

**Article type:** Advanced Review

**Article title:** Tropical cyclones and climate change

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This is the author manuscript accepted for publication and has undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1002/WCC.371](https://doi.org/10.1002/WCC.371)

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## Abstract

Recent research has strengthened understanding of the links between climate and tropical cyclones on various timescales. Geological records of past climates have shown century-long variations in tropical cyclone numbers. While no significant trends have been identified in the Atlantic since the late 19<sup>th</sup> century, significant observed trends in tropical cyclone numbers and intensities have occurred in this basin over the past few decades, and trends in other basins are increasingly being identified. However, understanding of the causes of these trends is incomplete, and confidence in these trends continues to be hampered by a lack of consistent observations in some basins. A theoretical basis for maximum tropical cyclone intensity appears now to be well established, but a climate theory of tropical cyclone formation remains elusive. Climate models mostly continue to predict future decreases in global tropical cyclone numbers, projected increases in the intensities of the strongest storms and increased rainfall rates. Sea level rise will likely contribute toward increased storm surge risk. Against the background of global climate change and sea level rise, it is important to carry out quantitative assessments on the potential risk of TC-induced storm surge and flooding to densely populated cities and river deltas. Several climate models are now able to generate a good distribution of both tropical cyclone numbers and intensities in the current climate. Inconsistent TC projection results emerge from modelling studies due to different downscaling methodologies and warming scenarios, inconsistencies in projected changes of large-scale conditions, and differences in model physics and tracking algorithms.

## Introduction

Estimates of the effect of anthropogenic climate change on tropical cyclones generally fall into two main topics: whether changes in the climate to date have already had a detectable effect on tropical cyclones and what portion of this is due to anthropogenic or natural causes, and how climate change might affect tropical cyclones in the future. Assessments of observed trends in tropical cyclone characteristics are affected by the same data homogeneity issues that affect all climate variables, so that a starting point for such an analysis is the construction of a data set that is free from spurious trends due to changes in observing and assessment practices. These issues are important for tropical cyclones, as the most comprehensive data sets of tropical cyclone records, the best track data sets<sup>1</sup>, were designed as best estimates of tropical cyclone data using the techniques available at the time

of compilation. Thus they were not primarily intended as data sets to be used for trend analysis. Nevertheless, recent advances in the production of more temporally homogeneous data sets have been made, and analysis of these is starting to reveal important new results<sup>2,3</sup>. The increasing use of atmospheric reanalysis data sets<sup>4,5,6,7,8,9</sup> has facilitated analysis of the impact of changes in climate variables on tropical cyclones, although reanalyses have significant potential homogeneity issues relevant to tropical cyclone activity<sup>10,11</sup>. Current reanalysis products have substantial limitations in their explicit representation of tropical cyclones<sup>12</sup>, and their performance in representing various tropical cyclone climatological metrics varies among available reanalyses<sup>13</sup>. Efforts have also been made using geological techniques to determine tropical cyclone incidence in the distant past, and these studies have revealed surprisingly large long-term variations in past tropical cyclone activity<sup>14,15,16</sup>.

For future projections of tropical cyclones, climate models (general circulation models or GCMs) have improved to the point where the best models can now give reasonable simulations of numbers of the average number of tropical cyclones in all tropical cyclone basins, including their year-to-year variability<sup>17,18</sup>. While there is still room for improvement, global GCMs are also showing an increasing ability to simulate the intensity distribution of observed tropical cyclones in both SST-forced<sup>19</sup> and coupled<sup>20</sup> configurations. This latter task in particular requires high model resolution, so various dynamical<sup>21</sup>, statistical<sup>22,23</sup> and hybrid<sup>5</sup> “downscaling” techniques have been developed to bridge the gap between the relatively low resolution of most climate models (e.g. the CMIP5 models used for many climate change projections<sup>24</sup>) and the fine detail required for reliable simulation of tropical cyclone intensities, an important capability for future climate projections of tropical cyclones (TCs).

Confidence in future projections has been increased by theoretical ideas and techniques that relate climate variables to tropical cyclones. These have enabled both a better understanding of tropical cyclone dynamics and improved confidence in future projections. While a generally accepted climate theory of tropical cyclone formation is still lacking, a climate theory of tropical cyclone maximum intensity (potential intensity, PI) is now well established<sup>25,26</sup>. Analysis and model experiments are beginning to determine the crucial climate variables associated with changes in tropical cyclone formation rate.

This review summarizes recent research in the interdisciplinary field of tropical cyclones and climate change. It does not attempt an updated assessment of the science beyond that given in the IPCC 5<sup>th</sup> Assessment Report<sup>27</sup>; that is, this review does not make synthesis statements regarding our overall level of confidence in predictions of climate change science. Nevertheless, this review is motivated by recent developments in this field since the previous review and assessment<sup>28</sup>. The increasing compilation and analysis of improved, more homogeneous tropical cyclone data sets has enabled more conclusive results to be produced about tropical cyclone trends. There is an increasing availability of datasets from before the period of written records. Additionally, the best-performing climate modeling systems are now producing not only a good simulation of numbers and geographical patterns of tropical cyclone formation but also a rapidly improving representation of

the distribution of tropical cyclone intensity. These three developments motivate a new review of this topic.

## OBSERVATIONS OF TROPICAL CYCLONES

### Paleotempestology

Paleotempestology is the study of storm occurrence in the past before written records became available. The purpose of paleotempestology is to establish whether there have been variations in the number and intensity of tropical cyclones over geologic time periods. This provides a way of establishing a longer climate baseline than the relatively short observational record and also for exploring the dependence of TC activity on climate change. Many types of geological proxies have been tested for reconstructing past hurricane activity; the most common proxies are based on hurricane-induced overwash deposits of sediments of coastal lakes and marshes<sup>29, 30, 16</sup>. Other emerging proxies are based on oxygen isotopic ratios of hurricane precipitation in caves (stalagmites), tree rings and corals<sup>15, 31, 194</sup>. Since these studies typically focus on a specific geographic location, a caveat that should be considered is that they cannot distinguish between basin-wide trends or variability and systematic changes in TC tracks, both of which may be modulated by climate<sup>32</sup>. One method to evaluate the significance of the obtained patterns of overwash reconstructions is to employ a large set of synthetic hurricane track for a specific site<sup>33</sup>.

A number of significant recent advances have been made in this work. In the Australian region, oxygen isotopic analysis of stalagmite records has been used<sup>34</sup> to infer that the tropical cyclone incidence in north-east Queensland is less at present than at any time in the past 1,500 years. In the Atlantic basin, for instance, Brandon et al.<sup>30</sup> use overwash deposits to show that a period of increased intense hurricane frequency is observed between ~1700 and ~600 years before the present (B.P.) and decreased intense storm frequency is observed from ~2500 to ~1700 and ~600 years B.P. to the present. Thus there have been large, unexplained variations in tropical cyclone climatology in the relatively recent geologic past<sup>29, 35, 16</sup>.

