.3) has been 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.

2.3.2. 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.

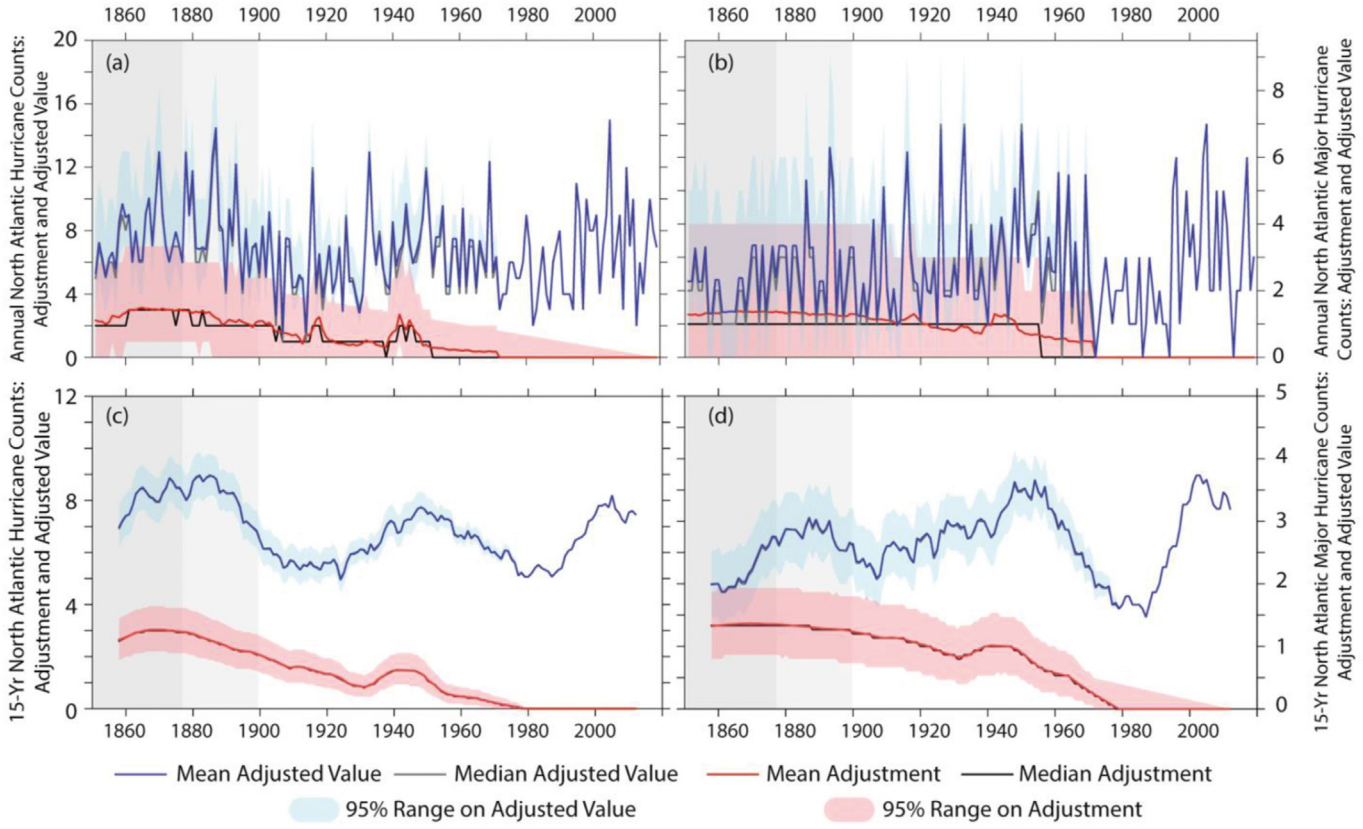

Fig. 2. NA missing storm adjustment and adjusted basin-wide hurricane and major hurricane frequency. Top panels (a) and (b) show adjusted values for each year 1851–2019, bottom panels c, d show the values for the 15-year centered average of basin-wide frequency; the frequency of NA hurricanes is shown on the left, and of NA major hurricanes on the right. In each panel, the red thick line shows the mean estimate of the missing storm adjustment, the thick black line shows the median estimate, and the pink shading shows the 95 % range on the adjustment based on a bootstrap resampling of the adjustments; the thick blue line shows the mean estimate on basin-wide frequency, the thin black line shows the median estimate of the adjusted frequency, the sky-blue shading shows the 95 % range on the adjusted value based on a bootstrap resampling of the adjustments. In the bottom panels (c) and (d) a dotted gray line shows the 15-year centered average of the recorded HURDAT2 counts. Gray background shadings between 1851 and 1877 and between 1878 and 1900 highlight times where we have reduced confidence in the frequency estimates even after adjusting for likely missing storms. Figure from Vecchi et al. (2021), licensed under CC BY-NC-ND 4.0. Used with permission.

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 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.

2.3.3. 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. Kranthi et al. (2022) observed similar trends for RI storms in the Arabian Sea, with an increase in their frequency duration, and LMI. These trends are absent for the Bay of Bengal.

2.3.4. South Indian Ocean 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.

3. Detection and attribution

3.1. 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. Wehner and Sampson (2021) used a hydraulic model to analyze the flooding associated with Hurricane Harvey (2017) and found that the attributable increase in the total volume of flood waters is the similar to the attributable increase in precipitation, but the total area of the flood is lower.

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) examined the role of

anthropogenic forcing on the active 2018 WNP TC season. The results of the two climate models used in the study had opposite TC frequency changes emphasizing the uncertainty and model dependence on the response of WNP TC activity to anthropogenic forcing.

3.2. Detection and attribution of tropical cyclone trends

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. 3). 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 can induce changes in TC activity in regions far from those where the aerosols are emitted through the changes in the atmospheric circulation. For instance, the reduction in anthropogenic aerosols in Europe and the United States led to a differential heating between the northern and southern hemispheres, which was responsible for an anomalous meridional atmospheric circulation.

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. In a follow up study, Bhatia et al. (2022) compared observed trends in intensification and tropical cyclone environmental parameters simulated in high-resolution climate models and detected a significant increase in intensification rates with a contribution from anthropogenic warming. 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 (multidecadal) 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) has been dominated by modulation by the Atlantic Multidecadal Variability, without identifying the specific mechanisms responsible for these variations (e.g., natural variability, aerosols).

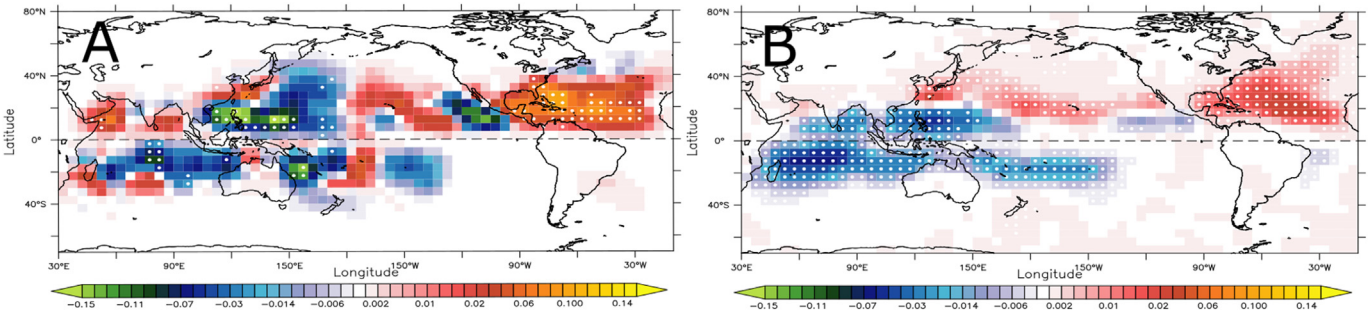

Fig. 3. (A) Observed trends in TC density during 1980–2018 (units: number per year). (B) As in (A), but for the ensemble mean of the historical experiments by the climate models considering anthropogenic forcing. TC positions were counted for each 5° × 5° grid box every 6-h within the global domain. The total count for each grid box was defined as TC density. The white dot indicates that the linear trend over the grid cell is statistically significant at the 95 % level according to the Mann–Kendall significance test. The similarity between (A) and (B) indicates a substantial effect of anthropogenic forcing on the observed trends in the spatial distribution of TCs over the past 40 years. Figure adapted from Murakami et al. (2020), licensed under CC BY-NC-ND 4.0, used with permission.

Trenary et al. (2019) could not identify a detectable trend in North Atlantic potential intensity using CMIP5 models and reanalyses due to large disagreements and uncertainties among the different products. 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 2020) was attributed to the trend in observed SSTs, but not directly to anthropogenic forcing.

3.3. 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. Hall and Kossin (2019) also reported a slowing trend in TCs along the North American coast over the period 1944–2017 and associated increases in TC rainfall. 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). Kossin (2019) documented a slowing trend in TCTS over the continental U.S. since 1900 after accounting for the dominant modes of variability in the Atlantic – 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 (2020) 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 inter-annual 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 role of the ocean in determining TCTS. For instance, 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).

4. Projections

4.1. 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. 4), indicating that the majority of studies (22 out of 27 studies) project a decrease in global TC frequency of ~13 % for 2 °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. (2020a) 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. In

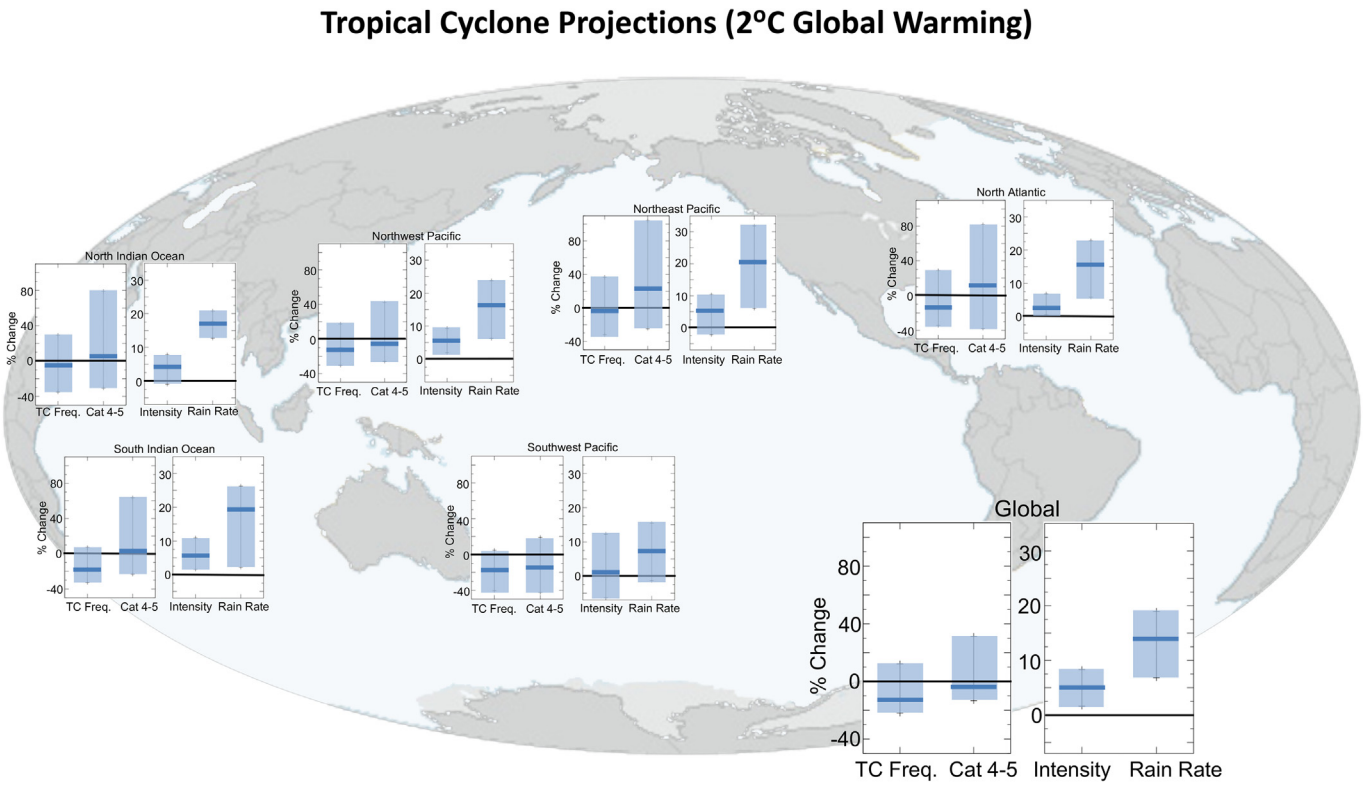

Fig. 4. Summary of TC projections for a 2 °C global anthropogenic warming reported in Knutson et al. (2020a). Shown for each basin and the globe are median and percentile ranges for projected percentage changes in TC frequency, Cat. 4–5 TC frequency, TC intensity, and TC near-storm rain rate. For TC 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. (2020b) (© American Meteorological Society, used with permission).

the isolated CO_2 increase experiments, both the TC seed frequency and the genesis probability decrease, leading to a consistent decrease in global TC frequency. In contrast, for the warming experiments, these changes are of opposite sign, which in some cases leads to an increase in TC frequency and in others a decrease (see the detailed discussion on TC seed in section 4.3).

