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Anthropogenic changes in tropical cyclones and its impacts

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Abstract

Intense tropical cyclones cause death and destruction somewhere on Earth every year. Global warming due to human consumption of fossil fuels and the resultant change in the composition of the atmosphere will result in more intense tropical cyclones with the strongest storms causing even more damage than today. Increasing forecast skill has reduced fatalities in developed nations but the developing nations, particularly island states, remain at significant risk.

1. Introduction

Tropical cyclones are the most intense class of storm on our planet. Also called "Hurricanes" in the Americas or Typhoons in Asia and Oceania, these storms cause serious death and destruction somewhere every year. Driven by the energy in warm tropical waters, other ambient conditions of high humidity, low wind shear (the difference between upper and lower level winds) and the presence of some initiating disturbance are necessary for their genesis. As a result, tropical cyclones are not uniformly distributed across the globe but are clustered in those regions favorable for their development. Because of their severity, tropical cyclones are usually given names and are categorized by the magnitude of the wind speeds. The Saffir-Simpson scale, shown in table 1, is the most commonly used method of categorizing tropical cyclones. This scale is based on estimates of the storm's highest 1 minute sustained wind speed and most storms' categorizations will evolve throughout their lifetimes. Storms are considered *tropical storms* when they reach category 0 or wind speeds of 18m/s and are usually given a name by one of the Tropical Cyclone Centers sanctioned by the World Meteorological Organization (https://www.nhc.noaa.gov/aboutrsmc.shtml). Tropical storms are considered *hurricanes* or *typhoons* when they reach category 1 or wind speeds of 33m/s, *major hurricanes* at category 3 or wind speeds of 50m/s and *intense hurricanes* at category 4 or wind speeds of 58m/s. The Japan Meteorological Agency further defines very *strong typhoons* at wind speeds of 44m/s, *violent typhoons* at wind speeds of 54m/s and *super typhoons* wind speeds of 65m/s. (Note that the Hong Kong Observatory has a different set of typhoon categorizations). Across all ocean basins, about 92 tropical storms occur on average every year (Knapp et al. 2010). However, there is considerable variability in this number with an interannual standard deviation of about 8.5 storms per year. This variability is more pronounced when one considers individual ocean basins as shown in table 2. The frequency of tropical storms that make landfall is significantly more variable and although efforts are being made to understand what control the general circulation has on landfalls, current understanding is limited (Villarini et al. 2011).

Five	≥ 70 m/s
Four	58–70 m/s
Three	50–58 m/s
Two	43–49 m/s
One	33–42 m/s
Tropical storm	18–32 m/s
Tropical depression	≤ 17 m/s

Table 1: The Saffir-Simpson scale of tropical storm 1-minute sustained wind speeds (m/s.)

	Global	North Atlantic	East Pacific	West Pacific	North Indian	South Indian	South Pacific
Tropical storms	91.6±8.5	11.8±5.1	17.5±4.9	27.3±4.2	4.9±1.9	17.9±3.3	12.1±4.1
Hurricanes	47.1±5.5	6.5±3.1	9.7±3.6	15.4±3.5	1.2±1.0	8.7±2.6	5.6±2.6
Intense Hurricanes	10.7±3.3	1.5±1.5	3.0±2.2	3.2±2.0	0.2±0.4	1.8±1.6	0.9±1.3

Table 2: Annual frequency of observed tropical cyclones from the IBTraCS dataset that reach tropical storm (cat. 0-5), hurricane (cat. 1-5) and intense hurricane (cat. 4 & 5) wind speeds for selected ocean basins. Uncertainty ranges are the interannual standard deviation. (Knapp et al, 2010)

Although the Saffir-Simpson scale is familiar to the public, arguably it is not the most informative way to communicate the relative danger of an impending storm. For instance, Hurricane Sandy weakened from category 2 to a post-tropical storm just prior to making landfall in New York and New Jersey but because of its enormous physical size, its very high storm surge caused billions of dollars in damages. By other metrics of storm intensity, such as Integrated Kinetic Energy (Misra, DiNapoli, & Powell, 2013), Accumulated Cyclonic Energy or Power Dissipation Index (K. Emanuel, 2005), Sandy was a storm of epic magnitude.