These sedimentary records only go back a few millennia, however. Therefore, dynamical<sup>36</sup>, statistical<sup>37</sup> and statistical-dynamical<sup>38</sup> modeling studies of more distant past climates have become more common. For both the Holocene (6ka before the present) and the Last Glacial Maximum (LGM; 21 ka), Kerty et al.<sup>39,40</sup> show that even though conditions during the LGM were cooler than today, there was not a systematic decrease in either potential intensity or other environmental variables associated with TC frequency. Sugi et al.<sup>41</sup> found that their model-simulated TC frequency significantly increases in a 4K cooler climate GCM experiment, indicating that there may be more TCs in a glacial period, consistent with the consensus finding that overall TC frequency decreases with warming<sup>42</sup> and showing that a climate with generally cooler SSTs does not imply fewer TCs<sup>43</sup>. They also pointed out that TC formation under these conditions can occur at sea surface temperatures

(SSTs) well below 26°C, a value conventionally used to indicate the minimum threshold for TC formation in our present-day climate<sup>44</sup>. Merlis<sup>45</sup> used the GFDL HiRAM model to show that TC frequency was simulated to increase during the LGM.

## Historical and satellite era

Observed tropical cyclone data during what is called the “historical” era (in this case typically from the 19<sup>th</sup> century onward, the period when ship observations became more routine) is compiled in what is known as “best track” data sets. These compilations are the best estimates of tropical cyclone characteristics such as position and intensity, but are subject to ongoing review<sup>47</sup>.

The recent introduction of the IBTrACS compilation of best track data sets<sup>1</sup> has considerably facilitated analysis of global climate trends. Creating an homogenous climate record from best track data continues to be a challenge, however, especially for cyclone intensity data<sup>48</sup>, as the quality of measuring techniques has generally improved over time. The parallel creation of more homogeneous satellite-derived datasets<sup>3</sup> increasingly enables analysis of climate variability for the recent decades.

In addition to cyclone intensity, both size and translation speed have been shown to be substantial contributors to the impacts resulting from hurricane passage<sup>49,50,51,52</sup>. Emphasis on increased attention to these parameters in the development of future data sets is therefore desirable, along with creative methods for developing new approaches to their determination from past climate<sup>53</sup>. It has been shown that for observed Atlantic tropical cyclone intensities and sea surface cooling due to the passage of a tropical cyclone, storm translation speed affects the amount of local cooling, but the cooling does not increase monotonically for all intensities<sup>54</sup>. This indicates a role for ocean subsurface thermal structure in modulating the ability of storms to intensify and thus alter the degree of cooling under intense tropical cyclones<sup>55</sup>.

## Global observations

A previous review of this topic<sup>28</sup> concluded that “it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes.” While there remain concerns about the temporal homogeneity of the best track record<sup>56,57</sup>, recent studies using satellite-based temporally homogenized data sets are beginning to suggest climate trends of various kinds in the tropical cyclone record over the past few decades. For example, a summary of trends in the lifetime maximum intensity of tropical cyclones in various ocean basins<sup>3</sup> is shown in Figure 5, for the period 1989-2009. Globally, there are modest significant trends in this quantity (at the 90% level), but individual basins have greater significance. In the North Atlantic and Western North

Pacific, trends are highly significant at the 95% level, with increases in the North Atlantic and decreases in the Western North Pacific. More modest trends significant at the 90% level are seen in the South Pacific and the South Indian basins (both upwards). Trends have not been significant in the Eastern North Pacific and the North Indian basin has insufficient data. More recently, Kossin et al.<sup>58</sup> find significant poleward movement in the latitude of the maximum intensity of tropical cyclones over the period 1982-2012. This result is potentially important as an indicator of the poleward expansion of the tropics, an outcome of anthropogenic climate change that is predicted by both theory<sup>59</sup> and model projections<sup>60</sup>. An expansion of the tropics implies a potential for tropical cyclone effects to be felt further poleward in a warmer world. The causes of the observed trends have not been fully established, however. Holland and Bruyere<sup>61</sup> considered trends in numbers of intense TCs using an early version of the homogenized satellite-based dataset of Kossin et al.<sup>3</sup> and in the IBTrACS data<sup>1</sup>. They find substantial relationships between an index of global warming and the observed proportion of very intense TCs (Saffir-Simpson category 4 and 5) in the IBTrACS data from 1975 to 2010, and similar although smaller trends in the Kossin data set. No change in global cyclone frequency or average intensity was found, but they concluded there has been a substantial increase in the proportion of intense hurricanes, both globally and individually in all basins except for the eastern North Pacific. This is consistent with trends in intense cyclones found by previous studies for individual basins<sup>62,63,64,65,66,67,68</sup>. Recently, Klotzbach and Landsea<sup>204</sup> added an additional 10 years of data to the analysis of Webster et al.<sup>62</sup>, finding a flattening out of the upward trend in 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. Since the early 1990s, global Accumulated Cyclone Energy (ACE) values have undergone a fairly sizeable decrease, with 24-month running mean values the lowest that they have been since the mid-1970s<sup>69</sup>.

### Western North Pacific

Several recent reviews have been conducted on trends in the western North Pacific (WNP) region<sup>70,71,72</sup>. There are several different best-track data sets that have been compiled for this region and they have differences in their representation of TC intensities<sup>73</sup>. Existing datasets show pronounced inter-decadal variations in a number of TC metrics in the western North Pacific basin, such as storm frequency, intensity, and power dissipation index (PDI; a measure that combines tropical cyclone intensity and frequency with lifetime). Multi-decadal trends in WNP basin-wide TC frequency are highly dependent on which best track data set is used. Among the four best track datasets assessed, the China Meteorological Administration (CMA, 1949–2010) and Hong Kong Observatory (HKO, 1961–2010) datasets show significant decreasing trends in TC (tropical storm or above) frequency, but for the Joint Typhoon Warning Center (JTWC, 1945–2010) and Regional Specialized Meteorological Center Tokyo (1977–2010) datasets only a nominal, statistically insignificant decreasing trend was found. Hsu et al.<sup>74</sup> reported an abrupt decrease in the late-season TC frequency that is consistent among best track datasets. Causes for interdecadal changes in

typhoon genesis in the WNP have been examined by Choi et al.<sup>75</sup> who conclude that the horizontal distribution of sea surface temperature, as opposed to its magnitude, can be a key factor.

For TC intensity, trends in intense category 4-5 typhoon frequencies in the WNP are particularly divergent among datasets in recent decades, and so remain uncertain. Increasing trends in intense typhoon frequencies in the WNP have been found by a number of studies<sup>61,62,63,64,65,66</sup>. However, these trends are not apparent in all the data sets available for the basin<sup>73</sup>, and satellite-based intensity trends since 1981<sup>3</sup> show more modest trends.

Efforts have been made to reconcile the differences in intensities of WNP tropical cyclones from the various agencies using a quantile method<sup>64</sup>, whereby more agreement is shown between the various best track datasets in this region when intensity ranks are used rather than raw intensity estimates themselves. Kang and Elsner<sup>64</sup> showed that the statistical analysis of consensus trends between the JBTC and JMA data sets indicate fewer but stronger storms since 1984. Nevertheless, the continued discrepancies between the various datasets in the WNP region continue to be a matter of concern.