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 and in most cases showed that future extratropical transitions led to events with greater intensity, heavier precipitation and stronger downstream mid-latitude development, though not all of the characteristics are statistically significant or present in all of the models analyzed. Idealized experiments suggest that the changes in the large-scale thermodynamic environment influence the characteristics of ET, rather than changes in baroclinicity.

4.2. 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, such as historical strengthening of the tropical Pacific zonal sea surface temperature gradient that is inconsistent with climate models (Seager et al. 2019)), 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 poleward. 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, across CMIP5 models there is a robust reduced low-level convergence and increased vertical wind shear and these are the most important factors responsible for the changes in TC activity in that region. 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. 4), 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. Recently, Balaguru et al. (2023) examined mechanisms for projections of increased hurricane frequency for the Gulf of Mexico and southern part of the US East coast. They found that the increased hurricane frequency was associated with changes in the steering flow, due to the development of an upper-level cyclonic circulation over the western Atlantic, which in turn was arising mainly from increased diabatic heating in the eastern tropical Pacific. 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 basin wide 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.

4.3. Role of the environment and seeds in determining tropical cyclone frequency

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. The efficiency with which TC seeds develop into TCs has an important role in determining TC frequency. Ikehata and Satoh (2021) analyzed the relative contribution of TC seed frequency and survival rate to TC frequency and showed that TC frequency variability is mainly controlled by the survival rate, which varies with environmental fields. 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) as they may depend on a different set of environmental variables than the subsequent TCs. 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; Danso et al. 2022). 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, in agreement with Ikehata and Satoh (2021). 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.

4.4. 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. (2020a)'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. As climate warms, TCs are also projected to shift towards higher latitudes (poleward migration). Lin et al. 2023 quantify poleward migration's impact on TC's PI. It is found that poleward migration can reduce the increasing trends of the proportion of Category-5 PI by 42 %; and averaged PI by 68 %, under the CMIP5 RCP 8.5 pathway.

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 an increase of ~10 % in storm intensity in the South China Sea.

4.5. 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, as in the case of Japan in the last 40 years (Islam et al. 2022). 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. (2020) 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).

5. Environmental factors influencing tropical cyclone activity

5.1. Relationship between ENSO and tropical cyclones – 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. 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 2020; 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 Central Pacific ENSO events, when compared to eastern Pacific ENSO 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. 5). 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 Matsuno-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

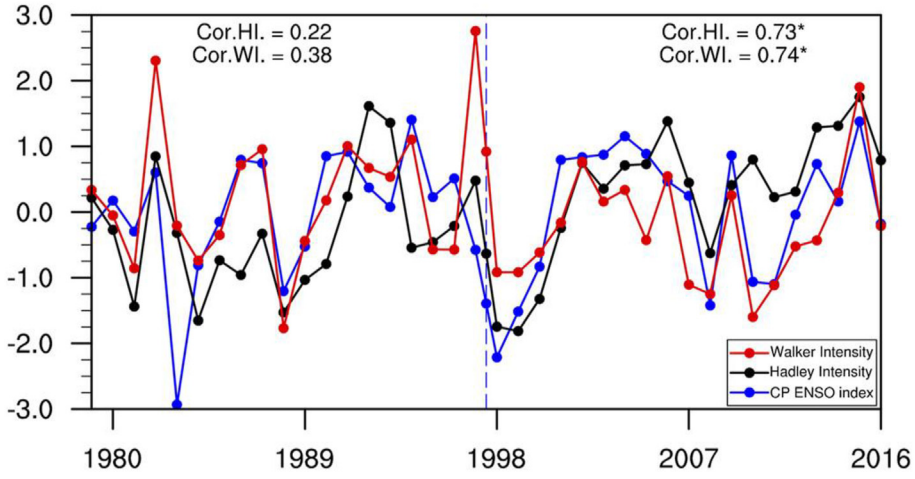

Fig. 5. Normalized time series of Walker circulation intensity (WI, red), Hadley circulation intensity (HI, black), and the CP ENSO index (blue). Correlations between the HI or WI and CP ENSO index during 1979–97 and 1998–2016 are also denoted. An asterisk indicates that the correlation is significant at a 95 % confidence level. Adapted from Zhao et al. (2019c). (© American Meteorological Society. Used with permission).

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, where a cluster analysis showed that in one of the SIO clusters, there are fewer TCs occurring in La Niña events in the RCP8.5 future scenario than in the historical simulation, while two other SIO clusters, which were not dominated by ENSO in the historical simulation, show an increase of TCs in La Niña events at the end of the century.

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 (see Fig. 6 and also Yoshida et al. 2017). 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

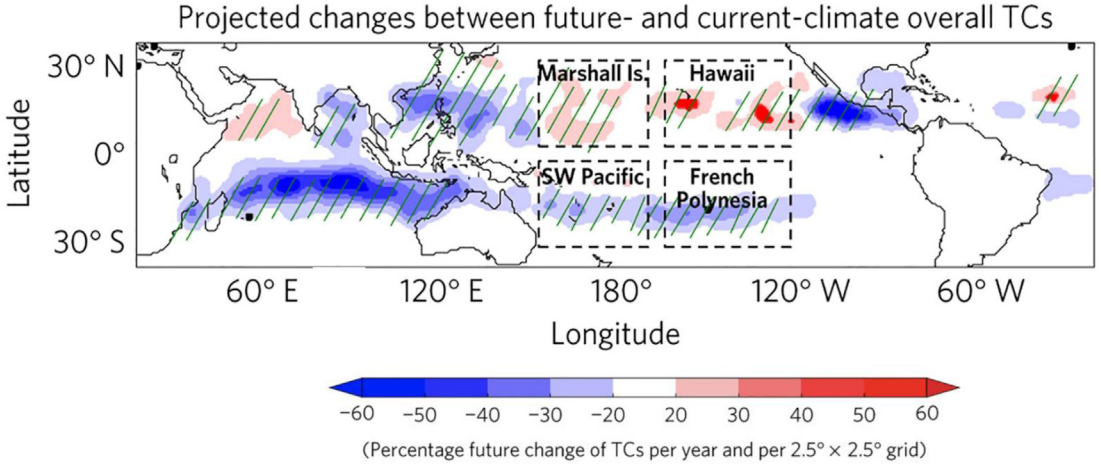

Fig. 6. Projected future changes in TC density showing "ocean-ward" migration projected by the CMIP5 models under the RCP8.5 scenario at the end of this century (2070–2100) relative to the 20th century (1970–2000). Stippling denotes changes that are statistically significant at the 95 % level, with at least 9 out of 12 models agreeing on the sign of change. Adapted from Chand et al. (2017), used with permission.

expectation that changes in ENSO characteristics may influence its relationship with TCs in the future.

5.2. Other environmental 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. 7). 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). Anomalies 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 anomalies are associated with *trans*-basin SST anomalies mainly modulated by the large-scale circulation (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).

5.3. 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

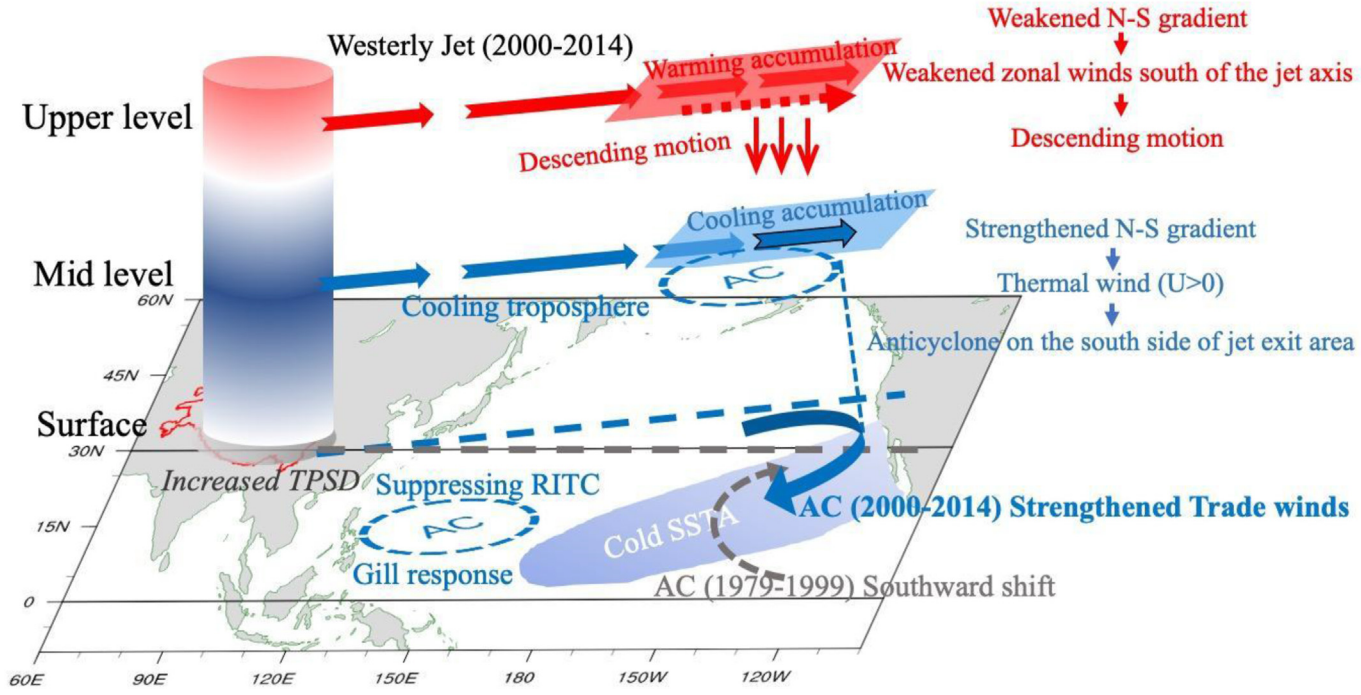

Fig. 7. Schematic diagram of the potential relationship between January–March Tibetan Plateau snow depth with July–November rapidly intensifying TCs over the WNP during 2000–2014. The red and blue vectors represent warm and cold advection at upper levels and mid-levels, respectively. The dotted arrow denotes weaker winds. The label "AC" represents an anticyclonic circulation at 850 hPa. The red curve represents the portion of the TP above 3000 m. Adapted from Cai et al. (2022). (© American Meteorological Society. Used with permission).

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 tropics in the CMIP6 models were investigated by Zhu et al. (2021), the thermoclines tend to be too shallow in the northwestern tropics and too deep in the northeastern tropics.

6. 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 on 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. (2020a), Emanuel (2021b) and Bloemendaal et al. (2022) also analyzed TC future risk. Lee et al. (2020a) 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. Xi et al. (2023) found that the risk of hazards or damage potential from two separate tropical cyclones impacting a given location within a 15-day period is projected to increase for the East and Gulf coasts of the U.S. under high and moderate emission scenarios in their model, due to the influence of both changes in storm characteristics and sea level rise. This, they found, could lead to higher impacts from the compound events than from single-hazard events–which could raise additional challenges for resilience planning.

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 and 97 years, and a Cat. 3100–500 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. Meiler et al. (2022) performed an intercomparison of regional loss estimates using three different synthetic TC hazard models. Baldwin et al. (2023) showed that varying the vulnerability function by administrative regions in the Philippines improves the accuracy of Philippines TC risk estimates.

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 areas corresponding to 10 % and 36 % of 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 storm on the scale of Cyclone Amphan (2020) could clead to 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 vulnerability (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).

7. 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 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, e.g. simulation of a small cyclone embedded within the broader circulation of a Mediterranean cyclone, which requires a horizontal resolution of the order of a few kilometres (Carrió et al. 2020; Flaounas et al. 2022). 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 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.

8. Future research and recommendations

In the last few years there has been significant progress in the TC climatology, trends and attribution, modulation by natural climate variability and projections. Building on that progress, we hope to see in the next few years new aspects of these topics explored, leading to a better understanding of the process involved in the response and feedback of TCs to climate modes, more in depth description of the risks posed by TCs and more robust future projections of TCs.

In paleotempestology, it is fundamental for the community to continue to obtain more paleohurricane records worldwide and to integrate different reconstruction records, which will help constrain basin-scale variability in TC activity. One potential new avenue for progress in this topic is the combination of millennial-scale simulations and paleohurricane records.

With the availability of a relatively observationally consistent period of TC record since 1990, we expect that some of the uncertainty of TC metrics trends will be reduced. However, this will be dependent on the continuous investment of the community in producing best-track datasets that are less sensitive to changes in technological and monitoring practices. It will be important to determine if some of the current observed trends (e.g. LMI poleward shift in the WNP) will continue, as well as striving for a better understanding of the processes responsible for some recently detected trends (e.g. migration of typhoons toward coastal regions, trends in translation speed). In particular, efforts towards new studies on the attribution of various TC trends to anthropogenic climate change, combined with more robust regional TC projections, and TC risk analysis–including social and economic aspects–will better inform local communities as they prepare for future TC risk.

