

TROPICAL CYCLONES AND CLIMATE CHANGE

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ABSTRACT

Since the Eighth International Workshop on Tropical Cyclones (IWTC-8), held in December 2014, progress has been made in our understanding of the relationship between tropical cyclone (TC) characteristics, climate and climate change. New analysis of observations has revealed trends in the latitude of maximum TC intensity and in TC translation speed. Climate models are demonstrating an increasing ability to simulate the observed TC climatology and its regional variations. The limited representation of air-sea interaction processes in most climate simulations of TCs remains an issue. Consensus projections of future TC behavior continue to indicate decreases in TC numbers, increases in their maximum intensities and increases in TC-related rainfall. Future sea level rise will exacerbate the impact of storm surge on coastal regions, assuming all other factors equal. Studies have also begun to estimate the effect on TCs of the climate change that has occurred to date. Recommendations are made regarding future research directions.

Keywords: tropical cyclone, climate change, climate variability

1. Introduction

As tropical cyclones (TCs) are some of the most destructive weather systems on Earth, the connection between climate change and TC activity, in particular the possible influence of human activities, has been a subject of intense research. Recent reviews of this general topic include Grossmann and Morgan (2011), Walsh et al. (2015, 2016), Camargo and Wing (2016), Sobel et al. (2016), Kossin et al. (2017) and Knutson et al. (2017). Knutson et al. (2019a) provide an assessment of our confidence in whether climate change has already had an effect on tropical cyclones, while Knutson et al. (2019b) give an assessment of present confidence in projections of the effect of future climate change. Important advances in the past four years (since the previous IWTC meeting, IWTC-8 in December 2014) have been the increasing number of paleoclimate records that have been analyzed to determine past TC incidence; a number of new results obtained from homogeneous records derived from satellite observations that point to the possibility of an increasing anthropogenic influence on aspects of tropical cyclone climatology; progress on understanding the links between climate and tropical cyclone formation

using increasingly realistic climate model simulations; a recognition that future substantial increases in tropical cyclone rainfall might be one of the more robust predictions of climate change relevant to tropical cyclones; and the advent of attribution of the influence of climate change on individual tropical cyclone events and seasons.

The purpose of this article is to provide a brief summary of the effect of climate change on TCs, and to make some recommendations regarding future research.

2. Observations of tropical cyclones

2.1 Paleotempestology

Paleoclimate records representing periods prior to the beginning of observational records, such as overwash deposits and stalagmites, are increasingly being used to constrain past tropical cyclone variations at specific locations (e.g. Frappier et al. 2014, Donnelly et al. 2015, Van Hengstum et al. 2016, Baldini et al. 2016; Bregy et al 2018). For instance, Burn and Palmer (2015) reconstruct Atlantic hurricane activity over the past millennium from a lake sediment record in Jamaica and find an increase in hurricane activity since the late 18th century, but this change is not outside the range of variability over the millennium. While confirming that centennial-scale variations in TC incidence

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do exist in various regions, Muller et al. (2017) note that there appears to be some inconsistency between the relationships with ENSO identified in the paleo records and those relationships identified with modern data. Using tree-ring records of 20th century variability, Altman et al. (2018) found evidence that the recent poleward migration of TCs in the best-track records lies outside the expected range of longer-term variability. Further discussion of these issues is contained in Knutson et al. (2019a,b), who concluded that while paleoclimate studies can provide useful information on tropical cyclone incidence at specific locations, there remains considerable uncertainty regarding their applicability and consistency over wider geographical regions.

2.2 Historical and satellite era

2.2.1 Global

Recently, satellite-based data have indicated a poleward trend in the latitude of TC maximum intensity (LMI; Kossin et al. 2014) that is projected to continue into the future (Kossin et al. 2016a; Fig. 1). Following the analysis of Kossin et al. (2014), which removed the contribution from interbasin frequency variability from the global analysis, Moon et al. (2015) found that removing this contribution and omitting data from the southern hemisphere causes the statistical significance of the rate of poleward migration to fall below 95%. Kossin et al. (2016b) argue that this result does not obviate the presence of a significant global trend, nor does it challenge the presence of significant poleward trends found in individual basins.

Kossin et al. (2016a) and Kossin (2018) suggest that the poleward shift of LMI in the western North Pacific is particularly robust and is unlikely to be due to natural variability alone (Fig. 2). A further study by Zhan and Wang (2017) suggested that this poleward migration over the WNP consists mainly of TCs with intensity below typhoon strength (maximum low-level wind less than 33 ms^{-1}), although this result relies on the accuracy of heterogeneous TC intensity data. Song and Klotzbach (2018) infer that both the In-

terdecadal Pacific Oscillation and basin SST warming and related potential intensity increase are factors affecting the poleward migration in the western North Pacific, by influencing genesis latitude and latitudinal distance from genesis to the LMI, respectively. Studholme and Gulev (2018) and Sharmila and Walsh (2018) followed up on the work of Daloz and Camargo (2018) to identify a relationship between an observed poleward movement of tropical cyclone formation and corresponding changes in various climate variables. Knapp et al. (2018) found that the regions where TCs have eyes have expanded poleward, which provides a somewhat independent check on the poleward TC migration deduced from best-track data. Recently, Altman et al. (2018) employed a tree-ring network in the western North Pacific and found a rapid increase in the destructive effects of TCs over the 20th century, associated with poleward TC migration. The changes are argued to be outside the range of natural variability and may be associated with climate change.

Kossin (2018) also found a global slowdown in translation speeds of TCs of 10% from 1949 to 2016, with greater slowdowns over land regions of Australia, the western North Pacific, and Atlantic, but the causal mechanism behind these trends is still unclear and unambiguous support from numerical simulations is presently lacking. A substantial part of the slowing trend has been shown to be due to meridional variability of the TC tracks in the best-track data, and this has been argued to be possibly due to data artifacts, primarily through changes in satellite data quality and availability (Moon et al. 2019; Lanzante 2019). Kossin (2019) acknowledges the potential for data artifacts to project onto the TC translation speed trend, but demonstrated that a significant and substantial slowing trend is observed over the conterminous United States over the 118-year period 1900–2017, a period that represents the most reliable data with comparatively minimal reliance on satellite data.

Holland and Bruyère (2014) find a significant increase in the proportion of category 4 and 5 storms globally in recent

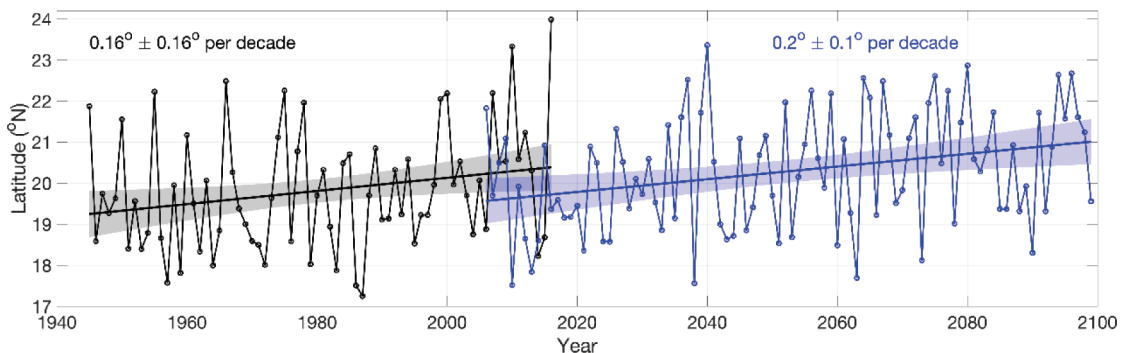


FIG. 1. Observed and projected latitude of maximum tropical cyclone intensity (left) JTWC best-track data; (right) a multi-model ensemble of tropical cyclones simulated in CMIP5 RCP8.5 simulations. Trend lines are indicated in degrees per decade, with shading giving the 95% confidence bounds. Adapted from Kossin et al. (2016a)