In principle, a good numerical simulation of TC trends in this basin could help resolve some of these issues. Wu and Zhao<sup>66</sup> used the Emanuel et al.<sup>5</sup> statistical downscaling approach to examine recent tropical cyclone trends for the WNP. They found an increasing intensity trend that was similar to though less than that in the JBTC data archive. This trend was not consistent with the decreasing or zero trends in other available data sets for the region. Reconciling the substantial differences in WNP tropical cyclone archives would aid future research in this area.

Despite the uncertainty in basin-wide changes in TCs, observations indicate some regional shifts in TC activity in the basin, such as a decreasing trend in TC occurrence in part of the South China Sea and an increasing trend along the east coast of China during the past forty years. This change is apparently related to local circulation variations in eastern Asia and the WNP<sup>70,71,76</sup>. Further observations and research will still be required to understand the influence and contribution of natural variability and anthropogenically-forced climate change on TC track changes in the WNP. Kossin et al.<sup>58</sup> identified a poleward migration over the past thirty years or so of around 0.5° latitude per decade in the location where WNP TCs reach their peak intensity. In this case, the migration was consistently found in the data from each regional data source. The migration appears to be related to systematic decadal changes in regional potential intensity and vertical wind shear and is occurring at roughly the same rate as the independently observed expansion of the tropics<sup>77</sup>. Zhao and Held<sup>78</sup> simulated some poleward migration of TC genesis frequency with climate warming in the North Pacific and North Atlantic ocean basins.

## North Atlantic

There are clear increasing trends in observed intensities of tropical cyclones in the Atlantic basin in the past few decades<sup>79</sup>. Kossin et al.<sup>3</sup> note very significant increases since 1982. Holland and

Bruyere<sup>61</sup> also find an upward trend in the proportion of intense hurricanes since 1975, significant at the 95% level when compared to their global warming index. Landsea et al.<sup>80</sup> emphasize the data homogeneity issues that exist in the Atlantic best track data over the past 100 years, but also note that observed increases have occurred in tropical cyclone activity in the Atlantic since the 1970s. Murakami et al.<sup>81</sup> find that the recent increase in TC genesis number in the Atlantic is the primary driver of the increase in aggregate activity measures such as the accumulated cyclone energy (ACE) or PDI. However, the Atlantic basin is noted for having significant multi-decadal variability in tropical cyclone activity levels. The basin was characterized by a more active period from the mid 1870s to the late 1890s as well as the mid 1940s to the late 1960s. These periods may have had levels of activity similar to what has been observed since the mid 1990s<sup>82</sup>. Crucial to this analysis has been the construction of more homogeneous data sets over this longer period of time<sup>80</sup>. Analysis of these suggests a general lack of long-term trends in this basin for both total numbers of tropical cyclones and for hurricanes only, as well as for landfalling hurricanes since 1900<sup>200, 201</sup>.

Causes for these trends are summarized in the latest Intergovernmental Panel on Climate Change (IPCC) report (AR5), which provided a synthesis of the relationship between climate and tropical cyclones<sup>83</sup>, with particular emphasis on the North Atlantic basin. Confidence has now increased to “medium” that in the Atlantic basin, external forcing factors such as anthropogenic greenhouse gases and aerosols are partly responsible for the increase in tropical cyclone formation since the comparatively quiescent 1970s-80s. In particular, the influence of atmospheric aerosols appears to be important in producing the quiescent period in Atlantic TC activity (from about the late 1960s to the early 1990s)<sup>84,85,86,87,23,88</sup>. An additional component of this variability is likely driven by fluctuations in the strength of the Atlantic thermohaline circulation that drive changes in SST patterns in the Atlantic Main Development Region<sup>89,90,91</sup>. In the Atlantic, observed multidecadal variability of the ocean and atmosphere has been attributed to natural internal variability via meridional overturning ocean circulation changes<sup>202</sup> natural external variability caused by volcanic eruptions<sup>203</sup> and Saharan dust outbreaks<sup>205,182</sup>, and anthropogenic external forcing via greenhouse gases and sulphate aerosols<sup>207</sup>. However, the relative contributions of each mechanism to the observed multidecadal variability in the Atlantic is presently an active area of research and debate.

It has also been hypothesized that changes in both frequency and intensity of tropical cyclones in the Atlantic basin are related to decreases in tropical tropopause temperatures in that basin. Emanuel et al.<sup>92</sup> used a tropical cyclone downscaling technique to show that this cooling has contributed to the estimated change in PI in this basin. It was also noted that the trends in this variable in the NCEP-1 reanalysis<sup>93</sup> are larger than those from other data sets and so likely overestimate these PI trends. Using a high-resolution model forced by observed SSTs, Vecchi et al.<sup>10</sup> showed that strong cooling in the tropical tropopause layer seen in the NCEP-1 reanalysis is not simulated by the model, nor is it evident in other observational estimates. In addition, the simulated



TC frequency changes in their model are not significantly affected by simulated tropical tropopause layer temperature changes, nor do they scale directly with potential intensity (PI), and yet the model is still able to simulate the observed TC trends since 1980. They concluded that the tropical tropopause layer temperature trends in the NCEP-1 Reanalysis are therefore unlikely to be accurate, and likely drive spuriously positive TC and PI trends, along with an inflated connection between absolute surface temperature warming and TC activity increases. A recent study by Kossin<sup>11</sup>, which uses tropical cyclones to more directly sample global upper tropospheric temperatures, lends some support to this claim.

Other TC-related data sets have been analysed for trends in this basin. Using tide gauge data, Grinsted et al.<sup>94</sup> conclude that there is a significant positive trend in eastern USA in storm surge incidence from 1923–2008. Peduzzi et al.<sup>95</sup> note that demographic pressures over the next 20 years will exacerbate the risk of tropical cyclone damage, due to increased exposure in the increasingly densely populated coastal regions.

### North Indian

During the period 1961-2008, several studies find substantial decreasing trends in tropical cyclone activity in the Bay of Bengal and Arabian Sea, particular during the monsoon season<sup>96,97,98</sup>. In contrast, Singh<sup>67</sup> found a marked increasing trend in the most intense tropical cyclones in recent decades. Holland and Bruyere<sup>61</sup> also found a very large increasing trend in the proportion of intense hurricanes in this region since 1975. This was shown to be consistent with global warming trends at the 95% significance level. B. Geetha and Balachandran<sup>99</sup> have studied the decadal variations in the translational speeds of cyclonic disturbances (CDs) over the North Indian Ocean over the period 1961-2010 and have noted that during the most recent decade, the most probable speeds of CDs have increased over the Bay of Bengal, but have decreased over the Arabian Sea.

There are substantial concerns about inhomogeneity due to changes in analysis and observing methods in this basin. For example, prior to the introduction of Meteosat-5 geostationary satellite imagery in 1998, viewing angles in the North Indian Ocean were quite oblique, making identification of the strongest storms quite challenging<sup>3</sup>.

In the adjacent Arabian Sea region, Evan et al.<sup>100</sup> linked reduced wind shear to the recent observed increase in the number of very intense storms in that region, including the five very severe cyclones that have occurred since 1998. The fundamental cause of this proposed linkage is not yet certain, however<sup>100,192</sup>.

Demographic changes in coastal regions of this basin are also driving changes in TC impacts. Raghaven and Rajesh<sup>102</sup> examined cyclone landfalls in Andhra Pradesh, India and found a marked increase in impacts, which they attributed to changing economic circumstances and coastal development.

