

TROPICAL CYCLONES AND CLIMATE CHANGE

K.J.E. WALSH¹, S.J. CAMARGO², T.R. KNUTSON³, J. KOSSIN⁴, T.-C. LEE⁵,
H. MURAKAMI⁶, AND C. PATRICOLA⁷

¹*School of Earth Sciences, University of Melbourne, Australia;* ²*Lamont-Doherty Earth Observatory, Columbia University, USA;* ³*NOAA/GFDL, Princeton, USA;* ⁴*NOAA/National National Centers for Environmental Information, USA;* ⁵*Hong Kong Observatory, Hong Kong, China;* ⁶*NOAA/GFDL, Princeton University, USA;* ⁷*Lawrence Berkeley National Laboratory, USA*

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

Corresponding author: Kevin J.E. Walsh, kevin.walsh@unimelb.edu.au

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

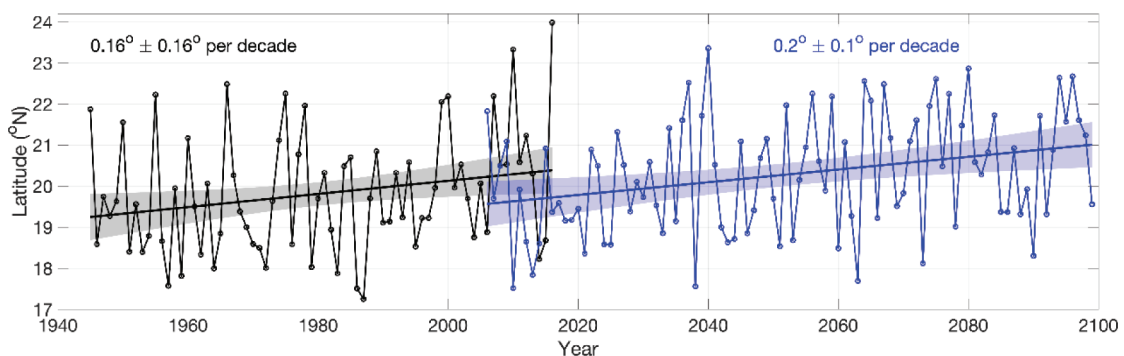


FIG. 1. Observed and projected latitude of maximum tropical cyclone intensity (left) JTWC best-track data; (right) a multi-model ensemble of tropical cyclones simulated in CMIP5 RCP8.5 simulations. Trend lines are indicated in degrees per decade, with shading giving the 95% confidence bounds. Adapted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

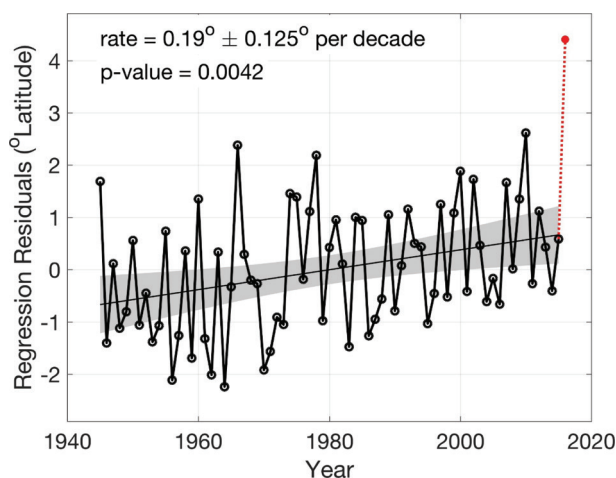


FIG. 2. Time series of residuals after regressing the annual-mean latitude of peak western North Pacific tropical cyclones (TC) intensity onto Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) indices (July–November mean). The statistics shown (poleward migration rate, two-sided 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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