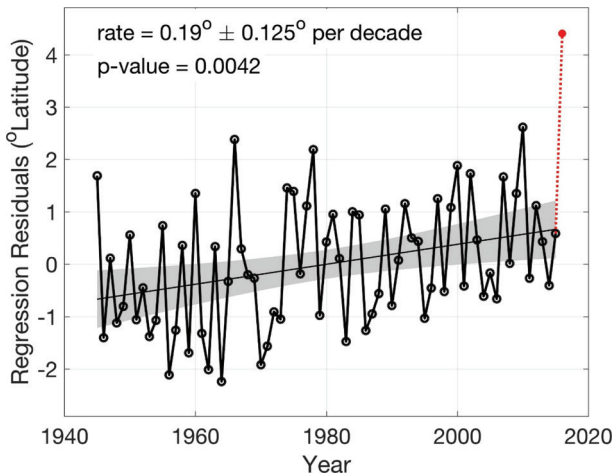


FIG. 2. Time series of residuals after regressing the annual-mean latitude of peak western North Pacific tropical cyclones (TC) intensity onto Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) indices (July–November mean). The statistics shown (poleward migration rate, two-sided 95% confidence interval, and p-value) are based on the period 1945–2015. The residual for 2016, which had the northern-most mean latitude of peak TC intensity ever recorded in the western North Pacific best-track (see Figure 2 below), is shown by the red dot (this point is not included in the regression). Gray shading shows the two-sided 95% confidence bounds on the trend. From Kossin et al. (2018).

decades, and confirmed that an increase also is seen using homogenized satellite-derived intensity data of Kossin et al. (2013) that begins in 1982. Klotzbach and Landsea (2015) find a recent slowing of the observed upward trend from 1970 to 2004 in the global numbers of Saffir-Simpson category 4 and 5 storm numbers. They also find a continuation in the increasing trend in the proportion of these storms, but that this trend is not statistically significant during the more recent period 1990–2014.

2.2.2 Western North Pacific (WNP)

Yan et al. (2017a) try to relate variations in simulated TC-related climate variables over the past millennium in the western North Pacific (WNP) to historical typhoon archives but find important differences between them. Mei et al. (2015) and Mei and Xie (2016) show that, over the past 37 years, landfalling typhoons that strike East and Southeast Asia have intensified by 12–15%, due to locally enhanced surface warming. Li et al. (2017) also found that TCs making landfall over East China have tended to be more destructive in recent decades. Lin and Chan (2015) examined recent trends in typhoon Power Dissipation Index (PDI) in the WNP, finding compensating decreases in typhoon frequency and duration combined with increases in intensity. Takahashi et al. (2017) suggested a significant aerosol influence on the recent decadal decrease in TC activity over the WNP. Zhao and Wu (2014) reported

a pronounced northwestward shift in TC tracks over the WNP after the late 1980s. He et al. (2015) also analyzed a pronounced decadal shift in WNP TC activity after the late 1990s, including genesis number, prevailing tracks and occurrence frequency. A number of subsequent studies have analyzed the implications of this decadal shift for the increase in the proportion of TCs undergoing rapid intensification in WNP (Zhao et al. 2018a) and the occurrence of intense TCs in the coastal regions along East Asia (Zhao et al., 2018c).

2.2.3 North Atlantic

There have been significant recent trends in TC incidence in this basin, whose causes remain controversial. Wing et al. (2015) found robust trends of TC potential intensity (Emanuel 1988) in North Atlantic over the period 1980–2013, indicating that the environment could support occurrence of increasingly intense TCs at the upper limit, but the results are sensitive to the choice of input dataset. There have been a number of studies aiming to identify the reasons for these and other TC-related trends. An important, though uncertain, possible mechanism is variations in aerosols (Booth et al., 2012; Dunstone et al., 2013; Ting et al. 2015; Sobel et al. 2016; Booth 2017; Zhang et al. 2017; Malavelle et al. 2017), along with internal (natural) decadal variability and associated atmospheric and oceanic conditions (Zhang et al. 2013; Camargo 2013; Ting et al. 2015; Yan et al. 2017b; Sutton et al. 2018; Zhao et al. 2018b). Trenary et al. (2019). Balaguru et al. (2018) and Bhatia et al. (2019) found trends in rapid intensification (RI) in the Atlantic. Bhatia et al. (2019) compared the observed trends in intensification rates over 1982–2009 with 28-year trends in a simulation of natural internal climate variability under pre-industrial (1860) climate forcing conditions. They found that the observed trend was unusual compared to the simulated internal variability with a p-value of about 0.01, and that the sign of change (increase) was consistent with the model-simulated influence of anthropogenic forcing on intensification rates. They noted that their results were only suggestive of a detectable increase in intensification rates (and without strict attribution to anthropogenic forcing) since their conclusions depend strongly on the fidelity of a single climate model at simulating the natural internal variability of TC intensification rates in the Atlantic basin, which is still uncertain. Shipwreck rates have been used to examine variations in TC incidence in the past few centuries, with Trouet et al. (2016) showing that TC activity in the North Atlantic appeared to be suppressed during the Maunder Minimum.

2.2.4 North Indian Ocean

Mohapatra et al. (2017) found during the satellite period (1961–2010), TCs and severe TCs over the NIO and BOB show significant decreasing frequency trends for the monsoon and post-monsoon seasons and for the year as

a whole. However, no significant trend is observed over the Arabian Sea during the same period. Analysed trends in this region appear to be sensitive to the period chosen, however. Balaji et al. (2018) use accumulated cyclone energy (ACE) to demonstrate an upward shift of this quantity in this basin in 1997, caused by an increase in number and duration of hurricane-strength TCs (maximum low level winds $> 33 \text{ ms}^{-1}$) over the period 1997–2014. Murakami et al. (2017a) reported the first documented occurrence of post-monsoon season severe TCs in the Arabian Sea during 2014 and 2015, but this conclusion is based on records extending only back to 1998. Model simulations indicate a potential anthropogenic contribution to the increase.

2.2.5 South Indian and South Pacific

Dowdy (2014) found a decrease in TC numbers in eastern Australia during the satellite era, after removing the substantial effects of ENSO variations on TC incidence in this region. Fitchett and Grab (2014) find few trends in landfalls in south-east Africa, but with an increasing number of TCs tracking south of Madagascar. A recent climatology of South Indian ocean TCs is given by Leroux et al. (2018). Nash et al. (2015) compared documentary 19th century records of TCs with post-satellite-era occurrence and found few TC landfalls in the 19th century.

2.3 ENSO, tropical cyclones and climate change

While Cai et al. (2015) delineate the anticipated changes in ENSO behavior due to climate change, there have been few recent studies that focus specifically on the implications for TCs. Chand et al. (2017) suggested that substantial changes in El Niño-driven TC incidence might occur in the 21st century in the central Pacific. In addition, it is critical to understand future changes in the diversity of ENSO events (Capotondi et al. 2014), as TC activity in the North Atlantic and Eastern and Western North Pacific depends strongly on the spatial pattern of warming during El Niño (Patricola et al. 2016, 2018; Wu et al. 2018). A new metric that for the first time uniquely describes the diversity of ENSO, reveals future increases in La Niña, El Niño, and Modoki events by accounting for the non-linear response of deep convection to SST (Williams and Patricola 2018). Finally, paired with ENSO, Atlantic SST variability can drive constructive or compensating influences on seasonal TC activity in the Atlantic and Eastern North Pacific (Patricola et al. 2014, 2017; Lim et al. 2016), indicating the importance of understanding future changes in the probabilities of SST patterns in each basin, rather than changes in mean SST, for future TC projections.