### South Indian, South Pacific and Northeast Pacific

Callaghan and Power<sup>103</sup> find a statistically significant decrease in eastern Australia land-falling tropical cyclones since the late 19th century, although Hartmann et al.<sup>104</sup> note that after including 2010/2011 season data, this trend becomes non-significant (i.e., a trend of zero lies just inside the 90% confidence interval). Holland and Bruyere<sup>61</sup> analyzed the South Indian and western South Pacific regions separately and found an increasing trend in the proportion of intense hurricanes that was significantly related to global warming at the 99% level. However, the South Indian Ocean basin had the same oblique viewing angle issues that characterized the North Indian Ocean<sup>3</sup> which could partially explain the trend found in that region.

In contrast, Kuleshov et al.<sup>105</sup> analyzed a compiled Southern Hemisphere best track data archive from 1981. They found no trends in the total numbers of TCs nor in numbers of TCs with central pressures of 970 hPa and lower in the Southern Indian Ocean and the South Pacific Ocean (such TCs being called “severe” in the Southern Hemisphere). Positive trends in the numbers of TCs with central pressures of less than 945 hPa in the Southern Indian Ocean are significant but appear to be influenced to some extent by changes in data quality. Malan et al.<sup>106</sup> reported an increased occurrence of severe storm days (category 3 or higher) in the Southwest Indian Ocean since the 1990s associated with the increase in tropical cyclone heat potential, although total cyclone numbers decreased. In the Australian region, Kuleshov et al.<sup>105</sup> found no significant trends in the total number of TCs, or in the proportion of the most intense TCs. While this conclusion of Kuleshov et al. is different from that of Holland and Bruyere, slight differences in the methodologies between these two studies may account for this difference.

For the northeast Pacific, studies that have examined trends in this region as part of global trend analysis have found no significant trends in intense TCs<sup>62,196</sup>. Interdecadal variability in landfalling storms on the Pacific coast of Mexico is substantial and appears to be modulated by the Pacific Decadal Oscillation<sup>197,198,199</sup>.

### ENSO, tropical cyclones and climate change

Tropical cyclone incidence in various formation basins is strongly tied to ENSO variations<sup>107,108,109,110,111,112</sup>. Thus any substantial change in the behavior of ENSO in a warmer world would cause substantial accompanying changes in tropical cyclone formation regions and tracks. Current high-resolution climate models simulate aspects of the relationship between ENSO and tropical cyclones well<sup>113,114,115,116,117,20</sup>. Nevertheless, Christensen et al.<sup>118</sup> concluded that at present there was still low confidence in projected changes of the intensity and spatial pattern of ENSO in a changed climate, and thus similarly low confidence in future changes in tropical cyclone formation regions due to changes in ENSO.

## Relationships between tropical cyclone formation and climate

Understanding the fundamental links between climate and tropical cyclone is vital to improving the confidence of our future projections of tropical cyclones. At present, there is no climate theory of tropical cyclone formation, in the sense that the number of tropical cyclones likely to be produced in a particular climate can be confidently calculated. Links between what appears to be the two-stage process of tropical cyclone formation (organization followed by intensification) and climate are not well understood. Recent results have strengthened the evidence that tropical cyclone numbers appear to be tied to changes in the mean vertical circulation in the tropics<sup>42,119,78,120</sup>. In addition, several results indicate the importance of mid-tropospheric moisture deficit in tropical cyclone formation<sup>5,121</sup>. Nevertheless, care needs to be taken to differentiate between the important role of mid-level moisture in the immediate environment of the tropical cyclone, and the impact of climatological mid-level moisture on broad TC formations. Bruyere et al.<sup>122</sup> found that climatological mid-level moisture variations were slightly negatively related to interannual variations in tropical cyclone frequency for the North Atlantic. Based on this analysis, humidity appears to be a threshold parameter for interannual tropical cyclone formation.

A number of GCM experiments have shown statistical links between climatological upward mass flux and TC formation. Using idealized climate experiments, Held and Zhao<sup>42</sup> and Sugi et al.<sup>119</sup> showed that both the CO<sub>2</sub> increase and SST increase contribute about equally to the reduction of future upward mass flux, which they suggested could lead to a reduction of TC frequency. The more recent US CLIVAR Hurricane Working Group experiments, where SST and CO<sub>2</sub> values were also changed separately to understand their effects, also reached similar conclusions<sup>123,120</sup>. In these experiments, it should be noted that the saturation moisture deficit does not change in the CO<sub>2</sub> increase (without SST increase) experiments, and thus it does not explain the reduction of TC frequency in the CO<sub>2</sub> increase experiments in these models<sup>120</sup>. A remaining issue is why the decrease of mean upward mass flux leads to a reduction of TC frequency. A recent study by Satoh and Yamada<sup>124</sup> proposed that an average TC intensity increase combined with a climate-related constraint for the total TC mass flux leads to the reduction of TC numbers.

Recent advances have also been made in the formulation of statistical relationships between climate and tropical cyclone formation, the so-called genesis potential indices (GPIs)<sup>125</sup>. Numerous issues remain regarding their application. Bruyere et al.<sup>122</sup> showed that care needs to be taken with the area selected for application of the genesis parameter. For the North Atlantic, application of these parameters to the Main Development Region east of the Lesser Antilles enables good reproduction of observed variability and trends, but using the whole basin substantially degrades this. They also found that potential intensity and vertical shear are good predictors, especially when used together. Low-level vorticity makes no contribution and mid-level moisture is weakly negatively related to cyclone formation frequency. These findings are in agreement with earlier studies by Tippett et al.<sup>126</sup>. However, the lack of mid-level moisture signal is not supported by Emanuel and Nolan<sup>127</sup> and

Emanuel<sup>128</sup>. Further, by modifying existing GPs by making the humidity predictor the column saturation deficit and by using potential intensity as the thermodynamic predictor, decreases in future tropical cyclone formation simulated by the HIRAM model<sup>17</sup> can be captured<sup>129</sup> (Figure 1). Peng et al.<sup>130</sup> also investigated environmental parameters controlling TC genesis in the North Atlantic using observations. They concluded that thermodynamic variables were more important controlling parameters than dynamic variables for TC genesis in the North Atlantic. Examining the eastern and western Atlantic separately (40W separation line), they concluded that 925–400-hPa water vapor content was the most important controlling parameter for TC genesis for both regions. Other important parameters included SST and 700 hPa vorticity in the east and, and horizontal shear and divergence in the west Atlantic.

Given the current uncertainties regarding the precise formulation of GPs, further work is needed on the contributions of various environmental parameters to tropical cyclone formation.