Most landfalling tropical storms are destructive or at least disruptive to both human and natural systems. Damages to building infrastructures from high winds depend on local building practices and codes (Done, et al. 2018). Coastal areas are most vulnerable to high winds as tropical storms generally weaken significantly as they pass over land and the removal of their principal energy source, the warm ocean waters. Coastal areas can also be vulnerable to *storm surge*, the flooding by ocean waters driven by a tropical cyclones' strong winds. The size of the surge depends on many factors including the near shore bottom topography and the angle of the storm track at landfall in addition to storm magnitude. *Inland flooding* can result from the copious amounts of rainfall associated with tropical cyclones and can be exacerbated if a storm stalls or is otherwise slow moving over land. Areas that experience larger numbers of tropical storm are often built to be more resistant to such wind induced damages but at the highest wind speeds or storm surges, no structure would go undamaged.

While there are strong theoretical and model-based reasons to expect that anthropogenic climate change affects tropical cyclone behavior and statistics, their large interannual variability has precluded the detection of any significant changes in the frequency of tropical storms. However, several natural modes of climate variability are clearly associated with tropical cyclone activity in particular basins both directly and remotely. For instance, either strong El Nino conditions or negative phases of the Atlantic Meridional Mode (AMM) can suppress Atlantic hurricane seasonal activity but strong La Nina conditions and strongly positive AMM phases are required for very active Atlantic hurricane seasons (Patricola et al. 2014). In the Eastern and Central Pacific, tropical cyclone activity is enhanced by strong El Nino conditions or negative AMM phases and vice versa (Patricola et al. 2016). While there are strong theoretical and modeling reasons supporting that climate change will lead to intensification of the more intense storms, a detectable signal is only beginning to emerge (Holland & Bruye, 2014; Kossin et al. 2013). A poleward shift in the observed location of peak intensities is detectible (Kossin et al. 2014) as is a slowing down of translational speed (Kossin 2018). It is not entirely clear that these changes are associated with global warming however.

2. Future climate change.

The effects of anthropogenic changes to the composition of the atmosphere on tropical cyclones can be complicated. While a comprehensive climate theory of tropical cyclones has yet to be developed (Walsh et al., 2014), multi-decadal global climate model simulations at horizontal resolutions high enough to permit these storms are now feasible due to advances in high performance computing. At the global scale, simulations from multiple modeling groups convincingly demonstrate that the most intense tropical storms become both more frequent and more intense (Walsh et al., 2014) as the oceans warm. This result is arguably not yet detectible in the observed record due to its high interannual variability and/or changes in observational techniques (Klotzbach & Landsea, 2015; Webster et al. 2005). However, there is a convincing theoretical argument that the climate models are correct. Emanuel (1986, 1987, 1995) proposed that the "perfect" large tropical cyclone may be thought of as a Carnot engine transporting energy from the bottom of the storm (the ocean surface) to its top (near the tropopause, the boundary between the troposphere and stratosphere). This theoretical concept provides the Maximum Potential Intensity (MPI), or a speed limit, on tropical cyclone winds speeds. The top panel of figure 1 shows the 1979-2005 annually averaged MPI calculated from 30 different climate models of the Coupled Model Intercomparison Project (CMIP5) under the *historical* forcing scenario. This was calculated from monthly values of temperature, humidity and pressure that were bias corrected each month using the ERA-interim reanalysis[1] (Dee et al., 2011) over the 1979-2005