Event attribution of TCs is another topic that will certainly continue to expand, as is happening for all types of extreme events. With clearer definitions and protocols for attribution for individual events (e.g. Philip et al. 2020; Otto et al. 2022), this type of analysis will become almost operationally routine (Otto et al. 2022), and better communicated and understood. So far, event attribution for TCs has focused on TC intensity and associated precipitation using an idealized storyline approach. It will be interesting to determine whether other aspects of individual events or anomalous TC seasons can be attributed to anthropogenic climate change. Even in the case of TC intensity, there are new aspects to explore, in particular 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.

The role of TC seeds in the present-day climate and future projections should be further explored, given that there are differing views on this issue in the community. While various studies propose that TC seeds and their efficiency in becoming TCs are fundamental in determining TC frequency, others argue that TC frequency is mainly determined by the large-scale environmental variability, with TC seeds playing a lesser role in determining TC frequency. This is a very active area of research, and we expect that research will continue over the coming years in order to make progress on this important issue.

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. Therefore, it is highly recommended to assess the models' capability to accurately reproduce the present-day climate, including its variability, along with past trends in environmental factors that affect TCs. In addition, the response of TCs to the past trends and variability of the environmental factors needs to be assessed in models, in order to gain more confidence in future projections. Such evaluations will be crucial for improving the reliability and confidence 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. 1d–f). In contrast, Chand et al. (2017) projected an oceanward shift of TCs in that region (Fig. 6). These are very different scenarios, especially from a disaster mitigation perspective. Whether the observed recent migrations towards the coast are due to anthropogenic forcing or natural variability, or the projected ocean-ward shift of the WNP TCs is influenced by model biases (e.g., related to ENSO) requires further investigation.

A diverse array of modeling approaches should be used to make progress in understanding relationship of TCs-climate. For instance, it is important to use larger ensemble sizes in high-resolution simulations of TCs, as single or small ensemble simulations do not allow for exploration of the full spectrum of the role of natural variability and its role, compared to anthropogenic climate change, in determining future TC activity. Possible alternatives to century scale simulations, such as time-slices or global warming levels, could be used in tandem with the standard long-simulations currently commonly used.

One important existing effort of the climate community in achieving these goals is HighResMIP. The first phase of HighResMIP (HighResMIPv1.0 for CMIP6; Haarsma et al. 2016) successfully produced a baseline multi-model assessment of global simulations for TC analysis with model grid spacings of around 0.5° or less in the atmosphere and 0.25° in the ocean, comparing to models with standard resolutions typically used as part of the CMIP6 DECK experiments with grid spacings of around 1.0° and larger. However, the use of a single future scenario (with a 2050 end date) for HighResMIPv1.0, the focus on resolution sensitivities, and the small ensemble sizes (often just one) for each model, limited broad application of the ensemble for the projection of TC characteristics into the future. In the coming years, HighResMIPv2.0 will focus on improving and extending on the previous phase to focus on science questions related to future TC projection, such as increasing the ensemble size for each participating model, using several future scenarios and extending them to 2100, and protocols for incorporating short simulations at even higher resolutions at specific time periods to connect to km-scale modeling and assess uncertainty. Future reports will evaluate advances made from this upcoming ensemble.

A complementary effort exists in kilometer-scale model simulations, such as DYAMOND (Stevens et al. 2019), which uses global storm-resolving models. These models open a new frontier in the simulation of TCs and improve upon some of the typical issues of current climate models, such as the simulation of the most intense TCs (Judt et al. 2021), however there are still necessary improvements which hopefully will happen in the next few years.

Risk analysis and TC risk models are a rapidly expanding field within academia, and we expect that is a trend that will continue in the near future. In particular, close collaboration between industry and universities provide important lessons on how to improve and interpret the TC risk analysis. Inclusion of the full range of TC hazards (wind, precipitation and storm surge), as well as improvements of vulnerability and exposure components of these models, will lead to more reliable risk estimates. We expect that studies that explore the full socio-economic impact of TCs (e.g. Smiley et al. 2022; Meiler et al. 2022; Baldwin et al. 2023) will become more common and will be useful to a range of decision makers, including government, private companies, non-profits.

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. The coordination across the community will be fundamental for progress in modeling, prediction and projections of medicanes. A

recent important perspective on this topic (Flaounas et al. 2022) provides useful guidance on the various pathways forward.

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Acronyms

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
RI	rapid intensification
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

References

Akter, A., Dayem, A., 2021. Tropical cyclone risk mapping for a coastal city using geospatial techniques. J. Coast. Conserv. 25, 1. https://doi.org/10.1007/s11852-020-00788-y.

Altman, J., Saurer, M., Dolezal, J., Maredova, N., Song, J.-S., Ho, C.-H., Treydte, K., 2021. Large volcanic eruptions reduce landfalling tropical cyclone activity: evidence from tree rings. Sci. Total Environ. 775, 145899. https://doi.org/10.1016/j.scitotenv.2021.145899.

Bacmeister, J.T., Reed, K.A., Hannay, C., Lawrence, P., Bates, S., Truesdale, J.E., Rosenbloom, N., Levy, M., 2018. Projected changes in tropical cyclone activity under future warming scenarios using a high-resolution climate model. Clim. Change 146, 547–560. https://doi.org/10.1007/s10584-016-1750-x.

Bakkensen, L.A., Mendelsohn, R.O., 2016. Risk and adaptation: evidence from global hurricane damages and fatalities. J. Assoc. Environ. Resour. Econ. 3, 555–587. https://doi.org/10.1086/685908.

Balaguru, K., Foltz, G.R., Leung, L.R., Kaplan, J., Xu, W., Reul, N., Chapron, B., 2020. Pronounced impact of salinity on rapidly intensifying tropical cyclones. Bull. Am. Meteorol. Soc. 101, E1497–E1511. https://doi.org/10.1175/BAMS-D-19-0303.1.

Balaguru, K., Foltz, G.R., Leung, L.R., Hagos, S.M., 2022. Impact of rainfall on tropical cyclone-Induced sea surface cooling. Geophys. Res. Lett. 49, e2022GL098187. https://doi.org/10.1029/2022GL098187.

Balaguru, K., Xu, W., Chang, C.-C., Leung, L.R., Judi, D.R., Hagos, S.M., Wehner, M.F., Kossin, J.P., Ting, M., 2023. Increased U.S. coastal hurricane risk under climate change. Sci. Adv. 9, eadf0259. https://doi.org/10.1126/sciadv.adf0259.

Baldwin, J.W., Lee, C.-Y., Walsh, B.J., Camargo, S.J., Sobel, A.H., 2023. Vulnerability in a tropical cyclone risk model: Philippines case study. Wea. Clim. Soc. 15, 503–523. https://doi.org/10.1175/WCAS-D-22-0049.1.

Basconcillo, J., Moon, I.-J., 2022. Increasing activity of tropical cyclones in East Asia during the mature boreal autumn linked to long-term climate variability. Npj Clim. Atmos. Sci. 5, 1–11. https://doi.org/10.1038/s41612-021-00222-6.

Bell, S.S., Chand, S.S., Camargo, S.J., Tory, K.J., Turville, C., Ye, H., 2019a. Western North Pacific tropical cyclone tracks in CMIP5 models: statistical assessment using a model-independent detection and tracking scheme. J. Clim. 32, 7191–7208. https://doi.org/10.1175/JCLI-D-18-0785.1.

Bell, S.S., Chand, S.S., Tory, K.J., Dowdy, A.J., Turville, C., Ye, H., 2019b. Projections of southern hemisphere tropical cyclone track density using CMIP5 models. Clim. Dyn. 52, 6065–6079. https://doi.org/10.1007/s00382-018-4497-4.

Bell, S.S., Chand, S.S., Tory, K.J., Turville, C., Ye, H., 2019c. Eastern North Pacific tropical cyclone activity in historical and future CMIP5 experiments: assessment with a model-independent tracking scheme. Clim. Dyn. 53, 4841–4855. https://doi.org/10.1007/s00382-019-04830-0.

Bell, S.S., Chand, S.S., Turville, C., 2020. Projected changes in ENSO-driven regional tropical cyclone tracks. Clim. Dyn. 54, 2533–2559. https://doi.org/10.1007/s00382-020-05129-1.

Bhatia, K., Vecchi, G., Murakami, H., Underwood, S., Kossin, J., 2018. Projected response of tropical cyclone intensity and intensification in a global climate model. J. Clim. 31, 8281–8303. https://doi.org/10.1175/JCLI-D-17-0898.1.

Bhatia, K.T., Vecchi, G.A., Knutson, T.R., Murakami, H., Kossin, J., Dixon, K.W., Whitlock, C.E., 2019. Recent increases in tropical cyclone intensification rates. Nat. Commun. 10, 635. https://doi.org/10.1038/s41467-019-08471-z.

Bhatia, K., Baker, A., Yang, W., Vecchi, G., Knutson, T., Murakami, H., Kossin, J., Hodges, K., Dixon, K., Bronselaer, B., Whitlock, C., 2022. A potential explanation for the global increase in tropical cyclone rapid intensification. Nat. Commun 13, 6626. https://doi.org/10.1038/s41467-022-34321-6.

Bieli, M., Sobel, A.H., Camargo, S.J., Murakami, H., Vecchi, G.A., 2020. Application of the Cyclone Phase Space to extratropical transition in a global climate model. J. Adv. Model. Earth Syst. 12. https://doi.org/10.1029/2019MS001878.

Bloemendaal, N., Koks, E.E., 2022. In: Collins, J.M., Done, J.M. (Eds.), Current and Future Tropical Cyclone Wind Risk in the Small Island Developing States. **Chapter 6**, Hurricane Risk in a Changing Climate, Hurricane Risk, 2. Springer International Publishing, pp. 121–142. https://doi.org/10.1007/978-3-031-08568-0_6.

Bloemendaal, N., Muis, S., Haarsma, R.J., Verlaan, M., Irazoqui Apecechea, M., de Moel, H., Ward, P.J., Aerts, J.C.J.H., 2019. Global modeling of tropical cyclone storm surges using high-resolution forecasts. Clim. Dyn. 52, 5031–5044. https://doi.org/10.1007/s00382-018-4430-x.

Bloemendaal, N., de Moel, H., Muis, S., Haigh, I.D., Aerts, J.C.J.H., 2020. Estimation of global tropical cyclone wind speed probabilities using the STORM dataset. Sci. Data 7, 377. https://doi.org/10.1038/s41597-020-00720-x.

Bloemendaal, N., de Moel, H., Martinez, A.B., Muis, S., Haigh, I.D., van der Wiel, K., Haarsma, R.J., Ward, P.J., Roberts, M.J., Dullaart, J.C.M., Aerts, J.C.J.H., 2022. A globally consistent local-scale assessment of future tropical cyclone risk. Sci. Adv. 8, eabm8438. https://doi.org/10.1126/sciadv.abm8438.

Bramante, J.F., Ford, R.M., Kench, P.S., Ashton, A.D., Toomey, M.R., Sullivan, R.M., Karnauskas, K.B., Ummenhofer, C.B., Donnelly, J.P., 2020. Increased typhoon activity in the Pacific deep tropics driven by Little Ice Age circulation changes. Nat. Geosci. 13, 806–811. https://doi.org/10.1038/s41561-020-00656-2.

Bruyère, C.L., Done, J.M., Jaye, A.B., Holland, G.J., Buckley, B., Henderson, D.J., Leplastrier, M., Chan, P., 2019. Physically-based landfalling tropical cyclone scenarios in support of risk assessment. Weather Clim. Extrem. 26, 100229. https://doi.org/10.1016/j.wace.2019.100229.

Burn, M.J., 2021. On the interpretation of natural archives of Atlantic tropical cyclone activity. Geophys. Res. Lett. 48, e2021GL092456. https://doi.org/10.1029/2021GL092456.

Cai, W., Santoso, A., Wang, G., Wu, L., Collins, M., Lengaigne, M., Power, S., Timmermann, A., 2020. ENSO response to greenhouse forcing. **Chapter 13**, *El Niño southern Oscillation in a changing climate*. In: McPhaden, M.J., Santoso, A., Cai, W. (Eds.), Geophysical Monograph Series. American Geophysical Union, pp. 289–307. https://doi.org/10.1002/9781119548164.ch13.

Cai, Y., Han, X., Zhao, H., Klotzbach, P.J., Wu, L., Raga, G.B., Wang, C., 2022. Enhanced predictability of rapidly intensifying tropical cyclones over the western North Pacific associated with snow depth changes over the Tibetan Plateau. J. Clim. 35, 2093–2110. https://doi.org/10.1175/JCLI-D-21-0758.1.

Camargo, S.J., Wing, A.A., 2021. Increased tropical cyclone risk to coasts. Science 371, 458–459. https://doi.org/10.1126/science.abg3651.

Carrió, D.S., Homar, V., Jansà, A., Picornell, M.A., Campins, J., 2020. Diagnosis of a high-impact secondary cyclone during HyMeX-SOP1 IOP18. Atmos. Res. 242, 104983. https://doi.org/10.1016/j.atmosres.2020.104983.