### Theoretical relationships between climate and intensity

The now well-established thermodynamic theory of tropical cyclone maximum potential intensity (PI)<sup>131,132</sup> continues to be investigated and refined. In addition, there has been considerable work done since 2010 analysing the “relative SST” argument, namely that tropical cyclone characteristics such as PI in a basin can be affected locally by basin SSTs because tropical upper troposphere temperatures tend to follow the global tropical average instead of the basin average. Thus the relative SST can serve as a useful although not perfect proxy for PI<sup>133</sup>. Camargo et al.<sup>134</sup> and Ting et al.<sup>135</sup> indicate that the decrease in PI in the Atlantic basin caused by aerosol forcing and its increase due to greenhouse gas forcing largely cancelled each other, and the sharp increase in the PI in the last 30 years in this region was dominated by multi-decadal natural variability. They argue that this is more effective in increasing PI than increases in SST related to climate change. In contrast, the observed increases in both global and basin proportions of intense hurricanes found by Holland and Bruyere<sup>61</sup> were all related to global changes which models indicated were arising from anthropogenic effects, and they could find no natural multi-decadal trend in the models that could explain this behavior. Projections are uncertain on whether relative SST (or tropical storm frequency) in the Atlantic basin will increase during the 21st century under GHG forcing<sup>136,23, 137</sup>. In addition, the role of tropopause temperature trends in observed changes in the potential intensity appears unresolved<sup>92,10,138,139</sup>, thus reducing our confidence in future projections of this relationship.

### Projection of future TC climatology

Climate models are the main tools for the projection of the future effect of anthropogenic warming, but for tropical cyclones they generally suffer from inadequate horizontal resolution. The horizontal

resolutions of climate models of tropical cyclones range from ~100-300 km for the CMIP5 models down to ~10-50 km for the new generation of high-resolution models. Christensen et al.<sup>118</sup> provide a synthesis of global and regional projections of future tropical cyclone climatology by 2081-2100 relative to 2000-2019. Globally, their consensus projection is for decreases in tropical cyclone numbers by approximately 5-30%, increases in the frequency of category 4 and 5 storms by 0-25%, an increase of 0-5% percent in typical lifetime maximum intensity, and increases in tropical cyclone rainfall rate by 5-20% (Fig. 2).

## TC Numbers and Occurrence

A number of new, high-resolution simulations of the generation of tropical cyclones by climate models have been performed in recent years. Several models are now able to give reasonable simulations of tropical cyclone formation in most basins<sup>17,137,140,141</sup>, although simulating formation in the Atlantic remains a challenge<sup>142,143</sup>. The most recent simulations indicate an improved ability to simulate Atlantic tropical cyclone formation<sup>144</sup>. Most models (with one or two exceptions) continue to simulate fewer tropical cyclones in a warmer world, particularly in the Southern Hemisphere<sup>145,146</sup>. For the direct detection of tropical cyclones in CMIP5 model projections, there are large biases in most models, due to their relatively low horizontal resolution<sup>147</sup>. If we exclude models that have an extremely poor tropical cyclone climatology in the present climate, most models projections are for a reduction of future global TC frequency. Using different detection method, Camargo<sup>148</sup> did not obtain a robust response in future changes in CMIP5 coupled models global TC frequency in the future warmer climate. A few showed an increase, others showed no change, and several showed a decrease in TC global frequency. However, a few models that were analyzed in common by both Tory et al.<sup>149</sup> and Camargo<sup>148</sup> were in agreement in having significant frequency decreases<sup>146</sup>. Murakami<sup>147</sup> also investigated the influence of model biases on future TC projections using an empirical statistical analysis.

Murakami et al.<sup>19</sup> present results from four experiments with 20km and 60km resolution MRI-AGCMs (Fig. 3), while Murakami et al.<sup>150</sup> present results of 12 simulations with 60km resolution MRI-AGCMs (Fig. 4). With these experiments, the number of experiments for global TC frequency change increases from 19 in Knutson et al.<sup>28</sup> (their Table S1) to 35 in Christensen et al.<sup>118</sup> (their Table 14.SM.4a). These newer results also indicate decreased numbers of TCs in a warmer world. One important point in Murakami et al.<sup>19</sup> is that the TC intensities simulated by the 20km resolution models with a different convection scheme are significantly different. The MRI-AGCM 3.2 (the new version of the model) with a new convection scheme simulates very intense TCs, comparable to observed intensities, while MRI-AGCM 3.1 (old version) significantly underestimates the TC intensity, indicating that the simulated TC intensity response depends not only on the resolution but also depends significantly on the convection scheme.

Murakami et al.<sup>150</sup> further examined systematically the impact of model physics and SST change patterns on global and regional TC frequency changes. Murakami et al.<sup>19,150</sup> indicated that there were three major source of uncertainty in the TC frequency change projections: 1) resolution, 2) physics (convection scheme) and 3) SST pattern change. The response of tropical cyclones to increased greenhouse gases depends on resolution, with finer-resolution models showing stronger decreases in tropical cyclone numbers<sup>151,140,152</sup>.

An exception to the general projection of decreases in future tropical cyclone numbers is Emanuel<sup>153</sup>, in which tropical cyclone numbers are projected to increase. In the method used in this study, a downscaling technique is applied in which a constant “seeding” rate for tropical disturbances is imposed under different climate conditions, and the “seeds” that develop into tropical cyclones are then counted. There is an indication that the seeding rate in at least one climate model decreases with climate warming (Ming Zhao, personal communication, 2015).

There remains considerable disagreement between models regarding projections for individual basins, however<sup>148,146</sup>. Regionally, an important new result is the possibility of an increase in tropical cyclone numbers in the region near Hawaii<sup>154,195</sup>. Modeling studies also suggest changes in future tropical cyclone activity for the WNP basin. More models project decreases than increases in tropical storm frequency. Most studies project an increase in the TC intensity and increases in TC precipitation rates<sup>72</sup>. In the North Indian Ocean, Murakami et al.<sup>155</sup> use a high-resolution ensemble to show a 46% increase in TC numbers over the Arabian Sea and a 31% decrease over the Bay of Bengal by the late 21<sup>st</sup> century.

Theoretical techniques have been applied in an effort to increase our confidence in regional projections. The influences of vertical wind shear, entropy deficit and potential intensity are combined by Tang and Emanuel<sup>132</sup> in a “ventilation” index. In Tang and Camargo<sup>156</sup>, this is used as a metric to assess possible changes in TC frequency in CMIP5 models. They showed that by the end of the 21<sup>st</sup> century there is an increase in the seasonal ventilation index, implying less favorable conditions for TC genesis or rapid intensification in the majority of the tropical cyclone basins, with the exception of the North Indian Ocean. Basin changes in the index are well correlated with changes in TC frequency and intensification in the models.

Another important question is whether the typical regions of occurrence and resulting impacts of tropical cyclones in today’s climate might change in a warmer world. Evans and Waters<sup>193</sup> examined results from coupled models to show that the threshold temperature for onset of deep convection – often associated with regions prone to tropical cyclogenesis – is likely to increase in a warmer world. A similar result has been obtained from observations for the amount of warming that has occurred so far<sup>157,158</sup>. One implication of this result may be little change in future regions of cyclogenesis, as an increase in the future threshold temperature of deep convection is also accompanied by a general increase in SSTs. However, if a substantial change in the threshold temperature for TC formation will

occur in the future, it has not been observed yet: Dare and McBride<sup>44</sup> examined all global individual tropical cyclone formation events from 1981 to 2008. Dividing the 27-yr dataset into an earlier versus a later 13.5-yr period, positive but small changes (+0.20°C) occur in the mean formation temperature.