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[1] 1 A reanalysis is a proxy for observations and is usually generated by running a climate model forced by available subdaily observations. They can be useful for estimating the actual climate in regions where observations are sparse or for

period. Because of this bias correction, there is little difference in this model result than that obtained from the reanalysis itself. The bottom panel of figure 1 shows the CMIP5 multi-model change in MPI at the end of the 21st century (2080-2099) relative to 1979-2005 under the RCP8.5 emissions scenario. The same bias correction in the top panel was applied to the model simulations of the future. Because MPI depends nonlinearly on temperature, humidity and pressure, it is preferable to bias correct these inputs to the MPI calculation rather than to bias correct MPI itself calculated with raw model output. The bottom panel of figure 1 indicates that significant increases in intense hurricane wind speeds are to be expected in nearly all regions that currently experience such storms. A significant exception can be seen in the blue region of the North Atlantic. This MPI decrease encompassing most of the main cyclogenesis region may affect the number of North Atlantic hurricanes that make landfall. However, as discussed below, the total number of tropical storms in the future and the controlling factors are uncertain. Note, as figure 1 is an annual average, expected increases during individual months of the hurricane seasons may exceed the values shown here.

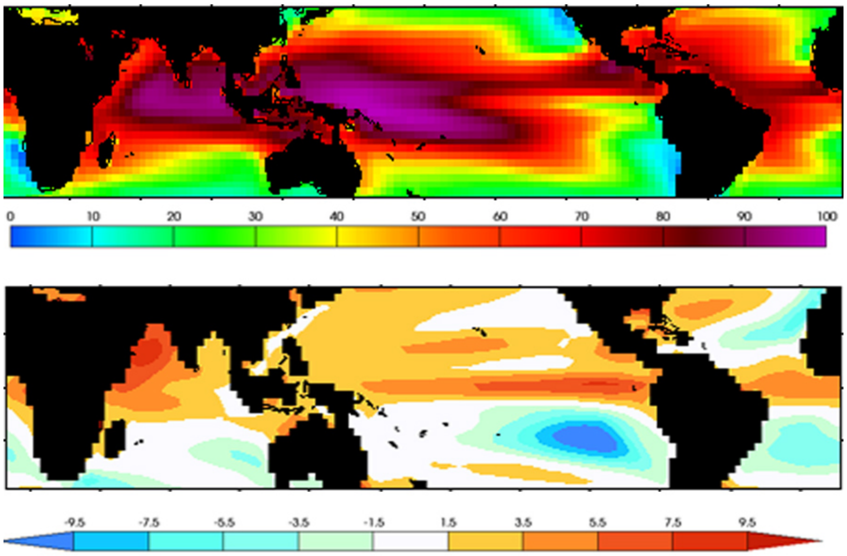

Figure 1. Top: Bias corrected CMIP5 multi-model simulation of average Maximum Potential Intensity (MPI) over the period 1979-2005. Bottom: CMIP5 multi-model simulation change in MPI over the period 2080-2099 from 1979-2005 under the RCP8.5 scenario. (Units for both panels are m/s).

The direct numerical simulation of tropical cyclone permitting climate models provides more complete information than a theoretical model as both the changes in the simulated distribution of wind speeds and the number by Saffir-Simpson category can be counted from appropriate numerical experiments. Precise details

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unobserved physical quantities. However, care must be exercised as the model does introduce its own errors despite the observational constraints.

depend on the specifics of the storm tracking methodology (Ullrich & Zarzycki, 2017) and results tend to be more robust at the higher end of the scale. In a 25km horizontal resolution configuration, the finite volume dynamical core version of the Community Atmospheric Model (fvCAM5.1) has been shown to realistically simulate the observed global number of named tropical storm and hurricane strength cyclones (Wehner et al., 2014). It also produces storms up to category 5, although the total number of intense tropical cyclones is a bit lower than observed due to resolution constraints. Figure 2 shows the fvCAM5.1 simulated changes in the distribution of global tropical cyclone counts at the end of the 21st century under the RCP8.5 forcing scenario. This model exhibits a clear increase in the number of intense (categories 4 and 5) tropical cyclones as well as an increase in the wind speeds of the most intense storms and is consistent with Emanuel's Carnot Engine theoretical model.