2.4 Relationships between tropical cyclone frequency and climate

GCM studies have helped explore some of the relationships between climate change and TC activity. Sugi et al. (2015) showed that it was not necessarily the case that a

cooler climate would mean fewer TCs. In contrast, Yoo et al. (2016) simulated similar TC numbers during the last glacial maximum to the current climate. Merlis et al. (2016) used globally uniform-SST aquaplanet simulations to show that increased SST caused increases in intensity but decreases in numbers. The experiments of the Hurricane Working Group (Walsh et al. 2015) separately changed SST and CO₂ to understand their influence on TC climate, with the idea that these contribute to the reduction in mass flux proposed to be associated with reduction in TC frequency (Sugi et al. 2012). This has relevance to projections of 21st century TC numbers. Satoh et al. (2015) proposed that an average TC intensity increase combined with a climate-related constraint for the total TC mass flux leads to a reduction of TC numbers. An alternative view (e.g., Camargo et al. 2014) holds that reduced global TC frequency with climate warming in at least one model (GFDL HiRAM model) is statistically related to the degree of column saturation deficit and changes in the TC potential intensity of the environment. In addition, idealized models have been used to investigate the impact of varying meridional temperature gradients on TCs (Ballinger et al. 2015; Fedorov et al. 2019), finding that a decreased gradient generally leads to more TCs.

Genesis potential indices (GPIs, e.g. Camargo 2013; Camargo et al. 2014) have been used to explore statistical relationships between climate and TC formation rates. Important uncertainties remain in the best representation and also how changes in GPI values in a different climate compare with changes in TC numbers directly simulated by GCMs (that is, which is more likely to represent real-world behavior). Many GPIs input TC potential intensity, which is a function of SST, leading to the development of the “Dynamic Potential Intensity” which can estimate the influence of air-sea interactions on TC potential intensity (Balaguru et al. 2015). Recent applications include the use of GPIs in the construction of a TC hazard model (Lee et al. 2018) and for diagnosing the interannual variability of TC formation in the Atlantic in millennia-long model runs (Lavender et al. 2018). Along these lines, Tory et al. (2018) used some novel diagnostics to establish some threshold relationships for geographical regions of TC formation.

2.5 Theoretical relationships between climate and intensity

The links between climate and TC intensity are largely through the successful theory of maximum potential intensity (Emanuel 1988). Further refinements by Chavas (2017) have clarified some of the constraints on this theory. Kang and Elsner (2015, 2016) used statistical analysis to suggest a trade-off between increases in TC intensity and fewer TCs.

3. Projections of future TC climatology

Climate models with horizontal resolutions of around 50

km are now able to simulate the spatial climatology and interannual variability of TC formation reasonably well (Camargo and Wing 2016). Nevertheless, finer horizontal resolution models (in some cases as fine as 6 km grid spacing for regional models or 25 km for global climate models) tend to show improved simulation of TC intensities (e.g. Knutson et al. 2015; Bhatia et al. 2018; Gettelman et al. 2018).

3.1 *TC numbers and occurrence*

A large majority of GCM simulations project future decreases in global TC numbers (Knutson et al., 2019b). An unresolved issue at present is the cause of model-projected increases in TC numbers in a small subset of models (e.g. Emanuel 2013; Bhatia et al. 2018). There remains limited confidence in the geographical details of projections of future TC track and occurrence (e.g. Daloz et al. 2015; Nakamura et al. 2017; Ramsay et al. 2018). Several models project a significant increase in TC track density in the central North Pacific (Murakami et al. 2013, Roberts et al. 2015, Knutson et al. 2015 and Yoshida et al. 2017). Tory et al. (2013) diagnosed a global decrease in TC frequency in climate model warming scenarios (CMIP5 models) using an alternative TC detection method not based on modeled storms but rather on large-scale dynamical and thermodynamical conditions.

3.2 *TC intensity*

A projected increase in TC intensity with climate warming by about 1-10% for a 2 degree Celsius global warming scenario (Knutson et al., 2019b) is generally consistent with potential intensity (PI) theory (e.g., Emanuel 1988) which also predicts such an increase in a greenhouse-warmed climate based on CMIP5 model results (Sobel et al. 2016). The prediction from PI theory is generally supported by the results of most fine-resolution global climate models, regional dynamical downscaling models, and other modelling systems (Knutson et al., 2019b). Bhatia et al. (2018) reported using a 25-km-mesh high-resolution GCM that TC intensification rate is projected to be higher at the end of this century relative to the present-day, resulting in more major hurricanes globally. Increases in the proportion of TCs that reach category 4 and 5 intensity are projected by some models (e.g., Holland and Bruyere 2014). Recent studies have begun to consider future changes in additional TC characteristics including TC size and destructiveness (Sun et al. 2017a, b; Schenkel et al. 2017).

3.3 *Air-sea interaction*

A limitation in the majority of GCM projections of future TC incidence is the lack of realistic air-sea interaction processes in most simulations, as these tend to employ specified SSTs rather than coupled ocean-atmosphere GCMs, due to the very considerable saving in computer time. In addition, prescribed SST simulations are often

preferred due to the problem that tropical SST biases common to coupled models (e.g. Richter 2015; Zuidema et al. 2016) can introduce substantial errors into the simulated TC climatology (Hsu et al. 2018). Lack of atmosphere-ocean coupling can produce greater simulated TC number and intensity compared to coupled simulations (Zarzycki 2016; Li and Srivier 2018). For TC-climate simulations performed in downscaling mode, rather than within a global climate simulation, there is potential for overestimating the impact of climate warming on TC intensity due to the influence of ocean coupling (Huang et al. 2015), though according to more recent studies, this moderating impact of the ocean vertical temperature gradient change is estimated to be relatively minor (Emanuel 2015; Tuleya et al. 2016). The limited number of fully coupled ocean-atmosphere GCM studies that have been performed give mixed results, with some tending to indicate similar results to the atmosphere-only models (Kim et al. 2014) and one study indicating that inclusion of ocean-atmosphere coupling can lead to an even larger increase of intense TC numbers than a case without ocean coupling, at least in some basins (Ogata et al. 2016).

3.4 *TC rainfall and other impacts*

Projected future increases in TC rainfall rates can be quite substantial (Villarini et al. 2014; Wright et al. 2015; Scoccimarro et al. 2017; Patricola and Wehner 2018), with values sometimes being larger than that expected simply from the increase in atmospheric moisture content (roughly 7% per degree Celsius of local surface warming). Increases in TC rainfall rates of about 6 to 22% are projected for a 2°C global warming scenario (Knutson et al., 2019b). The physical mechanism for this increase is reasonably well understood (e.g., Wang et al. 2015), being related to increased moisture convergence—primarily due to increased water vapor and secondarily to an enhanced convergence— and with a smaller contribution from increased evaporation.

The greatest impact from TCs in coastal regions is from storm surge, which is almost certain to be exacerbated by future sea level rise, all other factors assumed equal, and will also be influenced by regional changes in TC characteristics (Woodruff et al. 2013). The effects of storm surge vary strongly from location to location, and so the numerous studies that have been performed on this issue have usually been focused on specific locations (e.g. Garner et al. 2017). Moreover, the plausible increase in TC-induced extreme wind waves due to the projected increase in TC intensity may further aggravate the impacts of storm surge and sea level rise on coastal structures (Timmermans et al., 2017, 2018). A challenge in performing this kind of study is the relative impact of highly confident projections of sea level rise compared with rather less confident projections of changes in TC characteristics. In some locations, the sea level rise contribution is expected to dominate (McInnes et al. 2014).