Cao, X., Wu, R., Sun, Y., Wang, Z., Dai, Y., Song, L., Lan, X., Zhang, X., 2021. Impact of North America snow cover on tropical cyclogenesis over the western North Pacific. Environ. Res. Lett. 16, 124054. https://doi.org/10.1088/1748-9326/ac3bff.

Cattiaux, J., Chauvin, F., Bousquet, O., Malardel, S., Tsai, C.-L., 2020. Projected changes in the southern Indian Ocean cyclone activity assessed from high-resolution experiments and CMIP5 models. J. Clim. 33, 4975–4991. https://doi.org/10.1175/JCLI-D-19-0591.1.

Cavicchia, L., von Storch, H., Gualdi, S., 2014a. A long-term climatology of medicanes. Clim. Dyn. 43, 1183–1195. https://doi.org/10.1007/s00382-013-1893-7.

Cavicchia, L., von Storch, H., Gualdi, S., 2014b. Mediterranean tropical-like cyclones in present and future climate. J. Clim. 27, 7493–7501. https://doi.org/10.1175/JCLI-D-14-00339.1.

Cha, E.J., Knutson, T.R., Lee, T.-C., Ying, M., Nakaegawa, T., 2020. Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region – Part II: future projections. Trop. Cyclone Res. Rev. 9, 75–86. https://doi.org/10.1016/j.tcrr.2020.04.005.

Chaluvadi, R., Varikoden, H., Mujumdar, M., Ingle, S.T., 2021. Variability of West Pacific subtropical high and its potential importance to the Indian summer monsoon rainfall. Int. J. Climatol. 41, 4047–4060. https://doi.org/10.1002/joc.7057.

Chan, D., Vecchi, G.A., Yang, W., Huybers, P., 2021. Improved simulation of 19th- and 20th-century North Atlantic hurricane frequency after correcting historical sea surface temperatures. Sci. Adv. 7, eabg6931. https://doi.org/10.1126/sciadv.abg6931.

Chan, K.T.F., 2019. Are global tropical cyclones moving slower in a warming climate? Environ. Res. Lett. 14, 104015. https://doi.org/10.1088/1748-9326/ab4031.

Chand, S.S., Tory, K.J., Ye, H., Walsh, K.J.E., 2017. Projected increase in El Niño-driven tropical cyclone frequency in the Pacific. Nat. Clim. Change 7, 123–127. https://doi.org/10.1038/nclimate3181.

Chand, S.S., Dowdy, A.J., Ramsay, H.A., Walsh, K.J.E., Scott, P.B., Bell, S.S., Lavender, S.L., Ye, H., Kuleshov, Y., 2019. Review of tropical cyclones in the Australian region: climatology, variability, predictability, and trends. WIRES Clim. Change 10, e602. https://doi.org/10.1002/wcc.602.

Chand, S.S., Dowdy, A., Bell, S., Tory, K., 2020. In: Kumar, L. (Ed.), A Review of South Pacific Tropical Cyclones: Impacts of Natural Climate Variability and Climate Change. **Chapter 6,** Climate Change and Impacts in the Pacific. Springer Climate, Springer International Publishing, pp. 251–273. https://doi.org/10.1007/978-3-030-32878-8_6.

Chand, S.S., Walsh, K.J.E., Camargo, S.J., Kossin, J.P., Tory, K.J., Wehner, M.F., Chan, J.C.L., Klotzbach, P.J., Dowdy, A.J., Bell, S.S., Ramsay, H.A., Murakami, H., 2022. Declining tropical cyclone frequency under global warming. Nat. Clim. Change 12, 655–661. https://doi.org/10.1038/s41558-022-01388-4.

Chang, P., Zhang, S., Danabasoglu, G., Yeager, S.G., Fu, H., Wang, H., Castruccio, F.S., Chen, Y., Edwards, J., Fu, D., Jia, Y., Laurindo, L.C., Liu, X., Rosenbloom, N., Small, R.J., Xu, G., Zeng, Y., Zhang, Q., Bacmeister, J., Bailey, D.A., Duan, X., DuVivier, A.K., Li, D., Li, Y., Neale, R., Stössel, A., Wang, Li, Yuan, Zhuang, Baker, Allison, Bates, Susan, Dennis, John, Diao, Xiliang, Gan, Bolan, Gopal, A., Jia, D., Jing, Z., Ma, X., Saravanan, R., Strand, W.G., Tao, J., Yang, H., Wang, X., Wei, Z., Wu, L., 2020a. An unprecedented set of high-resolution Earth system simulations for understanding multiscale interactions in climate variability and change. J. Adv. Model. Earth Syst. 12, e2020MS002298. https://doi.org/10.1029/2020MS002298.

Chang, Y.-T., Lin, I.-I., Huang, H.-C., Liao, Y.-C., Lien, C.-C., 2020b. The association of typhoon intensity increase with translation speed increase in the South China Sea. Sustainability 12, 939. https://doi.org/10.3390/su12030939.

Chassignet, E.P., Yeager, S.G., Fox-Kemper, B., Bozec, A., Castruccio, F., Danabasoglu, G., Horvat, C., Kim, W.M., Koldunov, N., Li, Y., Lin, P., Liu, H., Sein, D.V., Sidorenko, D., Wang, Q., Xu, X., 2020. Impact of horizontal resolution on global ocean–sea ice model simulations based on the experimental protocols of the Ocean Model Intercomparison Project phase 2 (OMIP-2). Geosci. Model. Dev. 13, 4595–4637. https://doi.org/10.5194/gmd-13-4595-2020.

Chauvin, F., Pilon, R., Palany, P., Belmadani, A., 2020. Future changes in Atlantic hurricanes with the rotated-stretched ARPEGE-Climat at very high resolution. Clim. Dyn. 54, 947–972. https://doi.org/10.1007/s00382-019-05040-4.

Chen, J., Tam, C.-Y., Cheung, K., Wang, Z., Murakami, H., Lau, N.-C., Garner, S.T., Xiao, Z., Choy, C.-W., Wang, P., 2021a. Changing impacts of tropical cyclones on East and Southeast Asian inland regions in the past and a globally warmed future climate. Front. Earth Sci. 9, 769005. https://doi.org/10.3389/feart.2021.769005.

Chen, J., Tam, C.-Y., Wang, Z., Cheung, K., Li, Y., Lau, N.-C., Lau, D.-S.D., 2020. Impacts of climate change and induced storm surges in the Pearl River Delta region using pseudo-global-warming method. Sci. Rep. 10, 1965. https://doi.org/10.1038/s41598-020-58824-8.

Chen, J., Tam, C.Y., Wang, Z., Cheung, K., Li, Y., Lau, N.-C., Lau, D.-S.D., 2022a. Future thermodynamic impacts of global warming on landfalling typhoons and their induced storm surges to the Pearl River Delta region as inferred from high-resolution regional models. J. Clim. 35, 4905–4926. https://doi.org/10.1175/JCLI-D-21-0436.1.

Chen, S., Zhao, H., Klotzbach, P.J., Raga, G.B., Cao, J., Wang, C., 2021b. Decadal modulation of transbasin variability on extended Boreal summer tropical cyclone activity in the tropical North Pacific and Atlantic basins. J. Clim. 34, 7149–7166. https://doi.org/10.1175/JCLI-D-20-0249.1.

Chen, S., Zhao, H., Raga, G.B., Klotzbach, P.J., 2021c. Modulation of North Pacific and North Atlantic tropical cyclones by tropical transbasin variability and ENSO during may–October. J. Clim. 34, 2127–2144. https://doi.org/10.1175/JCLI-D-19-0866.1.

Chen, T., Chen, S., Zhou, M., Tu, C., Zhang, A., Chen, Y., Li, W., 2022b. Northward shift in landfall locations of tropical cyclones over the Western North Pacific during the last four decades. Adv. Atmos. Sci. 39, 304–319. https://doi.org/10.1007/s00376-021-1077-z.

Chung, E.-S., Timmermann, A., Soden, B.J., Ha, K.-J., Shi, L., John, V.O., 2019. Reconciling opposing Walker circulation trends in observations and model projections. Nat. Clim. Change 9, 405–412. https://doi.org/10.1038/s41558-019-0446-4.

Dai, Y., Wang, B., Sun, W., 2022. What drives the decadal variability of global tropical storm days from 1965 to 2019? Adv. Atmos. Sci. 39, 344–353. https://doi.org/10.1007/s00376-021-0354-1.

Danso, D.K., Patricola, C.M., Bercos-Hickey, E., 2022. Influence of African Easterly Wave suppression on Atlantic tropical cyclone activity in a convection-permitting model. Geophys. Res. Lett. 49. https://doi.org/10.1029/2022GL100590 e2022GL100590.

de la Vara, A., Gutiérrez-Fernández, J., González-Alemán, J.J., Gaertner, M.Á., 2021. Characterization of medicanes with a minimal number of geopotential levels. Int. J. Climatol. 41, 3300–3316. https://doi.org/10.1002/joc.7020.

Deshpande, M., Singh, V.K., Ganadhi, M.K., Roxy, M.K., Emmanuel, R., Kumar, U., 2021. Changing status of tropical cyclones over the north Indian Ocean. Clim. Dyn. 57, 3545–3567. https://doi.org/10.1007/s00382-021-05880-z.

Dominguez, C., Jaramillo, A., Cuéllar, P., 2021. Are the socioeconomic impacts associated with tropical cyclones in Mexico exacerbated by local vulnerability and ENSO conditions? Int. J. Climatol. 41, E3307–E3324. https://doi.org/10.1002/joc.6927.

Dullaart, J.C.M., Muis, S., Bloemendaal, N., Aerts, J.C.J.H., 2020. Advancing global storm surge modelling using the new ERA5 climate reanalysis. Clim. Dyn. 54, 1007–1021. https://doi.org/10.1007/s00382-019-05044-0.

Elsner, J.B., 2020. Continued increases in the intensity of strong tropical cyclones. Bull. Am. Meteorol. Soc. 101, E1301–E1303. https://doi.org/10.1175/BAMS-D-19-0338.1.

Emanuel, K., 2005. Genesis and maintenance of "Mediterranean hurricanes.". Adv. Geosci. 2, 217–220. https://doi.org/10.5194/adgeo-2-217-2005.

Emanuel, K., 2020. Evidence that hurricanes are getting stronger. Proc. Natl. Acad. Sci. 117, 13194–13195. https://doi.org/10.1073/pnas.2007742117.

Emanuel, K., 2021a. Atlantic tropical cyclones downscaled from climate reanalyses show increasing activity over past 150 years. Nat. Commun. 12, 1–8. https://doi.org/10.1038/s41467-021-27364-8.

Emanuel, K., 2021b. Response of global tropical cyclone activity to increasing CO_2: results from downscaling CMIP6 models. J. Clim. 34, 57–70. https://doi.org/10.1175/JCLI-D-20-0367.1.

Emanuel, K., 2022. Tropical cyclone seeds, transition probabilities, and genesis. J. Clim. 35, 3557–3566. https://doi.org/10.1175/JCLI-D-21-0922.1.

Feng, X., Wu, L., 2022. Roles of interdecadal variability of the western North Pacific monsoon trough in shifting tropical cyclone formation. Clim. Dyn. 58, 87–95. https://doi.org/10.1007/s00382-021-05891-w.

Feng, X., Klingaman, N.P., Hodges, K.I., 2021. Poleward migration of western North Pacific tropical cyclones related to changes in cyclone seasonality. Nat. Commun. 12, 6210. https://doi.org/10.1038/s41467-021-26369-7.

Flaounas, E., Davolio, S., Raveh-Rubin, S., Pantillon, F., Miglietta, M.M., Gaertner, M.A., Hatzaki, M., Homar, V., Khodayar, S., Korres, G., Kotroni, V., Kushta, J., Reale, M., Ricard, D., 2022. Mediterranean cyclones: current knowledge and open questions on dynamics, prediction, climatology and impacts. Weather Clim. Dynam. 3, 173–208. https://doi.org/10.5194/wcd-3-173-2022.

Fox-Kemper, B., Hewitt, H.T., Xiao, C., Aðalgeirsdóttir, G., Drijfhout, S.S., Edwards, T.L., Golledge, N.R., Hemer, M., Kopp, R.E., Krinner, G., Mix, A., Notz, D., Nowicki, S., Nurhati, I.S., Ruiz, L., Sallée, J.-B., Slangen, A.B.A., Yu, Y., 2021. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), Ocean, Cryosphere and Sea Level Change. **Chapter 9.** *Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362. https://doi.org/10.1017/9781009157896.011.

Frame, D.J., Wehner, M.F., Noy, I., Rosier, S.M., 2020. The economic costs of Hurricane Harvey attributable to climate change. Clim. Change 160, 271–281. https://doi.org/10.1007/s10584-020-02692-8.

Gaertner, M.A., Jacob, D., Gil, V., Domínguez, M., Padorno, E., Sánchez, E., Castro, M., 2007. Tropical cyclones over the Mediterranean Sea in climate change simulations. Geophys. Res. Lett. 34, L14711. https://doi.org/10.1029/2007GL029977.