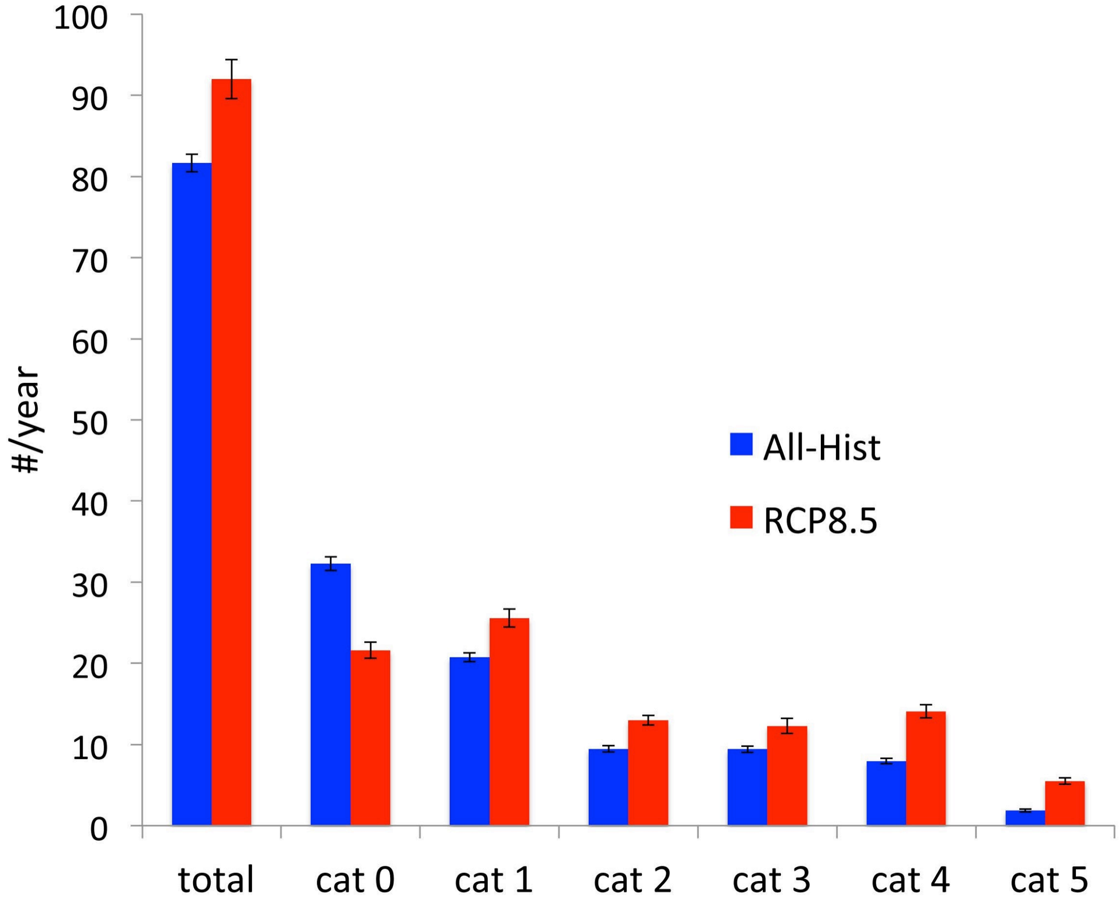

Figure 2. A projection of the global number of tropical storms by Saffir-Simpson scale. From a ~25km version of fvCAM5 under present day and end of 21st century RCP8.5 forcings.

