Tropical Cyclones and Climate Change

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1. Introduction

This extended abstract addresses the question of climate change impacts on tropical cyclones, with a focus on: 1) the detection or attribution of past anthropogenic changes in tropical cyclone activity and 2) projected changes by the late 21st century under the IPCC A1B scenario. A greater emphasis is placed on Atlantic hurricanes than other basins.

In February 2010, a World Meteorological Organization (WMO) Expert Team on Climate Change Impacts on Tropical Cyclones published an assessment of "Tropical Cyclones and Climate Change" in Nature Geoscience[1]. The WMO assessment forms the basis for the "consensus" or "best estimate" views in this abstract, which are presented in sections 2-3. Speakers at the workshop were also asked to address the range of possible outcomes. The ranges of future projections presented in the WMO assessment were not intended be interpreted as the range of *possible* future changes. Therefore, in sections 4-5, I expand on some issues which were not explicitly covered by the WMO team report, particularly in section 5 with some speculations concerning a wider range of possible tropical cyclone changes. These comments on the wider range of possible impacts and on statistical vs. dynamical models (section 4) represent my personal views and not necessarily those of the WMO team.

2. Detection of a climate change in tropical cyclones?

The term *climate change detection* as used in this abstract refers to a change which is anthropogenic in origin and is sufficiently large that the signal clearly rises above the background "noise" of natural climate variability (with the "noise" produced by internal climate variability, volcanic forcing, solar variability, and other natural forcings). As noted in IPCC AR4[2], the rise of global mean temperatures over the past half century is an example of a detectable climate change; in that case IPCC concluded that most the change was very likely attributable to human-caused increases in greenhouse gas concentrations in the atmosphere.

In the case of tropical cyclones, the WMO team concluded[1] that it was uncertain whether any changes in past tropical cyclone activity have exceeded the levels due to natural climate variability. While some long (century scale) records of both Atlantic hurricane and tropical storm counts show significant rising trends, further studies have pointed to potential problems (e.g., likely missing storms) in these data sets due to the limited density of ship traffic in the pre-satellite era. After adjusting for such changes in observing capabilities for non-landfalling storms, one study[3] found that the rising trend in tropical storm counts was no longer statistically significant. Another study[4] noted that almost the entire trend in tropical storm counts was due to a trend in short-duration (less than two days) storms, a feature of the data which those authors interpreted as likely due in large part to changes in observing capabilities.

A global analysis of tropical cyclone intensity trends over 1981-2006 found increases in the intensities of the strongest tropical cyclones, with the most significant changes in the Atlantic basin[5]. However, the short time period of this dataset, together with the lack of "Control run" estimates of internal climate variability of TC intensities, precludes a climate change detection at this point. The intensity data also have uncertainties, particularly in the Indian Ocean where the satellite record is less consistent over time.

3. Tropical Cyclone Projections for the Late 21st Century

Based on available studies, the WMO team concluded[1] the following regarding tropical cyclone projections for the late 21st century, assuming that the large-scale climate changes are as projected by the IPCC AR4 A1B scenario (quoted from Box 1 of the Nature Geoscience report):

> "**Frequency.** It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged owing to greenhouse warming. We have very low confidence in projected changes in individual basins. Current models project changes ranging from -6 to -34% globally, and up to +/-50% or more in individual basins by the late twenty-first century.
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> **Intensity.** Some increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally) with projected twenty-first century warming, although increases may not occur in all tropical regions. The frequency of the most intense (rare, high-impact) storms will more than not increase by a substantially larger percentage in some basins.
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> **Rainfall.** Rainfall rates are likely to increase. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone centre.
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> **Genesis, tracks, duration, and surge flooding.** We have low confidence in projected changes in tropical cyclone genesis-location, tracks, duration, and areas of impact. Existing model projections do not show dramatic large-scale changes in these features. The vulnerability of coastal regions to storm-surge flooding is expected to increase with future sea-level rise and coastal development, although this vulnerability will also depend on future storm characteristics."