Gaertner, M.Á., González-Alemán, J.J., Romera, R., Domínguez, M., Gil, V., Sánchez, E., Gallardo, C., Miglietta, M.M., Walsh, K.J.E., Sein, D.V., Somot, S., Dell'Aquila, A., Teichmann, C., Ahrens, B., Buonomo, E., Colette, A., Bastin, S., van Meijgaard, E., Nikulin, G., 2018. Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean–atmosphere coupling and increased resolution. Clim. Dyn. 51, 1041–1057. https://doi.org/10.1007/s00382-016-3456-1.

Gong, D., Tang, X., Chan, J.C.L., Wang, Q., 2022. Trends of tropical cyclone translation speed over the western North Pacific during 1980−2018. Atmosphere 13, 896. https://doi.org/10.3390/atmos13060896.

González-Alemán, J.J., Pascale, S., Gutierrez-Fernandez, J., Murakami, H., Gaertner, M.A., Vecchi, G.A., 2019. Potential increase in hazard from mediterranean hurricane activity with global warming. Geophys. Res. Lett. 46, 1754–1764. https://doi.org/10.1029/2018GL081253.

Gori, A., Lin, N., Xi, D., Emanuel, K., 2022. Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. Nat. Clim. Change 12, 171–178. https://doi.org/10.1038/s41558-021-01272-7.

Green, A.N., Cooper, J.A.G., Loureiro, C., Dixon, S., Hahn, A., Zabel, M., 2022. Stormier mid-Holocene southwest Indian Ocean due to poleward trending tropical cyclones. Nat. Geosci. 15, 60–66. https://doi.org/10.1038/s41561-021-00842-w.

Gutiérrez-Fernández, J., González-Alemán, J.J., de la Vara, A., Cabos, W., Sein, D.V., Gaertner, M.Á., 2021. Impact of ocean–atmosphere coupling on future projection of medicanes in the Mediterranean sea. Int. J. Climatol. 41, 2226–2238. https://doi.org/10.1002/joc.6955.

Guzman, O., Jiang, H., 2021. Global increase in tropical cyclone rain rate. Nat. Commun. 12, 5344. https://doi.org/10.1038/s41467-021-25685-2.

Haarsma, R., 2021. European windstorm risk of post-tropical cyclones and the impact of climate change. Geophys. Res. Lett. 48, e2020GL091483. https://doi.org/10.1029/2020GL091483.

Haarsma, R.J., Roberts, M., Vidale, P.L., Senior, C.A., Bellucci, A., Bao, Q., Chang, P., Corti, S., Fučjar, N.S., Guemas, V., von Hardenberg, J., Hazeleger, W., Kodama, C., Koenigk, T., Leung, L.R., Lu, J., Luo, J.-J., Mao, J., Mizielinski, M.S., Mizuta, R., Nobre, P., Satoh, M., Scoccimarro, E., Semmler, T., Small, J., von Storch, J.-S., 2016. Geosci. Model. Dev. Discuss. 11, 4185–4208. https://doi.org/10.5194/gmd-2016-66.

Hall, T.M., Kossin, J.P., 2019. Hurricane stalling along the North American coast and implications for rainfall. npj Clim. Atmos. Sci. 2, 17. https://doi.org/10.1038/s41612-019-0074-8.

Harr, P.A., Jordi, A., Madaus, L., 2022. Analysis of the future change in frequency of tropical cyclone-related impacts due to compound extreme events. **Chapter 5**, *Hurricane Risk in a Changing Climate*. In: Collins, J.M., Done, J.M. (Eds.), Hurricane Risk, 2. Springer International Publishing, pp. 87–120. https://doi.org/10.1007/978-3-031-08568-0_5.

Hassanzadeh, P., Lee, C.-Y., Nabizadeh, E., Camargo, S.J., Ma, D., Yeung, L.Y., 2020. Effects of climate change on the movement of future landfalling Texas tropical cyclones. Nat. Commun. 11, 3319. https://doi.org/10.1038/s41467-020-17130-7.

Hong, C.-C., Tsou, C.-H., Hsu, P.-C., Chen, K.-C., Liang, H.-C., Hsu, H.-H., Tu, C.-Y., Kitoh, A., 2021. Future changes in tropical cyclone intensity and frequency over the western North Pacific based on 20-km HiRAM and MRI models. J. Clim. 34, 2235–2251. https://doi.org/10.1175/JCLI-D-20-0417.1.

Hoogewind, K.A., Chavas, D.R., Schenkel, B.A., O'Neill, M.E., 2020. Exploring controls on tropical cyclone count through the geography of environmental gavorability. J. Clim. 33, 1725–1745. https://doi.org/10.1175/JCLI-D-18-0862.1.

Hoque, M.A.-A., Pradhan, B., Ahmed, N., Roy, S., 2019. Tropical cyclone risk assessment using geospatial techniques for the eastern coastal region of Bangladesh. Sci. Total Environ. 692, 10–22. https://doi.org/10.1016/j.scitotenv.2019.07.132.

Hsieh, T.-L., Vecchi, G.A., Yang, W., Held, I.M., Garner, S.T., 2020. Large-scale control on the frequency of tropical cyclones and seeds: a consistent relationship across a hierarchy of global atmospheric models. Clim. Dyn. 55, 3177–3196. https://doi.org/10.1007/s00382-020-05446-5.

Hsieh, T.-L., Yang, W., Vecchi, G.A., Zhao, M., 2022. Model spread in the tropical cyclone frequency and seed propensity index across global warming and ENSO-like perturbations. Geophys. Res. Lett. 49, e2021GL097157. https://doi.org/10.1029/2021GL097157.

Huang, H., Patricola, C.M., Collins, W.D., 2021. The influence of ocean coupling on simulated and projected tropical cyclone precipitation in the HighResMIP–PRIMAVERA simulations. Geophys. Res. Lett. 48, e2021GL094801. https://doi.org/10.1029/2021GL094801.

Ikehata, K., Satoh, M., 2021. Climatology of tropical cyclone seed frequency and survival rate in tropical cyclones. Geophys. Res. Lett. 48, e2021GL093626. https://doi.org/10.1029/2021GL093626.

Islam, M., Satoh, M., Takagi, H., 2022. Tropical cyclones affecting Japan central coast and changing storm surge hazard since 1980. J. Meteorol. Soc. Jpn. 100, 493–507. https://doi.org/10.2151/jmsj.2022-024.

Jewson, S., Lewis, N., 2020. Statistical Decomposition of the recent increase in the intensity of tropical storms. Oceans 1, 311–325. https://doi.org/10.3390/oceans1040021.

Jung, C., Lackmann, G.M., 2019. Extratropical transition of Hurricane Irene (2011) in a changing climate. J. Clim. 32, 4847–4871. https://doi.org/10.1175/JCLI-D-18-0558.1.

Jung, C., Lackmann, G.M., 2021. The response of extratropical transition of tropical cyclones to climate change: Quasi-idealized numerical experiments. J. Clim. 34, 4361–4381. https://doi.org/10.1175/JCLI-D-20-0543.1.

Judt, F., Klocke, D., Rios-Berrios, R., Vanniere, B., Ziemen, F., Auger, L., Biercamp, J., Bretherton, C., Chen, X., Düben, P., Hohenegger, C., Khairoutdinov, M., Kodama, C., Kornblueh, L., Lin, S.-J., Nakano, M., Neumann, P., Putman, W., Röber, N., Roberts, M., Satoh, M., Shibuya, R., Stevens, B., Vidale, P.L., Wedi, N., Zhou, L., 2021. Tropical cyclones in global storm-resolving models. J. Meteorol. Soc. Jpn. 99, 579–602. https://doi.org/10.2151/jmsj/2021-029.

Karnauskas, K.B., Zhang, L., Emanuel, K.A., 2021. The feedback of cold wakes on tropical cyclones. Geophys. Res. Lett. 48, e2020GL091676. https://doi.org/10.1029/2020GL091676.

Kawase, H., Yamaguchi, M., Imada, Y., Hayashi, S., Murata, A., Nakaegawa, T., Miyasaka, T., Takayabu, I., 2021. Enhancement of extremely heavy precipitation induced by Typhoon Hagibis (2019) due to historical warming. SOLA 17A, 7–13. https://doi.org/10.2151/sola.17A-002.

Kim, H.-K., Seo, K.-H., Yeh, S.-W., Kang, N.-Y., Moon, B.-K., 2020a. Asymmetric impact of Central Pacific ENSO on the reduction of tropical cyclone genesis frequency over the western North Pacific since the late 1990s. Clim. Dyn. 54, 661–673. https://doi.org/10.1007/s00382-019-05020-8.

Kim, S.-H., Moon, I.-J., Chu, P.-S., 2020b. An increase in global trends of tropical cyclone translation speed since 1982 and its physical causes. Environ. Res. Lett. 15, 094084. https://doi.org/10.1088/1748-9326/ab9e1f.

Klotzbach, P.J., Wood, K.M., Schreck III, C.J., Bowen, S.G., Patricola, C.M., Bell, M.M., 2022. Trends in global tropical cyclone activity: 1990–2021. Geophys. Res. Lett. 49, e2021GL095774. https://doi.org/10.1029/2021GL095774.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., Wu, L., 2019. Tropical cyclones and climate change assessment: Part I: detection and attribution. Bull. Am. Meteorol. Soc. 100, 1987–2007. https://doi.org/10.1175/BAMS-D-18-0189.1.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., Wu, L., 2020a. Tropical cyclones and climate change assessment: Part II: projected response to anthropogenic warming. Bull. Am. Meteorol. Soc. 101, E303–E322. https://doi.org/10.1175/BAMS-D-18-0194.1.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., Wu, L., 2020b. Tropical cyclones warming world: an assessment of projections. Bull. Am. Meteorol. Soc. 101, 771–774. https://doi.org/10.1175/BAMS-D-18-0194.A.

Knutson, T.R., Sirutis, J.J., Bender, M.A., Tuleya, R.E., Schenkel, B.A., 2022. Dynamical downscaling projections of late twenty-first-century U.S. landfalling hurricane activity. Clim. Change 171, 28. https://doi.org/10.1007/s10584-022-03346-7.

Koseki, S., Mooney, P.A., Cabos, W., Gaertner, M.Á., de la Vara, A., González-Alemán, J.J., 2021. Modelling a tropical-like cyclone in the Mediterranean Sea under present and warmer climate. Nat. Hazards Earth Syst. Sci. 21, 53–71. https://doi.org/10.5194/nhess-21-53-2021.

Kossin, J.P., 2018. A global slowdown of tropical-cyclone translation speed. Nature 558, 104–107. https://doi.org/10.1038/s41586-018-0158-3.

Kossin, J.P., 2019. Reply to: Moon, I.-J. et al.; Lanzante, J. R. Nature 570, E16–E22. https://doi.org/10.1038/s41586-019-1224-1.

Kossin, J.P., Knapp, K.R., Olander, T.L., Velden, C.S., 2020. Global increase in major tropical cyclone exceedance probability over the past four decades. Proc. Natl. Acad. Sci. 117, 11975–11980. https://doi.org/10.1073/pnas.1920849117.

Kranthi, G.M., Deshpande, M., Sunilkumar, K., Emmanuel, R., Ingle, S., 2022. Climatology and characteristics of rapidly intensifying tropical cyclones over the North Indian Ocean. Int. J. Climatol. 43, 1773–1795. https://doi.org/10.1002/joc.7945.

Lai, Y., Li, J., Gu, X., Chen, Y.D., Kong, D., Gan, T.Y., Liu, M., Li, Q., Wu, G., 2020. Greater flood risks in response to slowdown of tropical cyclones over the coast of China. Proc. Natl. Acad. Sci. 117, 14751–14755. https://doi.org/10.1073/pnas.1918987117.

Lanzante, J.R., 2019. Uncertainties in tropical-cyclone translation speed. Nature 570, E6–E15. https://doi.org/10.1038/s41586-019-1223-2.

Lee, C.-Y., Tippett, M.K., Sobel, A.H., Camargo, S.J., 2018. An environmentally forced tropical cyclone hazard model. J. Adv. Model. Earth Syst. 10, 223–241. https://doi.org/10.1002/2017MS001186.

Lee, C.-Y., Camargo, S.J., Sobel, A.H., Tippett, M.K., 2020a. Statistical–dynamical downscaling projections of tropical cyclone activity in a warming climate: two diverging genesis scenarios. J. Clim. 33, 4815–4834. https://doi.org/10.1175/JCLI-D-19-0452.1.

Lee, C.-Y., Sobel, A.H., Camargo, S.J., Tippett, M.K., Yang, Q., 2022. New York State hurricane hazard: history and future projections. J. Appl. Meteorol. Climatol. 61, 613–629. https://doi.org/10.1175/JAMC-D-21-0173.1.

Lee, M., Kim, T., Cha, D.-H., Min, S.-K., Park, D.-S.R., Yeh, S.-W., Chan, J.C.L., 2021. How does Pacific decadal Oscillation affect tropical cyclone activity over far East Asia? Geophys. Res. Lett. 48, e2021GL096267. https://doi.org/10.1029/2021GL096267.

