Tropical Cyclones *in a* Warming World

An Assessment of Projections

Adapted from “Tropical Cyclones and Climate Change Assessment: Part II: Projected Response to Anthropogenic Warming,” by Thomas Knutson (NOAA/GFDL), Suzana J. Camargo, Johnny C. L. Chan, Kerry Emanuel, Chang-Hoi Ho, James Kossin, Mrutyunjay Mohapatra, Masaki Satoh, Masato Sugi, Kevin Walsh, and Liguang Wu. Published online in *BAMS*, March 2020. For the full, citable article, see [DOI.10.1175/BAMS-D-18-0194.2](https://doi.org/10.1175/BAMS-D-18-0194.2).

The global proportion of * intense tropical cyclones is expected to increase. Super Typhoon Hagibis in the Western Pacific in 2019 was one of the most intense in recent years. It strengthened in less than a day by 160 km h⁻¹ (100 miles per hour) from a tropical storm to a category 5 typhoon. Here it is slightly weakened from its previous day's peak, near the Mariana Islands on 8 October. Suomi NPP image, courtesy NASA.

To address the important question of how tropical cyclones (TCs) could change with future anthropogenic warming, we assessed mainly research published since a 2010 WMO task team report on TCs and climate change. We focused on what changes in TC activity would be expected to accompany a 2°C anthropogenic warming, according to current models.

Confidence in several key TC projections has increased since that assessment due to support from additional studies, including new higher-resolution modeling studies. However, anthropogenic signals are not yet clearly detectable in observations for most TC metrics.

The most confident TC-related projection is that sea level rise over the coming century will lead to higher storm inundation levels on average for the TCs that do occur, assuming all other factors

Tropical Cyclone Projections (2°C Global Warming)

are unchanged. Additionally, an idealized 1-m sea level rise in one study increased inundation risk dramatically. However, the influence of climate change on inundation risk due to changes in the storm and storm-surge characteristics is much more uncertain than that of sea level rise, and the former has not yet been convincingly identified in historical sea level extreme data.

For near-storm TC precipitation rates, there is at least *medium-to-high confidence* in an increase at the global scale. A representative quantitative estimate for the increase in TC precipitation rates is about 14% for a 2°C global warming, or close to the rate of the tropical water vapor increase expected for atmospheric warming at constant relative humidity.

The physical mechanism producing the robust TC rainfall rate increases with climate warming is well understood—a warmer climate will contain increased atmospheric water vapor, which enhances moisture convergence, leading to higher rainfall rates. This was a particularly challenging metric for which to create multimodel aggregate projections, however, because different studies reported results using a variety of rainfall rate averaging radii around the storm center. For our assessment, if multiple estimates were available from a given study, we used the estimate closest to 150-km radius.

▲ * Median projected percentage changes for a 2°C global anthropogenic warming in TC frequency, category 4–5 TC frequency, TC intensity, and TC near-storm rain rate. For TC frequency, the 5th–95th-percentile range across published estimates is shown; all other bars show the 10th–90th-percentile range. Note the different vertical-axis scales for the combined TC frequency, and category 4–5 frequency plot vs the combined TC intensity and TC rain rate plot.

While existing modeling studies agree on a projected increase in global average TC rainfall rates, there is less agreement on details of this increase, such as whether the fractional rain increase will increase or decrease as one moves away from the storm center by hundreds of kilometers. Available studies provide conflicting results: there is dependence on the basin, relative SST warming, and whether land regions or oceanic regions are considered. Narrowing these uncertainties will be a challenge for future studies and would benefit from observational guidance on TC precipitation rate changes.

For TC intensity, which is based on simulated lifetime maximum surface wind speeds, 10 of 11 authors had at least *medium-to-high confidence* that the global average intensity will increase. The average increase projected for a 2°C global warming is about 5% (range:

1%–10%) in available higher-resolution studies. All eight of these studies used dynamical models with grid spacing of 60 km or finer, and all projected increased average intensity. A few studies using much coarser resolution models (grid spacing of over 100 km) project no change in TC intensity, but they should be treated with caution.

A balance of evidence suggests that global TC intensity has undergone a weakly detectable increase, with most authors concluding that anthropogenic influence contributed to the increase. This suggestive finding provides some additional support for projections of global TC intensity increases. For individual basins, the author ratings were broadly similar, though slightly less confident; the weakest signal was projected for the southwest Pacific basin.

There is at least *medium-to-high confidence* that the global proportion of TCs that reach very intense (category 4–5) levels will increase, with a median projected change of +13%. This is of great scientific and societal interest, as category 4–5 TCs account for almost half of normalized economic damage in the United States despite representing only about 6% of TC occurrences. An increase in this proportion metric is projected by almost all modeling studies we examined that simulated or statistically inferred category 4–5 frequency of TCs.

Our confident assessment of an increase in *proportion* of category 4–5 TCs does not apply for the actual frequency of category 4–5

On Model Evaluation

Projections of future TC activity involve two problems: (1) projecting changes in environmental factors (e.g., SSTs, atmospheric circulation) that can affect TCs, and (2) projecting changes in TCs given a set of changes in environmental factors. Confidence in future TC projections relies on confidence in both of these tasks and depends on scientific understanding of underlying physical mechanisms, robustness of TC projections across models/studies and our confidence in the models, and supporting evidence such as detection of anthropogenic signals in observations.

