SUPPLEMENTARY MATERIAL:

Tropical Cyclones and Climate Change Assessment: Part II. Late 21st Century Projections

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Version 6: July 25, 2019

Revised Submission to the *Bulletin of the American Meteorological Society*

A. Process Used to Develop the Assessment.

The process used to develop the assessment was as follows. A seven-member assessment task team was selected by the WMO's Working Group on Tropical Meteorology Research within the World Weather Research Program. In addition, four authors (Chan, Emanuel, Kossin, and Sugi) from the previous assessment (Knutson et al. 2010) agreed to participate as additional authors on the new assessment. The full author team developed the assessment and deliberated on its content via email, with no in-person meetings. Because unanimous agreement could not be reached on some important issues, the opinions (confidence levels) of each individual author were elicited for a specific set of agreed-upon statements, as in Part I (Knutson et al. 2019). The distribution of author opinion from this elicitation is summarized in the main text, and detailed in Supplemental Material Table 5. Author elicitation responses were not anonymous and were distributed among all authors once available. Authors were permitted to alter their own elicitation table responses at any time up until final acceptance of the manuscript.

B. Previous Assessment Summary of TCs and Climate Change:

Previous global assessments of this topic include Knutson et al (2010), which was a WMO task team report, and the IPCC AR5 assessment (Christensen et al. 2013). Some key aspects of the IPCC AR5 assessment on TC activity are reproduced here for reference and comparison to the current assessment.

For TC projections, Christensen et al. (2013) concluded: "Based on process understanding and agreement in 21st century projections, it is likely that the global frequency of occurrence of TCs will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean TC maximum wind speed and precipitation rates. The future influence of climate change on TCs is likely to vary by region, but the specific characteristics of the changes are not yet well quantified and there is low confidence in region-specific projections of frequency and intensity. However, better process understanding and model agreement in specific regions provide medium confidence that precipitation will be more extreme near the centres of TCs making landfall in North and Central America; East Africa; West, East, South and Southeast Asia as well as in Australia and many Pacific islands. Improvements in model resolution and downscaling techniques increase confidence in projections of intense storms, and the frequency of the most intense storms will more likely than not increase substantially in some basins."

C. Evaluation of Future Projections of TC-Relevant Environmental Parameters

The reliability of future projections of the large-scale environment that affect TCs is a broad problem of climate science. Since IPCC AR5 presented assessments of confidence in model projections for a number of key environmental variables of relevance to TC activity and its impacts (IPCC 2013; Collins et al. 2013), the reader is referred to that report for more detailed assessment of these, since the focus of our assessment is more narrowly on TC projections, rather than the related environmental parameters. In this supplemental material, we provide a summary for some of the more relevant TC-related environmental variables.

The most confident projection and detection/attribution statements in IPCC AR5 were generally for temperature and closely related variables, such as atmospheric moisture content and sea level rise. For example, Collins et al. conclude that global mean temperatures will continue to rise over the 21st century for high (unabated) emission scenarios, with a *likely* warming range of 2.6°C to 4.8°C for the RCP8.5 scenario. They do not make as confident a projection statement about spatial details of surface warming, such as the relative SST warming of different tropical basins. They note that a consistent enhanced equatorial Pacific warming pattern (distinct from El Nino-like warming) is seen in model projections, although estimates of even observed (twentieth century) trends in equatorial Pacific mean SST and the Walker Circulation remain uncertain (e.g., Vecchi et al., 2006; Deser et al. 2010; Solomon and Newman 2012). IPCC (2013) concludes that there is only *low confidence* in any specific projected change in El Niño/Southern Oscillation. An enhanced warming of the upper tropical troposphere relative to the surface is *likely* but with *medium confidence* according to Collins et al. – which is a climate change detail that appears very relevant for TC intensity change in a warming climate (e.g., Tuleya et al. 2016).

IPCC assessments have been very confident about future increases in water vapor in a warmer climate. For example, in IPCC AR4, Randall et al. (2007) state that "In the planetary boundary layer, humidity is controlled by strong coupling with the surface, and a broad-scale quasi-unchanged [relative humidity] response [to climate warming] is uncontroversial." A quasi-unchanged relative humidity response implies higher water vapor content as the air temperature increases. Related to this highly confident increase in moisture, IPCC AR5 projects that "over wet tropical regions, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world" (Collins et al. 2013). Concerning sea level rise, according to IPCC AR5, global mean sea level rise will continue through the 21st century, and it is *very likely* that the rate of sea level rise will exceed the rate observed during 1971–2010 (IPCC 2013), although the amount of rise expected at various locations remains uncertain (IPCC 2013; Garner et al. 2017).