While the WMO team judged that a substantial increase in the frequency of the most intense storms over the 21st century is more likely than not globally, their confidence in this finding was limited, since the model-projected change results from a competition between the influence of increasing storm intensity and decreasing overall storm frequency. An example of such a change projected for the Atlantic basin is found in a recent downscaling study[6] by Bender et al. (GFDL) using an operational (9 km grid) hurricane prediction model. This downscaling framework projects a doubling in the frequency of Atlantic category 4-5 hurricanes over the 21st century (A1B scenario) using an 18-model average climate change signal. However, when four of the 18 individual models were downscaled, three showed an increase and one a decrease in category 4-5 frequency. Differences in regional SST projections in the various climate models appeared to be important for producing this large range of projections, implying that uncertainties in future regional SST pattern changes must be narrowed to reduce the uncertainty in Atlantic hurricane projections. The study also presented preliminary estimates of the climate-induced change in hurricane damage potential for the Atlantic basin (+28% by 2100 for the 18-model average, with a range of -54% to +71% for the 4 individual models runs). These damage potential projections do not include important influences such as sea level rise, coastal development, and societal adaptation.

4. Methodologies for projecting Tropical Cyclone changes: statistical vs. dynamical models

The projections in the previous section rely heavily on dynamical models including global climate models, higher resolution global atmospheric models forced by SSTs from global climate models, or even higher resolution regional downscaling models. In addition, some studies employed either statistical/dynamical hybrid models or theoretical intensity models. The WMO report also discussed an example of using purely statistical (correlation) methods to project late 21st century Atlantic hurricane power dissipation. In that case, two alternative statistical models of hurricane activity vs SST, both of which perform comparably during the historical period, give dramatically different projections of late 21st century activity, with the projection based on local tropical Atlantic SST showing a dramatic increase of about 300% in power dissipation by 2100. The second statistical approach (relative SST) projects much smaller changes in Atlantic power dissipation by 2100—a scenario strongly favored by current dynamical models. The differences between various dynamical model projections seem to be explained[7] in large part by differences in tropical Atlantic warming relative to the rest of the tropics as projected by the parent climate model used to drive the downscaling model.

The example for Atlantic power dissipation illustrates how dynamical and statistical downscaling techniques, or different statistical approaches, can differ substantially in their projections of the tropical cyclone response to a given climate change scenario. In terms of general modeling approaches, both dynamical modeling and statistical modeling techniques can provide complementary approaches and are worthy of pursuit, although each has its limitations, and results using either approach should be interpreted with due caution. Dynamical modeling attempts to use fundamental physical laws such as the equations of motion and the first law of thermodynamics, integrating systems of these equations forward in time using computer models. One reason this approach is often favored in the case of climate change is that one assumes that the fundamental laws are more likely to be applicable in a changed climate than empirical relations derived by training a statistical model on past climate data alone.

5. Some speculations on the range of possible outcomes

Here I regard the projections in section 3 from the WMO report as consensus statements based on available studies. However, it is possible that more dramatic future changes could occur over the 21st century. While, in my opinion, these more dramatic changes remain speculative, they are at least plausible enough to merit discussion here.

First, it is possible that 21st century changes in tropical cyclones will be less potentially damaging than the scenarios outlined in the projections section. For example, some studies suggest that TC activity in some basins, such as the NW Pacific and North Atlantic, could shift eastward away from current landfalling regions and thus perhaps reduce the percentage of storms that make landfall in major population regions. Global climate transient sensitivity or sea level rise could be at the low end, or even lower than, the range shown in IPCC AR4. Future greenhouse gas concentrations could be toward the lower end or lower than IPCC AR4 scenarios. Alternatively, it is also possible that the reverse could be true in these cases, i.e., that transient climate sensitivity, future greenhouse gas concentrations, sea level rise, and so forth could be higher than expected, or even that storm tracks could shift systematically more toward major landfalling regions, in contrast to a number of current projections.

In addition to these contributors to uncertainty, for the remainder of this section, I will focus on other more novel mechanisms under which future changes could imply substantially greater damage potential than the projections of the WMO report.