Lee, T.-C., Knutson, T.R., Nakaegawa, T., Ying, M., Cha, E.J., 2020b. Third assessment on impacts of climate change on tropical cyclones in the Typhoon Committee Region – Part I: observed changes, detection, and attribution. Trop. Cycl. Res. Rev. 9, 1–22. https://doi.org/10.1016/j.tcrr.2020.03.001.

Levin, E.L., Murakami, H., 2019. Impact of anthropogenic climate change on United States major hurricane landfall frequency. J. Mar. Sci. Eng. 7, 135. https://doi.org/10.3390/jmse7050135.

L'Heureux, M.L., Tippett, M.K., Wang, W., 2022. Prediction challenges from errors in tropical Pacific sea surface temperature trends. Front. Clim. 4, 837483. https://doi.org/10.3389/fclim.2022.837483.

Li, H., Sriver, R.L., 2019. Impact of air–sea coupling on the simulated global tropical cyclone activity in the high-resolution Community Earth System Model (CESM). Clim. Dyn. 53, 3731–3750. https://doi.org/10.1007/s00382-019-04739-8.

Li, L., Chakraborty, P., 2020. Slower decay of landfalling hurricanes in a warming world. Nature 587, 230–234. https://doi.org/10.1038/s41586-020-2867-7.

Lian, T., Ying, J., Ren, H.-L., Zhang, C., Liu, T., Tan, X.-X., 2019. Effects of tropical cyclones on ENSO. J. Clim. 32, 6423–6443. https://doi.org/10.1175/JCLI-D-18-0821.1.

Lima, M.M., Hurduc, A., Ramos, A.M., Trigo, R.M., 2021. The increasing frequency of tropical cyclones in the Northeastern Atlantic sector. Front. Earth Sci. 9, 745115. https://doi.org/10.3389/feart.2021.745115.

Lin, I.-I., Pun, I.-F., Lien, C.-C., 2014. "Category-6" supertyphoon Haiyan in global warming hiatus: contribution from subsurface ocean warming. Geophys. Res. Lett. 41, 8547–8553. https://doi.org/10.1002/2014GL061281.

Lin, I.-I., Camargo, S.J., Patricola, C.M., Boucharel, J., Chand, S., Klotzbach, P., Chan, J.C.L., Wang, B., Chang, P., Li, T., Jin, F.-F., 2020. In: McPhaden, M.J., Santoso, A., Cai, W. (Eds.), ENSO and Tropical Cyclones. **Chapter 17**, *El Niño Southern Oscillation in a Changing Climate*, Geophysical Monograph Series. American Geophysical Union, pp. 377–408. https://doi.org/10.1002/9781119548164.ch17.

Lin, I.-I., Rogers, R.F., Huang, H.-C., Liao, Y.-C., Herndon, D., Yu, J.-Y., Chang, Y.-T., Zhang, J.A., Patricola, C.M., Pun, I.-F., Lien, C.-C., 2021. A tale of two rapidly intensifying supertyphoons: Hagibis (2019) and Haiyan (2013). Bull. Am. Meteorol. Soc. 102, E1645–E1664. https://doi.org/10.1175/BAMS-D-20-0223.1.

Lin, I.-I., Camargo, S.J., Lien, C.-C., Shi, C.-A., Kossin, J.P., 2023. Poleward migration as global warming's possible self-regulator to restrain future western North Pacific tropical cyclone's intensification. npj Clim. Atmos. Sci. 34, 6. https://doi.org/10.1038/s41612-023-00329-y.

Liu, I.C., Camargo, S.J., Sobel, A.H., 2021. Understanding differences in tropical cyclone activity over the Arabian Sea and Bay of Bengal. Mausam 72, 187–198. https://doi.org/10.54302/mausam.v72i1.3591.

Liu, K.S., Chan, J.C.L., 2022. Growing threat of rapidly-intensifying tropical cyclones in East Asia. Adv. Atmos. Sci. 39, 222–234. https://doi.org/10.1007/s00376-021-1126-7.

Liu, L., Wang, Y., 2020. Trends in landfalling tropical cyclone–induced precipitation over China. J. Clim. 33, 2223–2235. https://doi.org/10.1175/JCLI-D-19-0693.1.

Liu, L., Wang, Y., Zhan, R., Xu, J., Duan, Y., 2020a. Increasing destructive potential of landfalling tropical cyclones over China. J. Clim. 33, 3731–3743. https://doi.org/10.1175/JCLI-D-19-0451.1.

Liu, M., Yang, L., Smith, J.A., Vecchi, G.A., 2020b. Response of extreme rainfall for landfalling tropical cyclones undergoing extratropical transition to projected climate change: hurricane Irene (2011). Earth's Future 8, e2019EF001360. https://doi.org/10.1029/2019EF001360.

Loehle, C., Staehling, E., 2020. Hurricane trend detection. Nat. Hazards 104, 1345–1357. https://doi.org/10.1007/s11069-020-04219-x.

Loizou, P., Guishard, M., Mayall, K., Vidale, P.L., Hodges, K.I., Dierer, S., 2022. Development of a simple, open-source hurricane wind risk model for Bermuda with a sensitivity test on decadal variability. **Chapter 7**, *hurricane Risk in a changing climate*. In: Collins, J.M., Done, J.M. (Eds.), Hurricane Risk, 2. Springer International Publishing, pp. 143–160. https://doi.org/10.1007/978-3-031-08568-0_7.

Ma, Z., Fei, J., Lin, Y., Huang, X., 2020. Modulation of clouds and rainfall by tropical cyclone's cold wakes. Geophys. Res. Lett. 47, e2020GL088873. https://doi.org/10.1029/2020GL088873.

Marsooli, R., Lin, N., Emanuel, K., Feng, K., 2019. Climate change exacerbates hurricane flood hazards along US Atlantic and Gulf Coasts in spatially varying patterns. Nat. Commun. 10, 3785. https://doi.org/10.1038/s41467-019-11755-z.

Maxwell, J.T., Bregy, J.C., Robeson, S.M., Knapp, P.A., Soulé, P.T., Trouet, V., 2021. Recent increases in tropical cyclone precipitation extremes over the US East Coast. Proc. Natl. Acad. Sci. 118, e2105636118. https://doi.org/10.1073/pnas.2105636118.

Mayo, T.L., Lin, N., 2022. Climate change impacts to the coastal flood hazard in the northeastern United States. Weather Clim. Extrem. 36, 100453. https://doi.org/10.1016/j.wace.2022.100453.

Michaelis, A.C., Lackmann, G.M., 2019. Climatological changes in the extratropical transition of tropical cyclones in high-resolution global simulations. J. Clim. 32, 8733–8753. https://doi.org/10.1175/JCLI-D-19-0259.1.

Miglietta, M.M., 2019. Mediterranean tropical-like cyclones (Medicanes). Atmosphere 10, 206. https://doi.org/10.3390/atmos10040206.

Miglietta, M., Rotunno, R., 2019. Development mechanisms for Mediterranean tropical-like cyclones (Medicanes). Q. J. R. Meteorol. Soc. 145, 1444–1460. https://doi.org/10.1002/qj.3503.

Miglietta, M.M., Laviola, S., Malvaldi, A., Conte, D., Levizzani, V., Price, C., 2013. Analysis of tropical-like cyclones over the Mediterranean Sea through a combined modeling and satellite approach. Geophys. Res. Lett. 40, 2400–2405. https://doi.org/10.1002/grl.50432.

Mitchell, D., Hawker, L., Savage, J., Bingham, R., Lord, N.S., Khan, M.J.U., Bates, P., Durand, F., Hassan, A., Huq, S., Islam, A.S., Krien, Y., Neal, J., Sampson, C., Smith, A., Testut, L., 2022. Increased population exposure to Amphan-scale cyclones under future climates. Clim. Resil. Sustain. 1, e36. https://doi.org/10.1002/cli2.36.

Moon, I.-J., Kim, S.-H., Chan, J.C.L., 2019. Climate change and tropical cyclone trend. Nature 570, E3–E5. https://doi.org/10.1038/s41586-019-1222-3.

Mori, N., Shimura, T., Yoshida, K., Mizuta, R., Okada, Y., Fujita, M., Khujanazarov, T., Nakakita, E., 2019. Future changes in extreme storm surges based on mega-ensemble projection using 60-km resolution atmospheric global circulation model. Coast. Eng. J. 61, 295–307. https://doi.org/10.1080/21664250.2019.1586290.

Muis, S., Apecechea, M.I., Dullaart, J., de Lima Rego, J., Madsen, K.S., Su, J., Yan, K., Verlaan, M., 2020. A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. Front. Mar. Sci. 7, 263. https://doi.org/10.3389/fmars.2020.00263.

Murakami, H., 2022. Substantial global influence of anthropogenic aerosols on tropical cyclones over the past 40 years. Sci. Adv. 8, eabn9493. https://doi.org/10.1126/sciadv.abn9493.

Murakami, H., Wang, B., 2022. Patterns and frequency of projected future tropical cyclone genesis are governed by dynamic effects. Commun. Earth Environ. 3, 77. https://doi.org/10.1038/s43247-022-00410-z.

Murakami, H., Levin, E., Delworth, T.L., Gudgel, R., Hsu, P.-C., 2018. Dominant effect of relative tropical Atlantic warming on major hurricane occurrence. Science 362, 794–799. https://doi.org/10.1126/science.aat6711.

Murakami, H., Delworth, T.L., Cooke, W.F., Zhao, M., Xiang, B., Hsu, P.-C., 2020. Detected climatic change in global distribution of tropical cyclones. Proc. Natl. Acad. Sci. 117, 10706–10714. https://doi.org/10.1073/pnas.1922500117.

Murakami, H., Delworth, T.L., Cooke, W.F., Kapnick, S.B., Hsu, P.-C., 2022. Increasing frequency of anomalous precipitation events in Japan detected by a deep learning autoencoder. Earth's Future 10, e2021EF002481. https://doi.org/10.1029/2021EF002481.

Nastos, P.T., Karavana Papadimou, K., Matsangouras, I.T., 2018. Mediterranean tropical-like cyclones: impacts and composite daily means and anomalies of synoptic patterns. Atmos. Res. 208, 156–166. https://doi.org/10.1016/j.atmosres.2017.10.023.

Niu, Y., Touma, D., Ting, M., Camargo, S.J., Chen, R., 2022. Assessing heavy precipitation risk associated with tropical cyclones in China. J. Appl. Meteorol. Climatol. 61, 577–591. https://doi.org/10.1175/JAMC-D-21-0166.1.

Otto, F.E.L., Kew, S., Philip, S., Stott, P., Van Oldenborgh, G.J., 2022. How to provide useful attribution statements: lessons learned from operationalizing event attribution in Europe. Bull. Amer. Soc. 103, S21–S25. https://doi.org/10.1175/BAMS-D-21-0267.1.

Pasquero, C., Desbiolles, F., Meroni, A.N., 2021. Air-Sea interactions in the cold wakes of tropical cyclones. Geophys. Res. Lett. 48, e2020GL091185. https://doi.org/10.1029/2020GL091185.

Patricola, C.M., Wehner, M.F., 2018. Anthropogenic influences on major tropical cyclone events. Nature 563, 339–346. https://doi.org/10.1038/s41586-018-0673-2.

Patricola, C.M., Saravanan, R., Chang, P., 2018. The response of Atlantic tropical cyclones to suppression of African Easterly Waves. Geophys. Res. Lett. 45, 471–479. https://doi.org/10.1002/2017GL076081.

Patricola, C.M., Cassidy, D.J., Klotzbach, P.J., 2022. Tropical oceanic influences on observed global tropical cyclone frequency. Geophys. Res. Lett. 49, e2022GL099354. https://doi.org/10.1029/2022GL099354.

Pfleiderer, P., Nath, S., Schleussner, C.-F., 2022. Extreme Atlantic hurricane seasons made twice as likely by ocean warming. Weather Clim. Dyn. 3, 471–482. https://doi.org/10.5194/wcd-3-471-2022.

Philip, S., Kew, S., van Odenborgh, G.J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R., van Aalst, M., 2020. A protocol for probabilistic extreme event attribution analyses. Adv. Stat. Climatol. Meteorol. Oceanogr. 6, 177–203. https://doi.org/10.5194/ascmo-6-177-2020.

Pun, I.-F., Chan, J.C.L., Lin, I.-I., Chan, K.T.F., Price, J.F., Ko, D.S., Lien, C.-C., Wu, Y.-L., Huang, H.-C., 2019. Rapid intensification of typhoon Hato (2017) over shallow water. Sustainability 11, 3709. https://doi.org/10.3390/su11133709.

Qian, Y., Murakami, H., Nakano, M., Hsu, P.-C., Delworth, T.L., Kapnick, S.B., Ramaswamy, V., Mochizuki, T., Morioka, Y., Doi, T., Kataoka, T., Nasuno, T., Yoshida, K., 2019. On the mechanisms of the active 2018 tropical cyclone season in the North Pacific. Geophys. Res. Lett. 46, 12293–12302. https://doi.org/10.1029/2019GL084566.