3.5 Event attribution studies

A new development in the field has been the advent of event attribution of climate change studies for TCs. For example, these explore how the climate change that has occurred to date may have influenced individual TCs, including storm surge (e.g., Lackmann 2015; Takayabu et al. 2015; Risser and Wehner 2017; Oldenborgh et al. 2017; Emanuel 2017; Wang et al. 2018; Patricola and Wehner 2018; Wehner et al. 2019; Keellings and Ayala 2019), with some studies performed in real time (Reed 2018). These studies can also explore how anthropogenic climate change may have influenced a particular TC season (e.g., Murakami et al. 2015, 2017a,b, 2018; Zhang et al. 2016). An issue with establishing confidence levels for such studies is whether a significant observed trend in a TC metric or closely related metric can be identified to support the model-estimated anthropogenic influence. If not, then the inference about anthropogenic influence is based on the model simulation and will typically have lower confidence than for a case where a closely related significant observed climate trend has also been identified.

4. Future research and recommendations

Methods of performing event attribution studies are likely to be further refined in future studies. Producing a regionally and globally comprehensive paleotempestology record that is consistent with known physical relationships between current climate and TCs remains a research challenge. A methodology linking TC intensity with seismic noise (e.g., Chi et al. 2010; Gualtieri et al. 2018), opens the possibility to reconstruct past TC activity from existing seismic records. Increasingly, coupled ocean-atmosphere climate models will be employed, as these models more realistically simulate both the air-sea interaction processes that are known to be important to TC intensification, as well as the basin-scale SST patterns that influence basin-wide TC activity. Community modeling efforts, such as HighResMIP (Haarsma et al. 2016), will provide valuable datasets for understanding and improving the representation of TCs in high-resolution coupled climate models. A large ensemble simulation with a TC-permitting model can also be useful for isolating the effect of anthropogenic forcing from the effect of natural variability on any observed change or trend in TC metrics, similar to the simulations Yoshida et al. (2017) with a 60 km grid atmospheric model and 100 ensemble members. Future research should be able to resolve the issue of why some climate models are predicting future increases in TC numbers while the majority predict decreases. Detection and attribution studies will continue to search for evidence of human influence on TC activity, through a combination of observational and modeling studies. Research to assess changes in TC impacts at specific locations (e.g. coastal megacities) will also be valuable for climate change adaptation and resilience.

Some recommendations for future work, largely taken

from Walsh et al. (2018), with some additions based on the final recommendations of IWTC-9, are as follows:

1) Efforts should continue to develop, improve, and maintain climate-quality data sets of various TC metrics and related environmental variables, for use by the weather and climate change research communities for detection and attribution-related research. These data should include periodic reanalysis of TCs and impact-relevant TC metrics across all ocean basins, reanalysis of large-scale atmosphere/ocean fields (e.g., ERA-5, JRA-55, etc), and estimates of their error characteristics. The construction of dynamically-consistent reanalysis using high resolution models and improved TC representation in reanalysis and global climate models should also be considered. A particular focus should be the continued maintenance and creation of observational data sets that remove as much as possible the effects of temporal inhomogeneities in observing practices.

2) Modeling groups should continue to improve climate models for projecting future TC metrics and simulating past climate forcing changes as well as verifying the realism of model-simulated TCs. This will assist our understanding of the relationship between climate and TCs based on observations, theories, and climate models. Models should also include ocean coupling as a TC-relevant environmental condition. The evaluation of the skill of climate models in representing TC activity from monthly to climate change timescales should be expanded, using standardized verification techniques to allow comparison of different methodologies. WMO verification groups in TC sub-seasonal verification should be involved in this process, and the sharing of verification codes through public repositories should be encouraged.

3) Event attribution studies for TCs and climate change are more valuable scientifically when they have gone through peer review, as opposed to ‘real-time attribution’ studies, where attribution is attempted shortly after the event has occurred, without the benefit of peer review. This is needed to take advantage of the peer-review system which has proven valuable for maintaining and improving the scientific quality of studies. Trend attribution studies should include an expression of uncertainties and provide open access to the data used.

4) Further cross-disciplinary research to better understand and assess the possible changes in multi-hazard impacts of TCs to coastal cities in the context of climate change (e.g. coastal inundation caused by the combined effect of heavy rain, storm surge and wind waves) should be encouraged for further improvement of critical infrastructure design and the formulation of effective emergency preparedness measures.

5) Further efforts should be made to improve our theoretical understanding of the relationship between climate and TCs. For instance, a quantitative climate theory of TC formation would improve our confidence in future projec-

tions of TC numbers.