Some aspects of TC climate simulations improve with increased model resolution. With 100–200-km (i.e. coarse) grid spacing, models generally cannot simulate category 4–5 TCs. Models with 10–100-km grid spacing capture increasingly realistic structure of TCs, and in some cases even category 4–5 TCs. Global cloud-permitting models (1–10-km grid spacing) can capture some eyewall structures of TCs.

Some assumptions can degrade the reliability of projecting climate change influence on TCs. For example, many modeling studies use specified SSTs, where the atmosphere cannot affect the SSTs. This is an oversimplification of the real world, where TC-generated cool wakes, mixing, and salinity effects are examples of potential feedbacks of the ocean onto the storm.

These are examples of the multiple sources of uncertainty in future TC projections, which should be considered in assessing confidence levels.

Summary of the 11 authors' opinions on key tropical cyclone projections statements. The number in parentheses is the number of authors who * responded with the given confidence level.

Precipitation rates of TCs are projected to increase globally.

Confidence: High (6), Medium-to-high (5)

Intensity of TCs is projected to increase globally.

Confidence: High (3); Medium-to-high (7); Low-to-medium (1)

Proportion of category 4–5 TCs is projected to increase globally.

Confidence: High (3); Medium-to-high (8)

Frequency of category 4–5 TCs is projected to increase globally.

Confidence: High (1); Medium-to-high (4); Medium (1); Low-to-medium (2); Low (3)

Frequency of all TCs (category 0–5) is projected to decrease globally.

Confidence: Medium-to-high (3); Medium (1); Low-to-medium (7)

Latitude of maximum TC intensity in western North Pacific will migrate poleward.

Confidence: Medium-to-high: (2); Medium (4); Low-to-medium (4); Low (1)

TCs, because as the overall global frequency of TCs decreases, based on most projections, the actual numbers of very intense category 4s and 5s have relatively little change.

Author opinion was more mixed and confidence levels generally lower for some other TC projections, including a further poleward expansion of the latitude of maximum intensity of TCs in the western North Pacific basin, the decrease of global TC frequency, and an increase in the global frequency (as opposed to proportion) of very intense (category 4–5) TCs. The vast majority of modeling studies project decreasing global TC frequency (median of about –13% for 2°C global warming), while a few studies project an increase. It is difficult to identify/quantify a robust consensus in projected changes in TC tracks across studies, although several studies project either poleward or eastward expansion of TC occurrence over the North Pacific. Projected TC size changes are on the order of 10% or less, and highly variable between basins and studies. Confidence in projections of TC translation speed is low.

Reducing uncertainties in climate model projections of TC-related environmental variables will be important for reducing downstream impacts of these uncertainties on TC projections. Improved theories (e.g., for TC genesis), improved process understanding of TC responses to climate change, higher-resolution coupled model experiments, long-term observational programs, homogeneous climate-quality datasets, and combined model–observational analyses (e.g., detection and attribution) should all eventually help confirm or refute modeled projections and are important for future progress in the field. ●●

The authors of this report include the members of a WMO/WWRP Task Team on Tropical Cyclones and Climate Change, along with some former members of the expert team for a 2010 WMO 2010 assessment of this topic. This adaptation covers the second of a two-part article. Readers are encouraged to also see part one, about detection and attribution of observed tropical cyclone changes, in BAMS October 2019: <https://doi.org/10.1175/BAMS-D-18-0189.1>.

≡ METADATA

BAMS: What would you like readers to learn from this article?

Thomas Knutson (NOAA/GFDL): *We are trying to give readers a clear statement about what we know and what we don't know about how hurricanes will change if the global climate warms as projected by climate models over the coming century. Future hurricane activity is a much more difficult problem at this time than certain other metrics, such as global mean temperature. We're trying to give readers a sense of where things stand with regard to future hurricane activity even if some big uncertainties remain.*

BAMS: How did you become interested in the topic?

TK: *I became interested in the topic of hurricanes and climate change after reading an early paper on the topic by one of the coauthors of this study, Kerry Emanuel, who published an important paper on this in Nature in 1987.*

BAMS: What surprised you the most about the research you assessed?

TK: *I've been surprised that what initially seemed to be a major consensus around 2010—that tropical storm frequency was likely to decrease globally with climate warming—no longer seemed as likely because at least a few models were suggesting this may not happen. Our author team debated a lot on this topic and it still remains uncertain in my view.*

BAMS: What was the biggest challenge you encountered while doing this assessment?

TK: *Our team did the entire assessment with no person-to-person meetings—just email communication. And we had participants from all parts of the world, so immediate communications were often not possible. Finally, we had some disagreements among authors on some conclusions, so we had to work out a way of letting everyone express their views for the final product.*

BAMS: Will you reassess these conclusions in the future?

TK: *The WMO rotates members off of its expert teams and task teams, and so I will no longer be chair or a member of the WMO task team that put together this assessment. The next task team put together by the WMO will take a fresh look at this topic some years down the road. The IPCC is also following up on this topic through their sixth assessment report. Meanwhile the climate science and hurricane science communities will continue to research this topic.*