Vertical profile of temperature change. A common characteristic of climate model projections of greenhouse warmed climates is an increase in the temperature change with height, such that the upper troposphere about 4 miles above the earth's surface warms more than near the surface. This enhanced warming with height is one of the key factors leading to relatively modest changes in hurricane activity in future climate projections. If the warming were instead uniform with height through the troposphere, the atmosphere would become more unstable and much more conducive to hurricane activity over time, and the resulting increases in intensity could be several times larger than those currently projected. Interestingly, observed vertical profiles of air temperature changes since about 1980 using radiosondes and some satellite records actually show a relatively uniform warming with height through the troposphere. However, as argued by Santer et al.[8], such a change is not only inconsistent with climate models and with the notion that the tropical atmospheric remain close to a moist adiabatic profile, but such as uniform change also differs from the vertical profile of year-to-year fluctuations in temperature, where climate models and observations agree that an such temperature variations have an amplified signal with height in the troposphere. Further, Allen and Sherwood[9] argue that the observed destabilizing temperature trends are inconsistent with temperature trends inferred from wind fields. Therefore I consider it more likely that data problems with the radiosonde and satellite temperature datasets have led to unreliable observed temperature trend profiles that falsely indicate a substantial destabilization of the tropical atmosphere since 1980. Of course it remains important to confirm this assertion with further studies and to maintain a vigilant observing network to monitor the vertical profile of tropical temperatures and TC activity as the planet continues to warm.

Lower stratospheric temperatures. A variant on the theme of vertical profile of temperature changes is the recent study of Emanuel[10], who reports that a cooling trend in the lower stratospheric temperatures in recent decades implies an increase in potential intensity of hurricanes in the Atlantic. According to his statistical/dynamical model, this has further caused an increase in Atlantic tropical storm numbers. While the lower stratospheric temperature decrease remains a subject of further investigation as to its veracity and cause, preliminary results with another (dynamical) model from GFDL (G. Vecchi, personal communication) suggest that lower stratospheric temperatures do not affect tropical storm counts substantially in that model. Further work is needed to better constrain lower stratospheric and upper tropospheric temperature changes, their causes, and their impact on tropical cyclones in general. For example, one can speculate that ozone changes and related atmospheric effects could have affected tropical upper tropospheric temperatures enough to change tropical cyclone activity substantially. If so, this mechanism would have implications for past and future (projected) changes in Atlantic hurricane activity. For example, if it turns out that ozone depletion contributed substantially to the increased Atlantic hurricane activity in recent decades, then the higher activity levels since 1995 could be more persistent than expected on the basis of typical internal variability (Atlantic Multidecadal Oscillation) arguments. Those internal variability arguments typically suggest that hurricane activity will likely return toward pre-1995 levels sometime in the next few decades. In any case, the potential links between lower stratospheric and/or upper tropospheric temperatures, climate forcings, and hurricane activity mentioned here remain speculative.

Impact of Tropical Cyclones on Ocean Heat Transport. Previous work by Emanuel had suggested that tropical cyclones could influence the climate system through changes in the rate of vertical oceanic mixing, leading to changes in the global oceanic heat transport. More recent studies have estimated that this influence on heat transport is confined mainly to the tropics. For example, Jansen et al.[11] estimate that TC cause less than 10% of the global poleward heat transport.

From a paleoclimate perspective, changes in tropical cyclone activity have been proposed as a key mechanism for maintaining the ‘equable’ climates of the early Pliocene (3 to 5 million years ago), when some geologic proxy indicators suggest that the warm tropical SST region was markedly expanded poleward and the eastern equatorial Pacific cold tongue was absent. Federov et al.[12] simulated large increases in tropical cyclone activity during this time, and suggested that the very different temperatures of that time were linked to tropical cyclone feedbacks on climate. Enhanced tropical cyclone activity in their downscaling in the eastern Pacific eventually leads, in their climate model simulations, to permanent El Niño conditions. While the simulated changes in TC activity and in sea surface temperatures in their study are dramatic, the implications of their simulations for climate changes over the next century or so remain speculative.

6. Key research needs going forward

Among the key research needs going forward is the urgent need to have consistent, homogeneous long-term records of hurricane statistics (for trend and climate change assessment) and the need to narrow uncertainties in future sea level rise and regional SST pattern changes that drive regional tropical cyclone changes. Improved quantification or reduction of uncertainty in SST pattern projections will likely depend on reducing uncertainties in cloud feedback, aerosol forcing, and possibly in coupled ocean-atmosphere interaction, which remain central problems in climate change research. Continued monitoring of tropical cyclone activity globally for emergence of trends, as well as further research concerning the vertical structure of the atmospheric temperature changes and ocean mixing effects by tropical cyclones are all prudent measures for earlier detection and/or anticipation of future "surprises" in the hurricane/climate realm.

7. References

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