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References

- Altman, J., O. N. Ukhvatkina, A. M. Omelko, M. Macek, T. Plener, V. Pejcha, T. Cerny, P. Petrik, M. Srutek, J.-S. Song, A. A. Zhmerenetsky, A. S. Vozmishcheva, P. V. Krestov, T. Y. Petrenko, K. Treydte, and J. Dolezal, 2018: Poleward migration of the destructive effects of tropical cyclones during the 20th century. *Proc. Nat. Acad. Sci.*, 201808979; DOI:10.1073/pnas.1808979115
- Balaguru, K., G. R. Foltz, L. R. Leung, E. D'Asaro, K. A. Emanuel, H. Liu, and S. E. Zedler, 2015: Dynamic Potential Intensity: An improved representation of the ocean's impact on tropical cyclones. *Geophys. Res. Lett.*, **42**, 6739–6746, doi:10.1002/2015GL064822.
- Balaguru, K., G.R. Foltz, and L.R. Leung, 2018: Increasing magnitude of hurricane rapid intensification in the central and eastern tropical Atlantic. *Geophys. Res. Lett.*, **45**, 4238–4247, doi: 10.1029/2018GL077597.
- Balaji, M., A. Chakraborty, and M. Mandal, 2018: Changes in tropical cyclone activity in north Indian Ocean during satellite era (1981–2014). *Int. J. Climatol.*, **38**, 2819–2837.
- Baldini, L.M., J.U. Baldini, J.N. McElwaine, A.B., Frappier, Y., Asmerom, K.B., Liu, K.M., Prifer, H.E., Ridley, V., Polyak, D.J., Kennett, and C.G. Macpherson, 2016: Persistent northward North Atlantic tropical cyclone track migration over the past five centuries. *Sci. Rep.*, **6**, 37522.
- Ballinger, A.P., T.M. Merlis, I.M., Held, and M. Zhao, 2015: The sensitivity of tropical cyclone activity to off-equatorial thermal forcing in aquaplanet simulations. *J. Atmos. Sci.*, **72**, 2286–2302.
- Bhatia, K.T., G.A. Vecchi, T.R. Knutson, H. Murakami, J. Kossin, K.W. Dixon, and C.E. Whitlock, 2019: Recent increases in tropical cyclone intensification rates. *Nature Comm.*, **10**, 635, doi: 10.1038/s41467-019-08471-z.
- Bhatia, K., G. Vecchi, H. Murakami, S. Underwood, and J. Kossin, 2018: Projected response of tropical cyclone intensity and intensification in a global climate model. *J. Climate*, **31**, 8281–8303, <https://doi.org/10.1175/JCLI-D-17-0898.1>.
- Booth B.B.B., N.J. Dunstone, P.R. Halloran, T. Andrews, and N. Bellouin, 2012: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature*, **484**, 228–232.
- Booth, B., 2017: Origins of Atlantic decadal swings: External modulation. *Nature*, **548**, 284–285.
- Bregy, J.C., D.J. Wallace, R.T., Minzoni, and V.J. Cruz, 2018: 2500-year paleotempestological record of intense storms for the northern Gulf of Mexico, United States. *Mar. Geol.*, **396**, 26–42.
- Burn, M.J., and S.E. Palmer, 2015: Atlantic hurricane activity during the last millennium. *Sci. Rep.*, **5**, 12838.
- Cai, W., A. Santoso, G. Wang, S.W. Yeh, S.I. An, K.M. Cobb, M. Collins, E. Guilyardi, F.F. Jin, J.S. Kug, and M. Lengaigne, 2015: ENSO and greenhouse warming. *Nature Clim. Change*, **5**, 849–859.
- Camargo, S.J., M.K. Tippett, A.H. Sobel, G.A. Vecchi, and M. Zhao, 2014: Testing the performance of tropical cyclone genesis indices in future climates using the HIRAM model. *J. Climate*, **27**, 9171–9196.
- Camargo, S.J., and A.A. Wing, 2016: Tropical cyclones in climate models. *WIREs Clim. Change*, **7**, 211–237.
- Camargo, S.J., 2013: Global and regional aspects of tropical cyclone activity in the CMIP5 models. *J. Climate*, **26**, 9880–9902. doi: <http://dx.doi.org/10.1175/JCLI-D-12-00549.1>
- Capotondi, A., A.T. Wittenberg, M. Newman, E. Di Lorenzo, J.-Y. Yu, P. Braconnot, et al., 2014: Understanding ENSO diversity. *Bull. Amer. Meteorol. Soc.*, **96**, 921–938.
- Chand, S.S., K.J. Tory, H. Ye, and K.J. Walsh, 2017: Projected increase in El Nino-driven tropical cyclone frequency in the Pacific. *Nature Clim. Change*, **7**, 123–127.
- Chavas, D.R., 2017: A simple derivation of tropical cyclone ventilation theory and its application to capped surface entropy fluxes. *J. Atmos. Sci.*, **74**, 2989–2996.
- Chi, W.C., Chen, W.J., Kuo, B.Y. and Dolenc, D., 2010: Seismic monitoring of western Pacific typhoons. *Marine Geophysical Researches*, **31**(4), pp.239–251.
- Daloz, A.S., and S.J. Camargo, 2018: Is the poleward migration of tropical cyclone maximum intensity associated with a poleward migration of tropical cyclone genesis? *Clim. Dyn.*, **50**, 705–715.
- Daloz, A.S., S.J. Camargo, J.P. Kossin, K. Emanuel, M. Horn, J.A. Jonas, D. Kim, T. LaRow, Y.-K. Lim, C.M. Patricola, M. Roberts, E. Scoccimarro, D. Shaevitz, P.L. Vidale, H. Wang, M. Wehner, and M. Zhao, 2015: Cluster analysis of explicitly and downscaled simulated North Atlantic tropical cyclone tracks. *J. Climate*, **28**, 1333–1361, doi: 10.1175/JCLI-D-13-00646.1.
- Donnelly, J.P., A.D. Hawkes, P. Lane, D. MacDonald, B.N. Shuman, M.R. Toomey MR, P. van Hengstum, and J.D. Woodruff, 2015: Climate forcing of unprecedented intense-hurricane activity in the last 2,000 years. *Earth Future*, **3**, 49–65. doi:10.1002/2014EF000274.
- Dowdy, A.J., 2014. Long-term changes in Australian tropical cyclone numbers. *Atmos. Sci. Letters*, **15**, 292–298.
- Dunstone, N.J., D.M. Smith, B.B.B. Booth, L. Hermanson, and R. Eade, 2013: Anthropogenic aerosol forcing of Atlantic tropical storms. *Nat. Geosci.*, **6**, 534–539.
- Emanuel, K.A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143–1155.
- Emanuel, K.A., 2013: Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proc. Nat. Acad. Sci.*, **110**, 12219–12224, doi: 10.1073/pnas.1301293110.
- Emanuel, K., 2015: Effect of upper-ocean evolution on projected trends in tropical cyclone activity. *J. Climate*, **28**, 8165–8170.
- Emanuel, K., 2017: Assessing the present and future probability of Hurricane Harvey's rainfall. *Proc. Nat. Acad. Sci.*, **114**, 12681–12684.
- Fedorov, A.V., L. Muir, W.R. Boos, and J. Studholme, 2019: Tropical cyclogenesis in warm climates simulated by a cloud-system resolving model. *Clim. Dyn.*, **52**, 107–127.
- Fitchett, J.M., and S.W. Grab, 2014: A 66-year tropical cyclone record for south-east Africa: temporal trends in a global context. *Int. J. Climatol.*, **34**, 3604–3615.
- Frappier, A.B., J. Pyburn, A.D. Pinkey-Drobnis, X. Wang, D.R. Corbett, and B.H. Dahlin, 2014: Two millennia of tropical cyclone-induced mud layers in a northern Yucatán stalagmite: multiple overlapping climatic hazards during the Maya Terminal Classic “megadroughts”. *Geophys. Res. Lett.*, **41**, doi:10.1002/2014GL059882
- Garner, A.J., M.E. Mann, K.A. Emanuel, R.E. Kopp, N. Lin, R.B. Alley, B.P. Horton, R.M. DeConto, J.P. Donnelly, and D. Pollard, 2017: Impact of climate change on New York City's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 CE. *Proc. Nat. Acad. Sci.*, **114**, 11861–11866.
- Gottelman, A., D.N. Bresch, C.C., Chen, J.E. Truesdale, and J.T. Bacmeister, 2018: Projections of future tropical cyclone damage with a high-resolution global climate model. *Clim.*