Ramos-Valle, A.N., Curchitser, E.N., Bruyère, C.L., 2020. Impact of tropical cyclone landfall angle on storm surge along the Mid-Atlantic bight. J. Geophys. Res. Atmospheres 125, e2019JD031796. https://doi.org/10.1029/2019JD031796.

Rasmussen, E., Zick, C., 1987. A subsynoptic vortex over the Mediterranean with some resemblance to polar lows. Tellus A: Dyn. Meteorol. Oceanogr. 39, 408–425. https://doi.org/10.3402/tellusa.v39i4.11770.

Reale, O., Atlas, R., 2001. Tropical cyclone–like vortices in the extratropics: observational evidence and synoptic analysis. Weather Forecast. 16, 7–34. https://doi.org/10.1175/1520-0434(2001)016<0007:TCLVIT>2.0.CO;2.

Reed, K., Wehner, M.F., Stansfield, A.M., Zarzycki, C.M., 2021. Anthropogenic influence on Hurricane Dorian's extreme rainfall. Bull. Am. Meteorol. Soc. 102, S9–S15. https://doi.org/10.1175/BAMS-D-20-0160.1.

Reed, K.A., Bacmeister, J.T., Huff, J.J.A., Wu, X., Bates, S.C., Rosenbloom, N.A., 2019. Exploring the impact of dust on North Atlantic hurricanes in a high-resolution climate model. Geophys. Res. Lett. 46, 1105–1112. https://doi.org/10.1029/2018GL080642.

Reed, K.A., Stansfield, A.M., Wehner, M.F., Zarzycki, C.M., 2020. Forecasted attribution of the human influence on Hurricane Florence. Sci. Adv. 6, eaaw9253. https://doi.org/10.1126/sciadv.aaw9253.

Reed, K.A., Wehner, M.F., Zarzycki, C.M., 2022. Attribution of 2020 hurricane season extreme rainfall to human-induced climate change. Nat. Commun. 13, 1905. https://doi.org/10.1038/s41467-022-29379-1.

Roberts, M.J., Camp, J., Seddon, J., Vidale, P.L., Hodges, K., Vannière, B., Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, L.-P., Chauvin, F., Terray, L., Valcke, S., Moine, M.-P., Putrasahan, D., Roberts, C., Senan, R., Zarzycki, C., Ullrich, P., 2020a. Impact of model resolution on tropical cyclone simulation using the HighResMIP–PRIMAVERA multimodel ensemble. J. Clim. 33, 2557–2583. https://doi.org/10.1175/JCLI-D-19-0639.1.

Roberts, M.J., Camp, J., Seddon, J., Vidale, P.L., Hodges, K., Vannière, B., Mecking, J., Haarsma, R., Bellucci, A., Scoccimarro, E., Caron, L.-P., Chauvin, F., Terray, L., Valcke, S., Moine, M.-P., Putrasahan, D., Roberts, C.D., Senan, R., Zarzycki, C., Ullrich, P., Yamada, Y., Mizuta, R., Kodama, C., Fu, D., Zhang, Q., Danabasoglu, G., Rosenbloom, N., Wang, H., Wu, L., 2020b. Projected future changes in tropical cyclones using the CMIP6 HighResMIP multimodel ensemble. Geophys. Res. Lett. 47, e202GL088662. https://doi.org/10.1029/2020GL088662.

Rodysill, J.R., Donnelly, J.P., Sullivan, R., Lane, P.D., Toomey, M., Woodruff, J.D., Hawkes, A.D., MacDonald, D., d'Entremont, N., McKeon, K., Wallace, E., van Hengstum, P.J., 2020. Historically unprecedented Northern Gulf of Mexico hurricane activity from 650 to 1250 CE. Sci. Rep. 10, 19092. https://doi.org/10.1038/s41598-020-75874-0.

Romera, R., Gaertner, M.Á., Sánchez, E., Domínguez, M., González-Alemán, J.J., Miglietta, M.M., 2017. Climate change projections of medicanes with a large multi-model ensemble of regional climate models. Glob. Planet. Change 151, 134–143. https://doi.org/10.1016/j.gloplacha.2016.10.008.

Romero, R., Emanuel, K., 2013. Medicane risk in a changing climate. J. Geophys. Res. Atmos. 118, 5992–6001. https://doi.org/10.1002/jgrd.50475.

Romero, R., Emanuel, K., 2017. Climate change and hurricane-like extratropical cyclones: projections for North Atlantic polar lows and medicanes based on CMIP5 models. J. Clim. 30, 279–299. https://doi.org/10.1175/JCLI-D-16-0255.1.

Ruiz-Salcines, P., Appendini, C.M., Salles, P., Rey, W., Vigh, J.L., 2021. On the use of synthetic tropical cyclones and hypothetical events for storm surge assessment under climate change. Nat. Hazards 105, 431–459. https://doi.org/10.1007/s11069-020-04318-9.

Sainsbury, E.M., Schiemann, R.K.H., Hodges, K.I., Shaffrey, L.C., Baker, A.J., Bhatia, K.T., 2020. How important are post-tropical cyclones for European windstorm risk? Geophys. Res. Lett. 47, e2020GL089853. https://doi.org/10.1029/2020GL089853.

Schmitt, D., Gischler, E., Anselmetti, F.S., Vogel, H., 2020. Caribbean cyclone activity: an annually-resolved Common Era record. Sci. Rep. 10, 11780. https://doi.org/10.1038/s41598-020-68633-8.

Seager, R., Cane, M., Henderson, N., Lee, D.-E., Abernathey, R., Zhang, H., 2019. Strengthening tropical Pacific zonal sea surface temperature gradient consistent with rising greenhouse gases. Nat. Clim. Change 9, 517–522. https://doi.org/10.1038/s41558-019-0505-x.

Seneviratne, S.I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S.M., Wehner, M., Zhou, B., 2021. Weather and climate extreme events in a changing climate. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), **Chapter 11.** *Climate Change 2021: the Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766. https://doi.org/10.1017/9781009157896.013.

Smiley, K.T., Noy, I., Wehner, M.F., Frame, D., Sampson, C.C., Wing, O.E.J., 2022. Social inequalities in climate change-attributed impacts of Hurricane Harvey. Nat. Commun. 13, 3418. https://doi.org/10.1038/s41467-022-31056-2.

Sobel, A.H., Camargo, S.J., Hall, T.M., Lee, C.-Y., Tippett, M.K., Wing, A.A., 2016. Human influence on tropical cyclone intensity. Science 353, 242–246. https://doi.org/10.1126/science.aaf6574.

Sobel, A.H., Camargo, S.J., Previdi, M., 2019a. Aerosol versus greenhouse gas effects on tropical cyclone potential intensity and the hydrologic cycle. J. Clim. 32, 5511–5527. https://doi.org/10.1175/JCLI-D-18-0357.1.

Sobel, A.H., Lee, C.-Y., Camargo, S.J., Mandli, K.T., Emanuel, K.A., Mukhopadhyay, P., Mahakur, M., 2019b. Tropical cyclone hazard to Mumbai in the recent historical climate. Mon. Wea. Rev. 147, 2355–2366. https://doi.org/10.1175/MWR-D-18-0419.1.

Sobel, A.H., Wing, A.A., Camargo, S.J., Patricola, C.M., Vecchi, G.A., Lee, C.-Y., Tippett, M.K., 2021. Tropical cyclone frequency. Earth's Future 9, e2021EF002275. https://doi.org/10.1029/2021EF002275.

Song, J., Duan, Y., Klotzbach, P.J., 2020. Increasing trend in rapid intensification magnitude of tropical cyclones over the western North Pacific. Environ. Res. Lett. 15, 084043. https://doi.org/10.1088/1748-9326/ab9140.

Stevens, B., Satoh, M., Auger, L., Biercamp, J., Bretherton, C.S., Chen, X., Düben, P., Judt, F., Khairoutdinov, M., Klocke, D., Kodama, C., Kornblueh, L., Linn, S.-J., Neumann, P., Putman, W.M., Röber, N., Shibuya, R., Vanniere, B., Vidale, P.L., Wedi, N., Zhou, L., 2019. DYAMOND: the dynamics of the atmospheric general circulation modeled on non-hydrostatic domains. Prog. Earth Planet. Sci. 6, 61. https://doi.org/10.1186/s40645-019-0304-z.

Strauss, B.H., Orton, P.M., Bittermann, K., Buchanan, M.K., Gilford, D.M., Kopp, R.E., Kulp, S., Massey, C., de Moel, H., Vinogradov, S., 2021.

Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. Nat. Commun. 12, 2720. https://doi.org/10.1038/s41467-021-22838-1.

Strong, J.D.O., Vecchi, G.A., Ginoux, P., 2015. The response of the tropical Atlantic and West African climate to Saharan dust in a fully coupled GCM. J. Clim. 28, 7071–7092. https://doi.org/10.1175/JCLI-D-14-00797.1.

Strong, J.D.O., Vecchi, G.A., Ginoux, P., 2018. The climatological effect of Saharan dust on global tropical cyclones in a fully coupled GCM. J. Geophys. Res. Atmos. 123, 5538–5559. https://doi.org/10.1029/2017JD027808.

Sugi, M., Yamada, Y., Yoshida, K., Mizuta, R., Nakano, M., Kodama, C., Satoh, M., 2020. Future changes in the global frequency of tropical cyclone seeds. SOLA 16, 70–74. https://doi.org/10.2151/sola.2020-012.

Sun, Y., Zhong, Z., Li, T., Yi, L., Shen, Y., 2021. The slowdown tends to be greater for stronger tropical cyclones. J. Clim. 34, 5741–5751. https://doi.org/10.1175/JCLI-D-20-0449.1.

Swapna, P., Sreeraj, P., Sandeep, N., Jyoti, J., Krishnan, R., Prajeesh, A.G., Ayantika, D.C., Manmeet, S., 2022. Increasing frequency of extremely severe cyclonic Storms in the North Indian Ocean by anthropogenic warming and southwest monsoon weakening. Geophys. Res. Lett. 49, e2021GL094650. https://doi.org/10.1029/2021GL094650.

Tadesse, M.G., Wahl, T., 2021. A database of global storm surge reconstructions. Sci. Data 8, 125. https://doi.org/10.1038/s41597-021-00906-x.

Tang, T., Luo, J.-J., Peng, K., Qi, L., Tang, S., 2021. Over-projected Pacific warming and extreme El Niño frequency due to CMIP5 common biases. Natl. Sci. Rev. 8, nwab056. https://doi.org/10.1093/nsr/nwab056.

Tao, S., Coauthors, 2021. Poleward shift in tropical cyclone tracks in the Northwest Pacific during warm periods: past and future. Paleoceanogr. Paleoclimatol. 36, e2021PA004367. https://doi.org/10.1029/2021PA004367.

Tian, Y., Mcbride, J.L., Ren, F., Li, G., Feng, T., 2022. Changes in typhoon regional heavy precipitation events over China from 1960 to 2018. Adv. Atmos. Sci. 39, 272–283. https://doi.org/10.1007/s00376-021-1015-0.

Ting, M., Camargo, S.J., Li, C., Kushnir, Y., 2015. Natural and forced North Atlantic hurricane potential intensity change in CMIP5 models. J. Clim. 28, 3926–3942. https://doi.org/10.1175/JCLI-D-14-00520.1.

Ting, M., Kossin, J.P., Camargo, S.J., Li, C., 2019. Past and future hurricane intensity change along the. U.S. East Coast. Sci. Rep. 9, 7795. https://doi.org/10.1038/s41598-019-44252-w.

Touma, D., Stevenson, S., Camargo, S.J., Horton, D.E., Diffenbaugh, N.S., 2019. Variations in the intensity and spatial extent of tropical cyclone precipitation. Geophys. Res. Lett. 46, 13992–14002. https://doi.org/10.1029/2019GL083452.

Tous, M., Romero, R., 2013. Meteorological environments associated with medicane development. Int. J. Climatol. 33, 1–14. https://doi.org/10.1002/joc.3428.

Tous, M., Zappa, G., Romero, R., Shaffrey, L., Vidale, P.L., 2016. Projected changes in medicanes in the HadGEM3 N512 high-resolution global climate model. Clim. Dyn. 47, 1913–1924. https://doi.org/10.1007/s00382-015-2941-2.

Tran, T.L., Ritchie, E.A., Perkins-Kirkpatrick, S.E., 2022. A 50-Year tropical cyclone exposure climatology in Southeast Asia. J. Geophys. Res. Atmos. 127, e2021JD036301. https://doi.org/10.1029/2021JD036301.

Traxl, D., Boers, N., Rheinwalt, A., Bookhagen, B., 2021. The role of cyclonic activity in tropical temperature-rainfall scaling. Nat. Commun. 12, 6732. https://doi.org/10.1038/s41467-021-27111-z.

Trenary, L., DelSole, T., Camargo, S.J., Tippett, M.K., 2019. Are midtwentieth century forced changes in North Atlantic hurricane potential intensity detectable? Geophys. Res. Lett. 46, 3378–3386. https://doi.org/10.1029/2018GL081725.