TC occurrence can be affected by changes in typical TC tracks. Colbert et al.<sup>159</sup> used a statistical-dynamical modeling approach to estimate future changes in tropical cyclone tracks in the North Atlantic, finding a decrease in westward tracks and an increase in recurving tracks. This would imply a decrease in landfall in the Caribbean and North America independent of overall changes in activity. Murakami and Wang<sup>160</sup> reported that TC tracks would shift eastward in the North Atlantic in a warmer climate. In the WNP, Wang et al.<sup>161</sup> used singular value decomposition (SVD) analysis and found that the observed TC track changes are linked to the leading SVD mode of global sea surface temperature warming and to associated changes in large-scale steering flows. Wang et al. suggested that future changes in these steering flows using the SVD mode as simulated using five CMIP3 models implied that the currently-observed track changes in this region, with more storms over subtropical East Asia and less over the South China Sea, may persist until at least 2040. In another study, Murakami et al.<sup>162</sup> used a 20-km mesh global model to simulate possible future changes in TC activity over the WNP. They noted an eastward shift in the positions of the prevailing northward recurving TC tracks during the peak TC season (July–October) for 2075–99, resulting in a significant reduction in the number of TCs approaching coastal regions of Southeast Asia. Yokoi and Takayabu<sup>163</sup> also performed future projections of the regional TC passage frequency over the WNP by using seven CMIP3 general circulation models. The models project increases in the TC passage frequency over the tropical central North Pacific and decreases in regions to the west and northwest, including East Asian countries. Their analysis reveals that the gross horizontal contrast in the passage frequency changes is caused by a projected eastward shift of the main TC development region, probably caused by the pattern of projected sea surface temperature changes, which is uncertain. Moreover, the likely track changes would decrease the passage frequency over the Korean peninsula, Indochina peninsula and western Japan, but increase that over eastern Japan and the eastern coast of central China. A consistent projected increase in TC occurrence in the Central Pacific is also reported in a few studies<sup>154,164</sup>.

## TC intensity

A notable change in the capability of climate models of tropical cyclones in the last few years is that more high resolution climate simulations can now simulate reasonably well the observed intensity distribution of tropical cyclones<sup>21,165,19,166,137,167,20,168</sup>. These high resolution models typically predict an increase in the frequency of the most intense tropical cyclones. Ideally, though, even higher



resolutions would be preferable for the best representation of the tropical cyclone intensity response<sup>169,170</sup>. Along these lines, the sensitivity of limiting hurricane intensity (a statistical analogue of maximum potential intensity) has recently been estimated to be about  $8 \text{ ms}^{-1}\text{K}^{-1}$  in the Atlantic basin, which is similar to the estimated sensitivity to patterns of SST change of potential intensity computed across a suite of coupled GCMs<sup>157</sup>; but this sensitivity is not reached in some recent high-resolution climate models<sup>171</sup>, likely due to resolution issues. Statistical downscaling of the GCM simulated intensity distribution is also demonstrated to be useful for understanding present-day intensity variability and future change<sup>22</sup>.

For societal impacts, Christensen et al.<sup>118</sup> note that the number of very strong cyclones is usually more important than a measure such as mean intensity. Several studies<sup>50,51,52</sup> provide evidence that predicting societal impacts also requires explicit inclusion of hurricane size and translation speed changes. Note that physical factors like storm size and intensity are difficult for global models to simulate directly unless very fine resolution is used, yet these are factors that are important for societal impacts of TCs, which are largely dominated by the rarer, high-intensity storms.

### Air-sea interaction

The exchange of energy between the ocean and the atmosphere is the fundamental reason why TCs intensify<sup>171</sup>, so capturing this process in model simulations of TCs is important. Due to the very significant computational cost of running high-resolution coupled ocean-atmosphere GCMs, most very high resolution simulations of the effect of climate change on tropical cyclones have been performed using the time-slice method, whereby simulated SSTs from a coarser-resolution model are used as a boundary condition for the simulation of a finer-resolution atmosphere-only climate model. While this technique is far more economical in computer time than using a full coupled-ocean atmosphere GCM to perform the same projection, the lack of full air-sea interaction in the time-slice experiments has raised questions about their realism, especially for simulating intense tropical cyclones where air-sea energy exchanges are strong. On the other hand, the limited number of high-resolution coupled model simulations that have been performed to date obtain similar results to the atmosphere-only GCMs. Kim et al.<sup>172</sup>, using the GFDL CM2.5 coupled model at a horizontal atmospheric resolution of about 50 km, note a strong link in their model simulations between decreases in tropical cyclone occurrence and decreases in upward mid-tropospheric vertical velocity in tropical cyclone formation regions, similar to that found in the atmosphere-only models. In addition, like the atmosphere-only models, they also simulate too few storms in the Atlantic. The response to increased CO<sub>2</sub> in their model is a substantial decrease in tropical cyclone numbers in almost all basins, and an increase in average TC intensities by about 3 percent, again similar to results from atmosphere-only models. Nevertheless, a resolution of 50 km is still coarse compared to the resolution required to simulate reliably the tropical cyclone intensity distribution.



In addition to the effect of climate on TCs, TCs themselves also appear to have some effect on the global climate. State-of-the-art fully coupled GCMs are able to represent the TC interaction with the ocean and TC activity (given the aforementioned under-simulation of TC intensities) seems to significantly impact the ocean heat transport (OHT) within the tropical belt, on short time scales, but no significant changes appear to have occurred over the past century<sup>173</sup>. The role of tropical cyclones in the ocean heat transport has been quantified but the range of estimates is large and the tropical cyclone-induced transport response differs from study to study<sup>174</sup>.

## TC rainfall and other impacts

Christensen et al.<sup>118</sup> note that the increase in rainfall rates associated with tropical cyclones is a common response of numerical models under greenhouse warming<sup>172,137,175,176</sup>. Projected increases in TC rainfall typically range from 5-20%, although results can vary somewhat between different tropical cyclone basins<sup>168</sup>. The quantitative changes may also depend on the details of the TC precipitation metric chosen. Nonetheless, an increase in storm-relative rainfall rates from composite storms in a warmer climate is one of the more confident predictions of the effects of future climate on tropical cyclones.

There have not yet been any detected global trends in tropical cyclone rainfall rates<sup>177</sup>. Chang et al.<sup>52</sup> examined a multidecadal trend in rainfall from tropical cyclones affecting Taiwan. They found that the observed increases arose from relatively weaker typhoons and could largely be attributed to an increase in slow-moving systems. They could not find a mechanism that attributed this trend to anthropogenic climate change.

The most important impact of tropical cyclones in coastal regions is storm surge. Increases in storm surges due to tropical cyclones may be caused by a combination of sea level rise and increases in tropical cyclone wind speeds<sup>178</sup>. Woodruff et al.<sup>179</sup> reviewed this topic, noting that projections of sea level rise are more confident than projections of changes in tropical cyclones. In some locations, sea level rise may dominate the changes in storm surge climatology<sup>180</sup>. From the point of view of the prediction of societal impacts, this outcome actually makes future predictions of storm surge incidence more confident, due to the higher confidence in future sea level rise projections. All else being equal, sea level rise will cause increases in the total flood level associated with a given return period. Particularly for shorter return periods, it is likely that this effect will dominate over changes in the storm climate. The total flood levels associated with return periods on the order of 100 years or less, for example, are very likely to increase, according to calculations to date based on several climate models. At longer return periods, changes in the frequencies and intensities of tropical cyclones play a larger role, and increase the uncertainty in the flood levels for those more extreme events<sup>178</sup>.