This projection also shows a significant reduction in the global number of category 0 tropical storms. The high-resolution modeling groups usually simulate a reduction in a frequency of weaker tropical storms. These differences in the response at either end of the intensity spectrum are not inconsistent as different physical mechanisms control either tail of the tropical storm wind speed distribution. At the high end of the distribution, available energy (surface sensible heat energy and latent heat energy throughout the lower atmosphere) generally increases with global warming and leads to higher MPI. While the outflow temperature at the top of the storm (i.e., the tropopause) may also increase and tend to diminish MPI, this effect is not so large in general as the effect of increased available energy. As multiple models are consistent with this physically plausible theoretical explanation, confidence is high that the most damaging tropical cyclones will become more frequent and yet more damaging in a warmer future. In addition to the increased direct damages from these higher wind speeds, the most severe storm surges will be also be higher and further compounded by sea level rise (Church et al., 2013).

Changes at the low end of the wind speed distribution are controlled both by environmental factors and the availability of the necessary initial disturbances. Many of the high-resolution climate models actually exhibit fewer overall tropical storms in a warmer climate (Walsh et al., 2014) including previous projections using the same model (Wehner et al., 2018; 2015). Although the community is far from a consensus on this point, it does appear that the pattern of surface ocean changes may matter as much or more than the magnitude of the temperature change (Murakami et al. 2018; 2016).

The set of available tropical cyclone permitting models is set to increase dramatically with the upcoming HighResMIP subproject of the sixth version of CMIP (Haarsma et al., 2016). Whether this reinforces conclusions drawn from results similar to those in figure 2 or not, a comprehensive climate theory explaining the modeled changes in the total number of tropical storms is necessary before confident quantitative projections can be made (Walsh et al., 2014). Projected changes in the tropical cyclone wind speed distributions for specific ocean basins are less confident and not necessarily of the same character as the global changes (Knutson et al., 2010) due to larger relative natural variability at smaller scales. Furthermore, dependence on the pattern of future ocean temperature changes is likely to be even more important at basin scales.

Precipitation within tropical cyclones can almost always be considered heavy and in many storms truly extreme. Extreme precipitation due to tropical cyclones is controlled by several factors including the amount of available water and the internal vertical updraft velocities. As air is warmed, the saturation specific humidity is controlled by the Clausius-Clapeyron (C-C) relationship that dictates an increase of about 6% per ^{o}C warming. As extreme precipitation often occurs when a column of air is nearly completely saturated (Allen & Ingram, 2002), C-C scaling provides some guidance as to expected increases due to thermodynamics. However, there is evidence from long climate model runs that tropical cyclone extreme precipitation rates may exceed this scaling (Villarini et al., 2014). Furthermore, detailed individual event attribution studies of Hurricane Harvey (Risser & Wehner, 2017; van Oldenborgh et al., 2017; Wang, et al. 2018) concluded that both its observed and simulated precipitation accumulations substantially exceeded this rate. Although Harvey is a special case as it stalled for about 5 days off the coast of Texas, these conclusions are reinforced by a regional model analysis of 15 different intense storms in a warmer world that finds precipitation increases in all storms and super C-C scaling in the most intense precipitation rates of a few including Katrina, Maria and Irma (Patricola & Wehner, 2018). This super C-C scaling of precipitation with temperature implies that warming changes the dynamical structure of tropical cyclones. The effect of global warming on tropical cyclones is a very active research area and scientific opinion reflects a diversity of viewpoints. The work cited here suggests that while the expected increase in winds of the most intense storms has not yet emerged, it will relatively soon if current warming trends continue. However, an anthropogenically induced increase in the most extreme precipitation of intense tropical cyclones has already emerged and it exceeds that expected from thermodynamic considerations alone.