Tu, S., Xu, J., Chan, J.C.L., Huang, K., Xu, F., Chiu, L.S., 2021. Recent global decrease in the inner-core rain rate of tropical cyclones. Nat. Commun. 12, 1948. https://doi.org/10.1038/s41467-021-22304-y.

Utsumi, N., Kim, H., 2022. Observed influence of anthropogenic climate change on tropical cyclone heavy rainfall. Nat. Clim. Change 12, 436–440. https://doi.org/10.1038/s41558-022-01344-2.

Vecchi, G.A., Delworth, T.L., Murakami, H., Underwood, S.D., Wittenberg, A.T., Zeng, F., Zhang, W., Baldwin, J.W., Bhatia, K.T., Cooke, W., He, J., Kapnick, S.B., Knutson, T.R., Villarini, G., van der Wiel, K., Anderson, W., Balaji, V., Chen, J.–H., Dixon, K.W., Gudgel, R., Harris, L.M., Jia, L., Johnson, N.C., Lin, S.-J., Liu, M., Ng, C.H.J., Rosati, A., Smith, J.A., Yang, X., 2019. Tropical cyclone sensitivities to CO_2 doubling: roles of atmospheric resolution, synoptic variability and background climate changes. Clim. Dyn. 53, 5999–6033. https://doi.org/10.1007/s00382-019-04913-y.

Vecchi, G.A., Landsea, C., Zhang, W., Villarini, G., Knutson, T., 2021. Changes in Atlantic major hurricane frequency since the late-19th century. Nat. Commun. 12, 4054. https://doi.org/10.1038/s41467-021-24268-5.

Wallace, E., Donnelly, J., van Hengstum, P., Winkler, T., Dizon, C., LaBella, A., Lopez, I., d'Entremont, N., Sullivan, R., Woodruff, J., Hawkes, A., Maio, C., 2021a. Regional shifts in paleohurricane activity over the last 1500 years derived from blue hole sediments offshore of Middle Caicos Island. Quat. Sci. Rev. 268, 107126. https://doi.org/10.1016/j.quascirev.2021.107126.

Wallace, E.J., Donnelly, J.P., Hengstum, P.J., Wiman, C., Sullivan, R.M., Winkler, T.S., d'Entremont, N.E., Toomey, M., Albury, N., 2019. Intense hurricane activity over the past 1500 years at South andros island, Bahamas. Paleoceanogr. Paleoclimatol. 34, 1761–1783. https://doi.org/10.1029/2019PA003665.

Wallace, E.J., Coats, S., Emanuel, K., Donnelly, J.P., 2020. Centennial-scale shifts in storm frequency captured in paleohurricane records from the Bahamas arise predominantly from random variability. Geophys. Res. Lett. 48, e2020GL091145. https://doi.org/10.1029/2020GL091145.

Wallace, E.J., Donnelly, J.P., van Hengstum, P.J., Winkler, T.S., McKeon, K., MacDonald, D., d'Entremont, N.E., Sullivan, R.M., Woodruff, J.D., Hawkes, A.D., Maio, C., 2021b. 1,050 years of hurricane strikes on Long Island in the Bahamas. Paleoceanogr. Paleoclimatol. 36. https://doi.org/10.1029/2020PA004156.

Wallace, E.J., Dee, S.G., Emanuel, K.A., 2021c. Resolving long-term variations in North Atlantic tropical cyclone activity using a pseudo proxy paleotempestology network approach. Geophys. Res. Lett. 48, e2021GL094891. https://doi.org/10.1029/2021GL094891.

Walsh, K., Giorgi, F., Coppola, E., 2014. Mediterranean warm-core cyclones in a warmer world. Clim. Dyn. 42, 1053–1066. https://doi.org/10.1007/s00382-013-1723-y.

Walsh, K.J.E., Camargo, S.J., Knutson, T.R., Kossin, J., Lee, T.-C., Murakami, H., Patricola, C., 2019. Tropical cyclones and climate change. Trop. Cyclone Res. Rev. 8, 240–250. https://doi.org/10.1016/j.tcrr.2020.01.004.

Wang, C., Wang, B., 2019. Tropical cyclone predictability shaped by western Pacific subtropical high: integration of trans-basin sea surface temperature effects. Clim. Dyn. 53, 2697–2714. https://doi.org/10.1007/s00382-019-04651-1.

Wang, C., Wang, B., 2021. Impacts of the South Asian high on tropical cyclone genesis in the South China sea. Clim. Dyn. 56, 2279–2288. https://doi.org/10.1007/s00382-020-05586-8.

Wang, C., Wu, L., Lu, J., Liu, Q., Zhao, H., Tian, W., Cao, J., 2020a. Interannual variability of the basinwide translation speed of tropical cyclones in the western North Pacific. J. Clim. 33, 8641–8650. https://doi.org/10.1175/JCLI-D-19-0995.1.

Wang, Q., Li, J., 2022a. Feedback of tropical cyclones on El Niño diversity. Part I: Phenomenon. Clim. Dyn. 59, 169–184. https://doi.org/10.1007/s00382-021-06122-y.

Wang, Q., Li, J., 2022b. Feedback of tropical cyclones on El Niño diversity. Part II: possible mechanism and prediction. Clim. Dyn. 59, 715–735. https://doi.org/10.1007/s00382-022-06150-2.

Wang, Q., Li, J., 2022c. Feedback of tropical cyclones over the western North Pacific on La Niña flavor. Geophys. Res. Lett. 49, e2021GL097210. https://doi.org/10.1029/2021GL097210.

Wang, Q., Li, J., Jin, F.-F., Chan, J.C.L., Wang, C., Ding, R., Sun, C., Zheng, F., Feng, J., Xie, F., Li, Y., Li, F., Xu, Y., 2019. Tropical cyclones act to intensify El Niño. Nat. Commun. 10, 3793. https://doi.org/10.1038/s41467-019-11720-w.

Wang, R., Wu, L., 2019. Influence of track changes on the poleward shift of LMI location of western North Pacific tropical cyclones. J. Clim. 32, 8437–8445. https://doi.org/10.1175/JCLI-D-18-0855.1.

Wang, S., Toumi, R., 2021. Recent migration of tropical cyclones toward coasts. Science 371, 514–517. https://doi.org/10.1126/science.abb9038.

Wang, S., Toumi, R., 2022. More tropical cyclones are striking coasts with major intensities at landfall. Sci. Rep. 12, 5236. https://doi.org/10.1038/s41598-022-09287-6.

Wang, S., Rashid, T., Throp, H., Toumi, R., 2020b. A shortening of the life cycle of major tropical cyclones. Geophys. Res. Lett. 47, e2020GL088589. https://doi.org/10.1029/2020GL088589.

Wang, S.-Y.S., Zhao, L., Yoon, J.-H., Klotzbach, P., Gillies, R.R., 2018. Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. Environ. Res. Lett. 13, 054014. https://doi.org/10.1088/1748-9326/aabb85.

Wehner, M.F., Reed, K.A., Loring, B., Stone, D., Krishnan, H., 2018. Changes in tropical cyclones under stabilized 1.5 and 2.0°C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols. Earth Syst. Dyn. 9, 187–195. https://doi.org/10.5194/esd-9-187-2018.

Wehner, M., Sampson, C., 2021. Attributable human-induced changes in the magnitude of flooding in the Houston, Texas region during hurricane Harvey. Clim. Change 166, 20. https://doi.org/10.1007/s10584-021-03114-z.

Wilson, K.M., Baldwin, J.W., Young, R.M., 2022. Estimating tropical cyclone vulnerability: a review of different open-source approaches. In: Collins, J.M., Done, J.M. (Eds.), **Chapter 11**, *Hurricane Risk in a Changing Climate*, Hurricane Risk, 2. Springer International Publishing, pp. 255–281. https://doi.org/10.1007/978-3-031-08568-0_11.

Winkler, T.S., van Hengstum, P.J., Donnelly, J.P., Wallace, E.J., Sullivan, R.M., MacDonald, D., Albury, N.A., 2020. Revising evidence of hurricane strikes on Abaco Island (The Bahamas) over the last 700 years. Sci. Rep. 10, 16556. https://doi.org/10.1038/s41598-020-73132-x.

Winkler, T.S., van Hengstum, P.J., Donnelly, J.P., Wallace, E.J., D'Entremont, N., Hawkes, A.D., Maio, C.V., Sullivan, R.M., Woodruff, J.D., 2022. Oceanic passage of hurricanes across Cay Sal Bank in the Bahamas over the last 530 years. Mar. Geol. 443, 106653. https://doi.org/10.1016/j.margeo.2021.106653.

Xi, D., Lin, N., Gori, A., 2023. Increasing sequential tropical cyclone hazards along the US East and Gulf coasts. Nat. Clim. Change 13, 258–265. https://doi.org/10.1038/s41558-023-01595-7.

Yamada, Y., Kodama, C., Satoh, M., Sugi, M., Roberts, M.J., Mizuta, R., Noda, A.T., Nasuno, T., Nakano, M., Vidale, P.L., 2021. Evaluation of the contribution of tropical cyclone seeds to changes in tropical cyclone frequency due to global warming in high-resolution multi-model ensemble simulations. Prog. Earth Planet. Sci. 8, 11. https://doi.org/10.1186/s40645-020-00397-1.

Yamaguchi, M., Maeda, S., 2020. Slowdown of typhoon translation speeds in mid-latitudes in September influenced by the Pacific Decadal Oscillation and global warming. J. Meteorol. Soc. Jpn. 98, 1321–1334. https://doi.org/10.2151/jmsj.2020-068.

Yamaguchi, M., Chan, J.C.L., Moon, I.-J., Yoshida, K., Mizuta, R., 2020. Global warming changes tropical cyclone translation speed. Nat. Commun. 11, 47. https://doi.org/10.1038/s41467-019-13902-y.

Yang, W., Hsieh, T.-L., Vecchi, G.A., 2021. Hurricane annual cycle controlled by both seeds and genesis probability. Proc. Natl. Acad. Sci. 118, e2108397118. https://doi.org/10.1073/pnas.2108397118.

Yang, Y., Zhou, L., Normandeau, A., Jia, J., Yin, Q., Wang, Y.P., Shi, B., Gao, L., Gao, S., 2020. Exploring records of typhoon variability in eastern China over the past 2000 years. GSA Bull 132, 2243–2252. https://doi.org/10.1130/B35600.1.

Yoshida, K., Sugi, M., Mizuta, R., Murakami, H., Ishii, M., 2017. Future changes in tropical cyclone activity in high-resolution large-ensemble simulations. Geophys. Res. Lett. 44, 9910–9917. https://doi.org/10.1002/2017GL075058.

Zhang, G., Murakami, H., Knutson, T.R., Mizuta, R., Yoshida, K., 2020. Tropical cyclone motion in a changing climate. Sci. Adv. 6, eaaz7610. https://doi.org/10.1126/sciadv.aaz7610.

Zhang, W., Villarini, G., Scoccimarro, E., Napolitano, F., 2021. Examining the precipitation associated with medicanes in the high-resolution ERA-5 reanalysis data. Int. J. Climatol. 41, E126–E132. https://doi.org/10.1002/joc.6669.

Zhao, H., Wang, C., 2019. On the relationship between ENSO and tropical cyclones in the western North Pacific during the boreal summer. Clim. Dyn. 52, 275–288. https://doi.org/10.1007/s00382-018-4136-0.

Zhao, H., Chen, S., Raga, G.B., Klotzbach, P.J., Wu, L., 2019a. Recent decrease in genesis productivity of tropical cloud clusters over the Western North Pacific. Clim. Dyn. 52, 5819–5831. https://doi.org/10.1007/s00382-018-4477-8.

Zhao, H., Wu, L., Wang, C., Klotzbach, P.J., 2019b. Consistent late onset of the Western North Pacific tropical cyclone season following major El Niño events. J. Meteorol. Soc. Jpn. 97, 673–688. https://doi.org/10.2151/jmsj.2019-039.

Zhao, H., Zhang, J., Klotzbach, P.J., Chen, S., 2019c. Recent increased covariability of tropical cyclogenesis latitude and longitude over the Western North Pacific during the extended boreal summer. J. Clim. 32, 8167–8179. https://doi.org/10.1175/JCLI-D-19-0009.1.

Zhou, M., Kuang, Y., Ruan, Z., Xie, M., 2021. Geospatial modeling of the tropical cyclone risk in the Guangdong Province, China. Geomat. Nat. Haz. Risk 12, 2931–2955. https://doi.org/10.1080/19475705.2021.1972046.

Zhou, X., Liu, Z., Yan, Q., Zhang, X., Yi, L., Yang, W., Xiang, R., He, Y., Hu, B., Liu, Y., Shen, Y., 2019. Enhanced tropical cyclone intensity in the Western North Pacific during warm periods over the last two millennia. Geophys. Res. Lett. 46, 9145–9153. https://doi.org/10.1029/2019GL083504.

Zhu, Y., Zhang, R.-H., Li, D., Chen, D., 2021. The thermocline biases in the tropical North Pacific and their attributions. J. Clim. 34, 1635–1648. https://doi.org/10.1175/JCLI-D-20-0675.1.