- Change*, **146**, 575-585.
- Grossmann, I., and M.G. Morgan, 2011: Tropical cyclones, climate change, and scientific uncertainty: what do we know, what does it mean, and what should be done? *Clim. Change*, **108**, 543-579.
- Gualtieri, L., S.J. Camargo, S. Pascale, F.M.E. Pons, and G. Ekström, 2018: The persistent signature of tropical cyclones in ambient seismic noise. *Earth Planet. Sci. Lett.*, **484**, 287-294, doi: 10.1016/j.epsl.2017.12.026.
- Haarsma, R. J., M.J. Roberts, P.L. Vidale, C.A. Senior, A. Bellucci, Q. Bao, P. Chang, S. Corti, N. S. Fučkar, V. Guemas, J. von Hardenberg, W. Hazeleger, C. Kodama, T. Koenigk, L.R. Leung, J. Lu, J.-J. Luo, J. Mao, M.S. Mizieliński, R. Mizuta, P. Nobre, M. Satoh, E. Scoccimarro, T. Semmler, J. Small, and J.S.- von Storch, 2016: High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6. *Geosci. Model Dev.*, **9**, 4185-4208.
- He, H., J. Yang, D. Gong, R. Mao, Y. Wang, and M. Gao, 2015: Decadal changes in tropical cyclone activity over the western North Pacific in the late 1990s. *Clim. Dyn.*, **45**, 3317-3329.
- Holland G.J., and C. Bruyère, 2014: Recent intense hurricane response to global climate change. *Clim. Dyn.*, **42**, 617-627, doi: 10.1007/s00382-013-1713-0.
- Hsu, W.-C., C.M. Patricola, and P. Chang, 2018: The impact of climate model sea surface temperature biases on tropical cyclone simulations. *Clim. Dyn.*, in press.
- Huang, P., I. I. Lin, C. Chou, and R.-H. Huang, 2015: Change in ocean subsurface environment to suppress tropical cyclone intensification under global warming. *Nature Comm.*, **6**, 7188, doi:10.1038/ncomms8188.
- Kang, N.Y., and J.B. Elsner, 2015: Trade-off between intensity and frequency of global tropical cyclones. *Nature Clim. Change*, **5**, 661-664.
- Kang, N.Y., and J.B. Elsner, 2016: Climate mechanism for stronger typhoons in a warmer world. *J. Clim.*, **29**, 1051-1057.
- Keellings, D., and J.J. Hernández Ayala, 2019: Extreme rainfall associated with Hurricane Maria over Puerto Rico and its connections to climate variability and change. *Geophys. Res. Letters*, **46**. <https://doi.org/10.1029/2019GL082077>
- Kim, H.S., G.A. Vecchi, T.R. Knutson, W.G. Anderson, T.L. Delworth, A. Rosati, F. Zeng, and M. Zhao, 2014: Tropical cyclone simulation and response to CO2 doubling in the GFDL CM2.5 high-resolution coupled climate model. *J. Climate*, **27**, 8034-8054.
- Klotzbach, P.J., and C.W. Landsea, 2015: Extremely intense hurricanes: revisiting Webster et al. (2005) after 10 years. *J. Climate*, **28**, 7621-7629.
- Knapp, K.R., C.S. Velden, and A.J. Wimmers, 2018: A global climatology of tropical cyclone eyes. *Mon. Wea. Rev.*, **146**, 2089-2101.
- Knutson, T.R., J.J. Sirutis, M. Zhao, R.E. Tuleya, M. Bender, G.A. Vecchi, G. Villarini, and D. Chavas, 2015: Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *J. Climate*, **28**, 7203-7224.
- Knutson, T., S. J. Camargo, J. C. L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019a: Tropical cyclones and climate change assessment: Part I, Detection and attribution. *Bull. Amer. Meteorol. Soc.*, in press.
- Knutson, T., S. J. Camargo, J. C. L. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, and L. Wu, 2019b: Tropical cyclones and climate change assessment: Part II, Late 21st century projections. *Bull. Amer. Meteorol. Soc.*, in press.
- Knutson, T., J.P. Kossin, C. Mears, J. Perlwitz, and M.F. Wehner, 2017: Detection and attribution of climate change. Climate Science Special Report: Fourth National Climate Assessment, Volume I, D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 114-132, doi: 10.7930/J01834ND.
- Kossin, J.P., T. Hall, T. Knutson, K.E. Kunkel, R.J. Trapp, D.E. Waliser, and M.F. Wehner, 2017: Extreme storms. Climate Science Special Report: Fourth National Climate Assessment, Volume I, D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA, 257-276, doi: 10.7930/J07S7KXX.
- Kossin, J.P., 2018: A global slowdown of tropical-cyclone translation speed. *Nature*, **558**, 104-107.
- Kossin, J.P., T.L. Olander, and K.R. Knapp, 2013: Trend analysis with a new global record of tropical cyclone intensity. *J. Climate*, **26**, 9960-9976.
- Kossin, J.P., K.A. Emanuel, and G.A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349-352.
- Kossin, J.P., K.A. Emanuel, and S.J. Camargo, 2016a: Past and projected changes in western North Pacific tropical cyclone exposure. *J. Climate*, **29**, 5725-5739.
- Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, 2016b: Comment on "Roles of interbasin frequency changes in the poleward shifts of the maximum intensity location of tropical cyclones". *Env. Res. Lett.*, **11**, 068001.
- Kossin, J. P., 2018: Comment on "Spatial and Temporal Trends in the Location of the Lifetime Maximum Intensity of Tropical Cyclones" by Tennille and Ellis. *Atmosphere*, **9**, 241-244.
- Kossin, J. P., 2019: Reply. *Nature*, **570**, E16.
- Lackmann, G.M., 2015: Hurricane Sandy before 1900 and after 2100. *Bull. Amer. Meteor. Soc.*, **96**, 547-560. doi:10.1175/BAMS-D-14-00123.1
- Lanzante, J. R., 2019: Uncertainties in tropical-cyclone translation speed. *Nature (Matters Arising)*, **570**, E16.
- Lavender, S.L., K.J.E. Walsh, L-P. Caron, M. King, S. Monkiewicz, M. Guishard, Q. Zhang, and B. Hunt, 2018: Estimation of the maximum annual number of North Atlantic tropical cyclones using climate models. *Sci. Adv.*, **4**, doi: 10.1126/sciadv.aat6509.
- Lee, C.Y., M.K. Tippett, A.H. Sobel, and S.J. Camargo, 2018: An environmentally forced tropical cyclone hazard model. *J. Adv. Model. Earth Sys.*, **10**, 233-241, doi: 10.1002/2017MS001186.
- Leroux, M.D., J. Meister, D. Mekies, A.L. Dorla, and P. Caroff, 2018: A climatology of southwest Indian ocean tropical systems: their number, tracks, impacts, sizes, empirical maximum potential intensity, and intensity changes. *J. Appl. Meteorol. Climatol.*, **57**, 1021-1041.
- Li, H., and R.L. Sriver, 2018: Tropical cyclone activity in the high-resolution community earth system model and the impact of ocean coupling. *J. Adv. Model. Earth Sys.*, **10**, 165-186.
- Li, C.Y., W. Zhou, C.M. Shun, and T.C. Lee, 2017: Change in destructiveness of landfalling tropical cyclones over China in recent decades. *J. Climate*, **30**, 3367-3379, <http://dx.doi.org/10.1175/JCLI-D-16-0258.1>
- Lim, Y.K., S.D. Schubert, O. Reale, A.M. Molod, M.J. Suarez, and B.M. Auer, 2016: Large-scale controls on Atlantic tropical cyclone activity on seasonal time scales. *J. Climate*, **29**, 6727-6749.
- Lin, I.I., and J.C. Chan, 2015: Recent decrease in typhoon destructive potential and global warming implications. *Nature Comm.*, **6**, 7182.
- Malavelle, F. F., and Coauthors, 2017: Strong constraints on aerosol-cloud interactions from volcanic eruptions. *Nature*, **543**,