Tebaldi et al.<sup>181</sup> present projections of storm surges along the US coast based on historical tide gauge trends, which generally also include vertical land movement effects as well as sea level effects. They did not incorporate storm change effects. By 2050, today's 100-yr events become 'decadal-return-time' events for about a third of their study gauges. They noted that "Gulf locations appear in least danger of a rapid shift [in extreme return levels/periods], despite rapid relative sea level rise, due to the high amplitudes of historical storm extremes, which render the relative effect of sea level rise small."

In summary, model studies indicate that sea level rise contributes toward increased surge risk, although the full change in risk is influenced by storm climate changes as well, particularly for rarer, more extreme surge events.

Done et al.<sup>51</sup> examined potential future changes in North Atlantic hurricane impacts on offshore energy structures in the Gulf of Mexico. Using simulations of hurricane case studies, they found a future increase in the frequency of most intense hurricanes, but that the cyclones became smaller and moved faster. The net result is a predicted reduction in hurricane impacts on offshore energy structures in the Gulf.

## TC detection issues

Ideally, there should be no uncertainty introduced by the method used to detect tropical cyclones in a climate model simulation. In practice, climate model studies use a wide range of tropical cyclone tracking and detection schemes<sup>185</sup>, but no detection technique is perfect<sup>143,149</sup>. Traditional direct detection methods use (i) structural criteria to ensure a disturbance resembles a TC, and (ii) a wind speed threshold to determine if the disturbance is sufficiently intense to be considered a TC.

Some allowance needs to be made when setting these criteria for that fact that TC-like circulations in climate models are not well resolved, which introduces an element of subjectivity to the definition of what actually is a "climate model TC". Various attempts have been made to reduce this subjectivity, including the development of a relationship for wind speed thresholds as a function of grid resolution<sup>183</sup>, and the development of alternative direct detection methodologies<sup>184,143,149</sup>. The Camargo and Zebiak<sup>148</sup> method applies statistically determined thresholds to the windspeed and two structural criteria (vorticity and warm-core), so that extreme circulations, as determined by the variability within the TC basin of interest, are declared TCs. The Tory et al.<sup>142</sup> detection method attempts to identify the large-scale environment in which TCs form, and if this favorable environment persists for 48 hours, a TC is declared. The method is based on the Okubo-Weiss-Zeta Parameter (OWZP), which identifies the existence of large-scale regions of near-solid body rotation in the low- and mid-troposphere. Where these coincide with enhanced relative humidity and weak vertical wind shear, the environment is considered favorable for TC development.

Each method has strengths and weaknesses and indeed when applied to the same model they can produce somewhat different results<sup>146</sup>. Horn et al.<sup>185</sup> find some sensitivity to the choice of TC detection scheme when applied to the results from various perturbation climate experiments, although once minor differences between the schemes were removed, the results of the perturbation experiments became more similar. It is also noted that not all disturbances in the tropics with low-level wind speeds greater than  $17 \text{ ms}^{-1}$  are tropical cyclones (e.g. monsoon gyres<sup>186</sup>), so there will continue to be a need for a reliable TC detection method for the analysis of climate model output. Until climate models can be run at a fine enough resolution to resolve adequately inner-core TC structure, alternative methodologies such as the Camargo and Zebiak and Tory et al. detectors can offer valuable insight into detection uncertainty when used in parallel with the traditional direct detectors.

## Research topics for the future

### Detection methods as a source of uncertainty

The various methods used to detect tropical cyclones in climate models can be viewed as a form of modelling uncertainty. Given that current detection techniques can deliver different results when analyzing the same climate modelling system (as noted above), there could be value in analyzing subjectively the circulations that each detector detects. For example, does the detector that systematically detects fewer TCs only identify the strongest circulations? Such knowledge will better inform projection results. This still implies a need for standardized detection techniques, although it is noted that this outcome may need to wait until climate models can routinely simulate well the intense inner-core region of tropical cyclones. Furthermore, it is expected that the differences among detection methodologies will decrease as the models increase horizontal resolution and the TC activity is better simulated. Having unified detection methods across different resolutions will be important.

### Lack of a climate theory of tropical cyclone formation

As stated earlier, a theory of any kind that tells us what the probability of TC genesis is for a given large-scale environment is not available at this time. Therefore, historically, there has been a reliance on empirical genesis indices, and more recently, on the new generation of global atmospheric models that have begun to produce increasingly realistic results for tropical cyclone climatology. While this recent development is encouraging, confidence in the predictions of these models would be considerably enhanced if they could be compared to the results of a realistic climate theory of tropical cyclone formation, just as high-resolution model predictions of future

increases in maximum tropical cyclone intensities have been made more confident by a realistic theory of maximum potential intensity.

## Confidence in detection and attribution of observed changes in tropical cyclones to date

While there has certainly been an increase in tropical cyclone activity in the Atlantic basin since the 1970s, debate continues over the relative contributions of internal climate variability versus the radiatively-forced response. Similarly, debate still continues about trends in the temperatures of the tropical upper troposphere, which are important for evaluating climate-related changes in tropical cyclone activity.

Typically, climate models are needed in order to attribute changes in TC activity to a specific cause, such as anthropogenic forcing. For example, to assess whether an observed trend is “detectable” or unusual compared to trends expected from natural causes alone, a comparison of the trend with the distribution of trends from long simulations of natural variability alone (without anthropogenic forcing) is often used. Models run with and without a given set of forcings (e.g., with and without anthropogenic forcings) can be important tools for assessing causes of an observed change. If an observed change is consistent with that simulated by models that include a given set of forcings (e.g., anthropogenic plus natural forcings) and inconsistent with the simulation obtained using only a subset of the forcings (e.g., runs with natural forcings only), this indicates a change which is attributable, according to the models, to anthropogenic forcing. While such procedures have been used for surface temperature changes and other variables, their use for assessing historical tropical cyclone changes is relatively rare. One example is a modeling study of anthropogenic aerosol forcing of historical Atlantic tropical storm multidecadal variability by Dunstone et al.<sup>86</sup>, although other models differ on how much anthropogenic aerosols have contributed to the observed North Atlantic multidecadal TC variability<sup>23</sup>. In general, the relative contributions of aerosol forcing and internal climate variability to observed North Atlantic multidecadal SST variability remains a topic of research and discussion<sup>85,87</sup>.

The observed regional shifts in TC activity in the WNP basin in recent decades may have significant implication for landfalling TCs and associated impacts various countries in the WNP<sup>187,188</sup>. Further studies are required to identify the possible causes and relative contribution of global climate change to these changes. Similarly, while climate models project more precipitation from TCs in the WNP (and globally) in the 21st century, observational studies and model simulations are required to assess the long-term variations of the total and extreme rainfall induced by tropical cyclones for different countries in the WNP (and globally) in the past and the 21st century.