3. Discussion

The impacts of the most intense landfalling tropical cyclones are severe and will be profoundly worse in a warmer climate, even in the unlikely event that the stabilized 1.5 or 2K targets of the Paris agreement were to be achieved (Wehner et al., 2018). However, advances in forecast technology have dramatically reduced the immediate death tolls. The September 1900 Great Galveston Hurricane, estimated at category 4 at landfall, took at least 8000 lives by its storm surge and was the deadliest natural disaster in US history (Frank, 2013). In the modern era, such tragedies in developed nations have been substantially reduced due to dramatic improvements in hurricane track forecasting (Krishnamurti et al., 2016) although errors in intensity remain problematic (K. Emanuel & Zhang, 2016). However, massive death tolls in developing nations due to tropical storms still occur despite this increase in forecast skill. In 1998, Hurricane Mitch, a category 5 storm, killed over 11,000 people in Central America due to extensive flooding and massive landslides caused by heavy inland precipitation (NCDC 2004). Super typhoon Haiyan (Yolanda), also a category 5 storm, made a direct hit on the Philippines in November 2013 killing at least 6300 people primarily by a very large storm surge (Lagmay et al., 2015). As recently as 2017, Hurricanes Maria and Irma were catastrophic to Puerto Rico and Domenica respectively as these storms were larger than the actual size of these islands, leaving no place to evacuate to other than off the island, which was not possible for most people. A delayed and inadequate response led to many additional deaths in Puerto Rico after the storm itself had passed (Kishore et al., 2018; Rivera & Rolke, 2018) illustrating that small island communities remain particularly vulnerable. In active seasons such as 2017, some of the islands in the Caribbean experience more than one tropical storm per year compounding the damages.

An increasing awareness of the mental health issues associated with disasters has led to the documentation of the effect of the stress of recovering after major tropical storms. Kessler et al. (2008) found a high incidence of serious mental illnesses, Post-Traumatic Stress Syndrome and suicidality amongst a broad cross-section of the survivors of Hurricane Katrina nearly two years after the storm. Weisler et al.

(2006) further reported widespread unemployment and increased murder and suicide rates in the months after Katrina and advocated for the need to rebuild the health care infrastructure in the Gulf Coast area.

While the immediate human tragedy of a major hurricane can be significantly reduced when the warnings from modern forecasting are heeded, communication of impending danger remains a problem. As discussed in section 1, the Saffir-Simpson scale may not provide a serious enough warning for some storms as the risks from large tropical storms is multi-faceted. Additional information such as the experimental forecast products of storm surge from the National Hurricane Center provide very detailed information to be acted upon and can reduce fatalities. Some countries like Cuba, with enforced mandatory evacuations, have very successfully reduced fatalities (Sims & Vogelmann, 2002). Emergency plans including well designed evacuation routes (Robinson et al. 2018) pose a challenge for some coastal communities with limited access (Urbina & Wolshon, 2003). Social networking now also plays an important part in informing the public of the evacuation orders during tropical cyclones although its role may not be altogether positive (Mohaimin & Hugh 2017). Nonetheless, evacuations of major cities presents significant problems such as the massive traffic jams while evacuating Houston prior to Hurricane Rita or the inability of the poorer residents of New Orleans to evacuate prior to Hurricane Katrina due to inadequate public transportation (Todd, 2006).

Rapid response and leadership from the highest political offices is critical after a disastrous landfalling tropical storm. It is arguable that current resources are not enough to respond to the largest storms, even in a wealthy country such as the United States (Morris, 2006; Farber 2018). As climate change is already increasing some aspects of the severity of intense storms, this expenditure will very likely have to substantially increase if further loss of life is to be avoided.

More people die each year on average in heat waves, famine or armed conflict than in tropical cyclones. And climate change exacerbates each of these threats (Hsiang et al. 2013; Kharin et al. 2013; Siri, 2018). However, tropical cyclones pose a specific threat to the many millions of people who live in coastal areas, whether they be low lying or mountainous. Significant changes in societal behavior are clearly necessary as the most intense tropical cyclones are expected to become yet more damaging. These include revised building codes and their enforcement, improved evacuation procedures, post-storm response and the possible abandonment of some communities.

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