- 485–491, <https://doi.org/10.1038/nature22974>, 2017. a, b, c, d
- McInnes, K., K. Walsh, R.K. Hoeke, J. G. O’Grady, and F. Colberg, 2014: Quantifying storm tide risk in Fiji due to climate variability and change. *Glob. Plan. Change*, **116**, 115–129.
- Mei, W., S.P. Xie, F. Primeau, J.C. McWilliams, and C. Pasquero, 2015: Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. *Sci. Adv.*, **1**, e1500014.
- Mei, W., and S.P. Xie, 2016: Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. *Nature Geo.*, **9**, 753–757.
- Merlis, T.M., W. Zhou, I.M. Held, and M. Zhao, 2016: Surface temperature dependence of tropical cyclone-permitting simulations in a spherical model with uniform thermal forcing. *Geophys. Res. Letters*, **43**, 2859–2865.
- Mohapatra, M., A.K. Srivastava, S. Balachandran, and B. Geetha, 2017: Inter-annual variation and trends in tropical cyclones and monsoon depressions over the north Indian Ocean. *Observed Climate Variability and Change over the Indian Region*, M. N. Rajeevan, S. Nayak Eds. Springer, 89–106.
- Moon, I.-J., S.-H. Kim, P. Klotzbach, and J.C.L. Chan, 2015: Roles of interbasin frequency changes in the poleward shifts of the maximum intensity location of tropical cyclones. *Environ. Res. Lett.*, **10**, 104004.
- Moon, I.-J., S.-H. Kim, and J. C. L. Chan, 2019: Climate change and tropical cyclone trend. *Nature (Matters Arising)*, 570, E3.
- Muller, J., J.M. Collins, S. Gibson, and L. Paxton, 2017: Recent advances in the emerging field of paleotempestology. J.M. Collins, K. Walsh, Eds., *Hurricanes and Climate Change Vol 3*, Springer, 1–33.
- Murakami, H., E. Levin, T. L. Delworth, R. Gudgel, and P. -C. Hsu, 2018: Dominant effect of relative tropical Atlantic warming on major hurricane occurrence. *Science*, **362**, 794–799.
- Murakami, H., G. A. Vecchi, T. L. Delworth, K. Paffendorf, L. Jia, R. G. Gudgel, and F. Zeng, 2015: Investigating the influence of anthropogenic forcing and natural variability on the 2014 Hawaiian hurricane season. *Bull. Amer. Meteor. Soc.*, **96**, S115–S119, doi:10.1175/BAMS-EEE_2014_ch23.1.
- Murakami, H., G. A. Vecchi, T. L. Delworth, A. T. Wittenberg, S. Underwood, R. Gudgel, X. Yang, L. Jia, F. Zeng, K. Paffendorf, and W. Zhang, 2017b: Dominant role of subtropical Pacific warming in extreme eastern Pacific hurricane seasons: 2015 and the future. *J. Climate*, **30**, 243–264.
- Murakami, H., G. A. Vecchi, and S. Underwood, 2017a: Increasing frequency of extremely severe cyclonic storms over the Arabian Sea. *Nat. Clim. Change*, **7**, 885–889.
- Murakami, H., B. Wang, T. Li, and A. Kitoh, 2013: Projected increase in tropical cyclones near Hawaii. *Nat. Clim. Change*, **3**, 749–754.
- Nakamura, J., S.J. Camargo, A.H. Sobel, N. Henderson, K.A. Emanuel, A. Kumar, T.E. LaRow, H. Murakami, M.J. Roberts, E. Scoccimarro, P.L. Vidale, H. Wang, M.F. Wehner, and M. Zhao, 2017: Western North Pacific tropical cyclone model tracks in present and future climates. *J. Geophys. Res.*, **122**, 9721–9744, doi: 10.1002/2017JD027007.
- Nash, D.J., K. Pribyl, J. Klein, G.H. Endfield, D.R. Kniveton, and G.C. Adamson, 2015: Tropical cyclone activity over Madagascar during the late nineteenth century. *Int. J. Climatol.*, **35**, 3249–3261.
- Ogata, T., R. Mizuta, Y. Adachi, H. Murakami, and T. Ose, 2016: Atmosphere-ocean coupling effect on intense tropical cyclone distribution and its future change with 60 km-AOGCM. *Sci. Rep.*, **6**, 29800.
- Oldenborgh, G. J., and Coauthors, 2017: Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Env. Res. Letters*, **12**, 124009.
- Patricola, C.M., R. Saravanan, and P. Chang, 2014: The impact of the El Niño-Southern Oscillation and Atlantic Meridional Mode on seasonal Atlantic tropical cyclone activity. *J. Climate*, **27**, 5311–5328.
- Patricola, C.M., P. Chang, and R. Saravanan, 2016: Degree of simulated suppression of Atlantic tropical cyclones modulated by flavour of El Niño. *Nature Geo.*, **9**, 155–160.
- Patricola, C.M., R. Saravanan, and P. Chang, 2017: A teleconnection between Atlantic sea surface temperature and eastern and central North Pacific tropical cyclones. *Geophys. Res. Letters*, **44**, 1167–1174.
- Patricola, C.M., S.J. Camargo, P. Klotzbach, R. Saravanan, and P. Chang, 2018: The influence of ENSO flavors on western North Pacific tropical cyclones. *J. Climate*, **31**, 5395–5416.
- Patricola, C.M., and M.F. Wehner, 2018: Anthropogenic influences on major tropical cyclone events. *Nature*, **563**, 339–346.
- Ramsay, H.A., S.S. Chand and S.J. Camargo, 2018: A statistical assessment of Southern Hemisphere tropical cyclone tracks in climate models. *J. Climate*, **31**, 5395–5416, doi: 10.1175/JCLI-D-18-0377.1.
- Reed, K., 2018: Estimating the potential impact of climate change on Hurricane Florence. <https://www.somas.stonybrook.edu/2018/09/13/estimating-the-potential-impact-of-climate-change-on-hurricane-florence/>
- Richter, I., 2015: Climate model biases in the eastern tropical oceans: causes, impacts and ways forward. *WIREs Clim. Change*, **6**, 345–358.
- Risser, M.D., and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophys. Res. Letters*, **44**, 12,457–12,464.
- Roberts, M. J., P. L. Vidale, M. S. Mizieliński, M.-E. Demory, R. Schiemann, J. Strachan, K. Hodges, R. Bell, and J. Camp, 2015: Tropical cyclones in the UPSCALE ensemble of high-resolution global climate models. *J. Climate*, **28**, 574–596.
- Satoh, M., Y. Yamada, M. Sugi, C. Kodama, and A.T. Noda, 2015: Constraint on future change in global frequency of tropical cyclones due to global warming. *J. Meteorol. Soc. Japan. Ser. II*, **93**, 489–500.
- Schenkel, B.A., N. Lin, D.R. Chavas, G.A. Vecchi, T.R. Knutson, and M. Oppenheimer, 2017: Will outer tropical cyclone size change due to anthropogenic warming? AGU Fall Meeting, Washington, D.C. .
- Scoccimarro E., and Coauthors., 2017: Tropical cyclone rainfall changes in a warmer climate. *Hurricanes and Climate Change*, J. Collins and K. Walsh, Eds., Springer, 243–255.
- Sharmila, S., and Walsh, K.J.E., 2018: Recent poleward shift of tropical cyclone formation linked to Hadley cell expansion. *Nature Clim. Change*, **8**, 730–736.
- Sobel, A.H., S.J. Camargo, T.M. Hall, C.Y. Lee, M.K. Tippett, and A.A. Wing, 2016: Human influence on tropical cyclone intensity. *Science*, **353**, 242–246.
- Song, J., and P.J. Klotzbach, 2018: What has controlled the poleward migration of annual averaged location of tropical cyclone lifetime maximum intensity over the Western North Pacific since 1961? *Geophys. Res. Letters*, **45**, 1148–1156.
- Studholme, J., and S. Gulev, 2018: Concurrent changes to Hadley circulation and the meridional distribution of tropical cyclones. *J. Climate*, **31**, 4367–4389.
- Sugi, M., H. Murakami, and J. Yoshimura, 2012: On the mechanism of tropical cyclone frequency changes due to global warming. *J. Meteorol. Soc. Jpn.*, **90A**, 397–408.
- Sugi, M., K. Yoshida, and H. Murakami, 2015: More tropical cyclones in a cooler climate? *Geophys. Res. Lett.*, **42**, 6780–6784.
- Sun, Y., and Coauthors., 2017a: Impact of ocean warming on tropical cyclone size and its destructiveness. *Sci. Rep.*, **7**, 8154.