There remains considerable work that can be performed in producing more homogeneous data sets of tropical cyclones for climate analysis<sup>3,47,58,80</sup>. The production of data sets that make allowance for

undersampling of tropical cyclone counts in the pre-satellite era, as pioneered in the Atlantic basin, could be extended to other basins. In particular, reanalysis efforts to create more homogeneous records of landfalling tropical cyclones are needed.

It has been inferred from paleotempestology studies that variations in tropical cyclone activity over centennial time scales have been large, based on studies at a limited number of locations. Reasons for these apparent large centennial-scale TC activity variations are presently unknown.

### **Impact of uncertainty in future projections of large-scale climate fields**

One of the reasons that confidence in future regional projections of tropical cyclones remains limited is the variation between climate models of projections of mean patterns of change of regional SSTs. Therefore it remains important to improve climate model simulation in order to reduce uncertainties in the 21st century projections of the mean magnitude and patterns of change of both regional SST patterns and of the vertical structure of the atmosphere (temperature, winds, moisture), as these differences can lead to large differences in regional TC projections. Additionally, the future changes in climate modes such as ENSO and the resulting effects on TC projections are still unclear, given the lack of agreement and poor simulation by many climate models of those climate modes.

In this context, the CMIP5 experiments are important. Analysis of these experiments for changes in tropical cyclones has only started<sup>153,190,146</sup> and more results will need to be produced before a consensus can emerge on the likely effect of the CMIP5 experimental results on tropical cyclones.

### **Correct simulation of tropical cyclone frequency response in high resolution climate models**

Even if there were high confidence in future mean large-scale environmental changes, there would still be uncertainties due to the simulated response of tropical cyclones in the climate models. Improved theoretical understanding of the relationship between climate and tropical cyclones would assist in decreasing existing uncertainties. Model resolutions will soon become high enough for routine comparisons to be made between the small-scale mechanisms of tropical cyclone formation in models and in observations.

Most genesis indices predict an increase in future TC numbers, while the models predict decreases in TC frequency decreases in most cases. It is not clear whether this is a problem with the formulation of the genesis indices<sup>129</sup> or that the models are incorrect and so TC frequency will actually increase<sup>153</sup>.

## Conclusion

Paleotempestology work has identified large, centennial to millennial scale variations in regional tropical cyclone incidence, the causes of which are at present not understood. The paleotempestology record needs to be extended both in time and space, and combined with proxy-based and modeling studies to determine the reasons for these variations. Establishing these reasons might assist in the development of a climate theory of tropical cyclone formation. Analysis of both data and climate simulations may enable the development of quantitative constraints on the formation of tropical cyclones under various climate conditions. These could then be employed to inform the results of climate model projections.

A number of recent papers have documented global increases in the proportion of very intense cyclones and also of trends in the latitude of maximum tropical cyclone intensity, consistent with the model projections for future climate. Confidence in these projections continues to increase as simulations improve in quality. It is recommended that further research be undertaken to reduce the uncertainties in the detection of trends in tropical cyclones, particularly in the presence of continually improving observational capabilities. This could include (ideally) the extension of aircraft reconnaissance to other regions of the globe. Further improvements of the IBTrACS data set should be undertaken, especially reanalysis efforts in the WNP basin, where significant differences in intensities between various best track datasets remain.

The recent assessment of Christensen et al.<sup>118</sup> provided a synthesis of then-available global and regional projections of future tropical cyclone climatology by 2081-2100 relative to 2000-2019, for a mid-range A1B-like scenario. Globally, the consensus projection was for decreases in tropical cyclone numbers by approximately 5-30%, increases in the frequency of category 4 and 5 storms by 0-25%, an increase of a few percent in typical lifetime maximum intensity, and increases in tropical cyclone rainfall amounts by 5-20%. However, it is noted that there is a large uncertainty in these projections.

One source of uncertainty that has emerged is that somewhat different results can be obtained for model sensitivity experiments if different tropical cyclone detection methods are used. It is useful to pose the question whether the community should converge on a single method for the detection of tropical cyclones in climate models, although this may need to wait until climate models produce improved simulations of inner-core tropical cyclone dynamics and thus better intensities. In the meantime, the careful comparison and use of more than one detection method is needed for the assessment of climate model simulations.

Climate models will continue to improve, by incorporating improved physics and through increases in typical horizontal resolution. The next challenge for the tropical cyclone/climate change community is to use climate models to simulate the observed, cloud-scale processes leading to tropical cyclone formation, to ensure that such simulations give realistic depictions of this process. In addition, the climate modelling community should eventually move towards using coupled models

capable of more realistic tropical cyclone simulation. More analysis should be undertaken of existing coupled model experiments e.g. CMIP5, including possibly the inclusion of a bias correction for intensity<sup>191</sup>.

While the formulation of genesis potential indices continues to be in a state of flux, combining statistical and dynamical approaches to simulate past interannual variability of tropical cyclone activity has shown considerable promise, and it is recommended that this be expanded to consider new approaches.

Against the background of global climate change and sea level rise, it will be important to have quantitative assessments on the potential risk of TC induced storm surge and flooding to densely populated coastal cities / river delta regions in the coming decades and century. A more comprehensive database should be established on casualties and economic loss for monitoring any long-term trends of TC impacts in the different TC basins.

### Acknowledgements

This paper is a revised and extended version of section 5.1 of the workshop report for the 8th International Workshop on Tropical Cyclones, held at Jeju, Korea, 2-10 December 2014. The authors would like to thank Kerry Emanuel, Kevin Tory, and members of the Hurricane Working Group of U.S. CLIVAR and the WMO Expert Team on Climate Change Impacts on Tropical Cyclones for valuable comments on this manuscript.

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### Figure captions

Figure 1. Climatology of a revised genesis index per year for (a) HiRAM climatology, (b) NCEP reanalysis, and (c) ERA-40. From Camargo et al.<sup>129</sup>.

Figure 2. Consensus future projection of tropical storm characteristics. From Christensen et al.<sup>118</sup>(their Fig. 14.17).

Figure 3. Global distribution of TC tracks during all seasons from 1979 to 2003 for (a) observations, (b) and (c), two current climate TC simulations, and (d) the global warming projection using the same GCM as for (c). The numbers for each basin show the annual mean number of TCs. TC tracks are colored according to the intensities of the TCs as categorized by the Saffir–Simpson hurricane wind scale [e.g., tropical depression (TD), tropical storms (TSs), and TC category C1–C5]. From Murakami et al.<sup>19</sup>.

Figure 4. Fractional future changes [%] in TC genesis number for each basin for a group of ensemble experiments, for three different convection schemes and four different future SST patterns. The error bars indicate 90% confidence intervals. Blue bars indicate that projected future changes that are statistically significant at 90% level according to the two-sided Student's t test. The number in the top left corner of each panel shows the standard deviation of twelve ensemble experiments (YG experiment is not included). From Murakami et al.<sup>150</sup>.

Figure 5. Plots of quantiles (mean to 0.9) of the lifetime maximum intensity (LMI) of storms in the various tropical cyclone formation basins, from an homogenized satellite-based analysis of tropical cyclone intensity (1982-2009). From Kossin et al.<sup>3</sup>.



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