- Sun, Y., and Coauthors, 2017b: Impact of ocean warming on tropical cyclone track over the western North Pacific: A numerical investigation based on two case studies. *J. Geophys. Res. Atmos.*, **122**, 8617–8630, doi:10.1002/2017JD026959.
- Sutton, R.T., and Coauthors, 2018: Atlantic multidecadal variability and the UK ACSIS Program. *Bull. Amer. Meteorol. Soc.*, **99**, 415–425.
- Takahashi, C., M. Watanabe, and M. Mori, 2017: Significant aerosol influence on the recent decadal decrease in tropical cyclone activity over the western North Pacific. *Geophys. Res. Lett.*, **44**, 9496–9504, doi:10.1002/2017GL075369.
- Takayabu, I., and Coauthors., 2015: Climate change effects on the worst-case storm surge: a case study of Typhoon Haiyan. *Environ. Res. Lett.*, **10**, 064011.
- Timmermans, B., D. Stone, M. Wehner, and H. Krishnan, 2017: Impact of tropical cyclones on modeled extreme wind-wave climate. *Geophys. Res. Lett.*, **44**, 1393–1401, doi:10.1002/2016GL071681.
- Timmermans, B., C.M. Patricola, and M.F. Wehner, 2018: Simulation and analysis of hurricane-driven extreme wave climate under two ocean warming scenarios. *Oceanogr.*, **31**, DOI: 10.5670/oceanog.2018.218.
- Ting, M., S.J. Camargo, C. Li, and Y. Kushnir, 2015: Natural and forced North Atlantic hurricane potential intensity change in CMIP5 models. *J. Climate*, **28**, 3926–3942, doi: 10.1175/JCLI-D-14-00520.1.
- Tory, K.J., S.S. Chand, J.L. McBride, H. Ye, and R.A. Dare, 2013: Projected changes in late 21st century tropical cyclone frequency in CMIP5 models. *J. Climate*, **26**, 9946–9959.
- Tory, K.J., H. Ye, and R.A. Dare, 2018: Understanding the geographic distribution of tropical cyclone formation for applications in climate models. *Clim. Dyn.*, **50**, 2489–2512.
- Trenary, L., T. DelSole, S.J. Camargo, and M.K. Tippett, 2019: Are midtwentieth century forced changes in North Atlantic hurricane potential intensity detectable? *Geophys. Res. Lett.*, **46**, doi: 10.1029/2018GL081725.
- Trouet, V., G.L. Harley, and M. Domínguez-Delmás, 2016: Shipwreck rates reveal Caribbean tropical cyclone response to past radiative forcing. *Proc. Nat. Acad. Sci.*, 201519566.
- Tuleya, R.E., M.A. Bender, T.R. Knutson, J.J. Sirutis, B. Thomas, and I. Ginis, 2016: Impact of upper tropospheric temperature anomalies and vertical wind shear on tropical cyclone evolution using an idealized version of the operational GFDL hurricane model. *J. Atmos. Sci.*, **73**, doi:10.1175/JAS-D-16-0045.1.
- Van Hengstum, P.J., J.P. Donnelly, P.L. Fall, M.R. Toomey, N.A. Albury, and B. Kakuk, 2016: The intertropical convergence zone modulates intense hurricane strikes on the western North Atlantic margin. *Sci. Rep.*, **6**, 21728.
- Villarini, G., and Coauthors, 2014: Sensitivity of tropical cyclone rainfall to idealized global-scale forcings. *J. Climate*, **27**, 4622–4641.
- Walsh, K., S. Camargo, T. R. Knutson, J. Kossin, T.-C. Lee, H. Murakami, and C. Patricola, 2018: Climate change. Topic 7.1, Ninth International Workshop on Tropical Cyclones pre-conference report.
- Walsh, K.J.E., and Coauthors, 2015: Hurricanes and climate: the U.S. CLIVAR working group on hurricanes. *Bull. Amer. Meteorol. Soc.*, **96**, 997–1017.
- Walsh, K.J.E., and Coauthors, 2016: Tropical cyclones and climate change. *WIREs Clim. Change*, **7**, 65–89. doi: 10.1002/wcc.371.
- Wang C. C., B. X. Lin, C. T. Chen, and S. H. Lo, 2015: Quantifying the effects of long-term climate change on tropical cyclone rainfall using a cloud-resolving model: examples of two landfall typhoons in Taiwan. *J. Climate*, **28**, 66–85, https://doi.org/10.1175/JCLI-D-14-00044.1
- Wang, S.Y., and Coauthors., 2018: Quantitative attribution of climate effects on Hurricane Harvey's extreme rainfall in Texas. *Env. Res. Letters*, **12**, 054014.
- Wehner, M.F., C. Zarzycki, and C. Patricola, 2019: Estimating the human influence on tropical cyclone intensity as the climate changes. Hurricane Risk, J.M. Collins and K. Walsh, Eds., Springer, 235–260.
- Williams, I.N., and C.M. Patricola, 2018: Diversity of ENSO events unified by convective threshold sea surface temperature: a nonlinear ENSO index. *Geophys. Res. Letters*, **45**, 9236–9244.
- Wing, A.A., K. Emanuel, and S. Solomon, 2015: On the factors affecting trends and variability in tropical cyclone potential intensity. *Geophys. Res. Letters*, **42**, 8669–8677.
- Woodruff, J.D., J. L. Irish, and S. J. Camargo, 2013: Coastal flooding by tropical cyclones and sea level rise. *Nature*, **504**, 44–52. doi: 10.1038/nature12855.
- Wright, D. B., T.R. Knutson, and J.A. Smith, 2015: Regional climate model projections of rainfall from US landfalling tropical cyclones. *Clim. Dyn.*, **45**, 3365–3379.
- Wu, M. C., H. Zhang, J.-M. Chen, and T. Feng, 2018: Impact of two types of El Niño on tropical cyclones over the western North Pacific: Sensitivity to location and intensity of Pacific warming. *J. Climate*, **31**, 1725–1742.
- Yan, Q., T. Wei, and Z. Zhang, 2017a: Variations in large-scale tropical cyclone genesis factors over the western North Pacific in the PMIP3 last millennium simulations. *Clim. Dyn.*, **48**, 957–970.
- Yan, X., R. Zhang, and T. R. Knutson, 2017b: The role of Atlantic overturning circulation in the recent decline of Atlantic major hurricane frequency. *Nature Comm.*, **8**, 1695, DOI:10.1038/s41467-017-01377-8 .
- Yoo, J., J. Galewsky, S.J. Camargo, R. Korty, and R. Zamora, 2016: Dynamical downscaling of tropical cyclones from CCSM4 simulations of the Last Glacial Maximum. *J. Adv. Model. Earth Sys.*, **8**, 1229–1247.
- Yoshida K., M. Sugi, R. Mizuta, H. Murakami, and M. Ishii, 2017. Future changes in tropical cyclone activity in high-resolution large-ensemble simulations. *Geophys. Res. Lett.*, **44**, 9910–9917, doi: 10.1002/2017GL075058.
- Zarzycki, C.M., 2016: Tropical cyclone intensity errors associated with lack of two-way ocean coupling in high-resolution global simulations. *J. Climate*, **29**, 8589–8610.
- Zhan, R.F., and Y.Q. Wang, 2017: Weak tropical cyclones dominate the poleward migration of the annual mean location of lifetime maximum intensity of northwest Pacific tropical cyclones since 1980. *J. Climate*, **30**, 6873–6882, https://doi.org/10.1175/JCLI-D-17-0019.1.
- Zhang, L., T. Retchman, K. K. Karneauskas, L. Li, J. P. Donnelly, and J. P. Kossin, 2017: Longwave emission trends over Africa and implications for Atlantic hurricanes. *Geophys. Res. Lett.*, **44**, 9075–9083, doi: 10.1002/2017GL073869.
- Zhang R., T. L. Delworth, R. Sutton, D. Hodson, K. W. Dixon, I. M. Held, Y. Kushnir, D. Marshall, Y. Ming, R. Msadek, J. Robson, A. Rosati, M.Ting, and G. A. Vecchi, 2013: Have aerosols caused the observed Atlantic multidecadal variability? *J. Atmos. Sci.*, **70**, 1135–1144.
- Zhang, W., G.A. Vecchi, H. Murakami, T. L. Delworth, K. Paffen-dorf, L. Jia, G. Villarini, R. G. Gudgel, F. Zeng, and X. Yang, 2016: Influences of natural variability and anthropogenic forcing on the extreme 2015 accumulated cyclone energy in the western North Pacific. *Bull. Amer. Meteor. Soc.*, **97**, S131–S135, doi:10.1175/BAMS-D-16-0146.1 S131–S135.
- Zhao, H.K., and L.Wu, 2014 : Inter-decadal shift of the prevailing tropical cyclone tracks over the western North Pacific and its mechanism study. *Meteorol. Atmos. Phys.*, **125**, 89–101.

- Zhao, H., X. Duan, G.B. Raga, and P.J. Klotzbach, 2018a: Changes in characteristics of rapidly intensifying western North Pacific tropical cyclones related to climate regime shifts. *J. Climate*, **31**, 8163-8179.
- Zhao, H., X. Duan, G.B. Raga, and F. Sun, 2018b: Potential large-scale forcing mechanisms driving enhanced North Atlantic tropical cyclone activity since the mid-1990s. *J. Climate*, **31**, 1377-1397.
- Zhao, J., R. Zhan, and Y. Wang, 2018c: Global warming hiatus contributed to the increased occurrence of intense tropical cyclones in the coastal regions along East Asia. *Sci. Rep.*, **8**, 6023.
- Zuidema, P. and Coauthors, 2016: Challenges and prospects for reducing coupled climate model SST biases in the eastern tropical Atlantic and Pacific oceans: The U.S. CLIVAR Eastern Tropical Oceans Synthesis Working Group. *Bull. Amer. Meteorol. Soc.*, **97**, 2305-2328.