Atmospheric circulation change projections are generally even less confident than the temperature projections. For example, Collins et al. (2013) conclude: "In the tropics, the Hadley and Walker Circulations are *likely* to slow down. Poleward shifts in the mid-latitude jets of about 1to 2 degrees latitude are *likely* at the end of the 21st century under RCP8.5 in both hemispheres (*medium confidence*), with weaker shifts in the NH. In austral summer, the additional influence of stratospheric ozone recovery in the Southern Hemisphere opposes changes due to GHGs there, though the net response varies strongly across models and scenarios ... The Hadley Cell is *likely* to widen, which translates to broader tropical regions…" IPCC AR5 did not provide confidence statements on whether certain regional changes in circulation would occur, such as changes in steering flows or vertical wind shear that could alter TC tracks, genesis, or intensity.

In summary, the large-scale TC-relevant environmental changes where IPCC AR5 has most confidence in future projections include surface temperatures (warming), atmospheric temperatures (warming), atmospheric moisture content (increasing), and sea level rise (increasing). Projections of changes in tropical and subtropical circulation features and regional patterns of SST change are in general less confident. These findings have important implications for confidence in TC projections.

D. Recommended metrics for future studies.

As a step toward future progress in this topic area, we recommend that more standardized TC spatial occurrence metrics be used in future studies to facilitate comparison between studies and to facilitate constructing multi-model and/or multi-study ensemble findings.

Basic information: Model name/source, model resolution, forcing scenario, years of integrations, description of ocean coupling used. Cite methodology used for TC detection.

TC metrics: provide a number or value in control run or present-day simulation, percent change in climate change experiment (except as noted below); report these for globe, NH, SH, and each of the 6 following basins:

Basin definitions:

North Atlantic: ~265°E–360°E, eq–90°N*

NE Pacific: 180°E–~265°E, eq–90°N*

NW Pacific: 100°E–180°E, eq–90°N

North Indian: 30°E–100°E, eq–90°N

South Indian: 20°E–135°E, 90°S–eq

SW Pacific: 135°E–295°E, 90°S–eq

South Atlantic: South America to Africa, 90°S-eq.

* Note: the N. Atlantic/NE Pacific boundary is on a diagonal tracing a path through Mexico and Central America.

<u>List of recommended metrics</u>:

1. Frequency (Cat 0-5 combined)
2. Intense TC frequency (Cat 4-5 combined)
3. Lifetime maximum TC intensity (10-m near-surface windspeed)
4. Lifetime maximum TC intensity (percent change in pressure fall, which is the difference between central pressure and an environmental pressure; note that method used for estimating the environmental pressure should be consistent for the present-day and warm climate storms)
5. Proportion of all TCs (Cat 0–5) that are very intense (Cat 4–5)
6. Accumulated Cyclone Energy (ACE)
7. Power Dissipation Index (PDI)
8. TC Precipitation Rate (averaged within 100, 300, and 500 km of storm center)
9. TC Size (radius of hurricane force wind; radius of 12 m/s wind)
10. TC propagation speed (while storm is classified as a TC)
11. TC duration (time classified as a TC)
12. Surge damage potential (Powell and Reinhold, BAMS, 2007)
13. Latitude of maximum intensity (in degrees latitude, not percent change)

<u>Further recommendations:</u>

We have noted in this assessment the difficulties in obtaining a clear consensus in projected TC track and occurrence, and the sensitivity of such projections for future patterns of SST change. To help address this issue encourage coordinated AGCM experiments using the same SST and climate forcing change across models (e.g., CMIP5 ensemble mean) and coupled GCM experiments nudged to the same future SST change. This will facilitate quantification of at least the component of uncertainty in TC projections associated with the simulated TC response to a common SST change pattern.

E. Supplemental Projections Tables

Detailed information on TC projections, as summarized in this report, is presented in Supplemental Tables 1–4 (see attached tables), where projections are provided for different cyclone domains, including the globe (all basins), by hemisphere, and for six individual TC basins. In the tables, decreases are depicted by blue text, increases by red text, and bold numbers denote statistically significant results as reported by the original authors. In some cases, highly idealized experiments are included in the table, such as 2xCO2 change only (with no change in SST) or uniform +2K increase in SST only, with no change in CO2 content. These are flagged by using green text, indicating that they will not be included in the summary figures alongside more realistic projection types.

To create our summary projection figures (Figs. 1–4), we use published results from a substantial number of available modeling studies to inform our estimates. The separate studies and projection details are provided in Tables 1–4 and accompanying supplemental references. The "raw projections" from individual studies shown in Tables 1–4 provide a traceable account of published results we used to develop our projection summaries and assessment statements, although we needed to use judgement and some subjectivity in combining information from the multiple available studies into summary ranges or other summary information for various TC metrics, as discussed in the main text.

Table 1 for TC (Cat 0–5) frequency of occurrence shows that, at the global scale, the vast majority of separate projection estimates from the various studies are blue, showing the dominant tendency for current models to project a decrease in overall TC frequency as the climate warms. Twenty two out of 27 studies report that global TC frequency decreases in greenhouse warming scenarios, while five studies project an increase or mixed changes in global TC frequency. Among these five studies, one study (Emanuel 2013) finds an increase in global TC frequency using a statistical downscaling framework—in one of five CMIP3 models (A1B scenario) and in all six CMIP5 models (RCP8.5 scenario). Some other studies that examined CMIP5 model results find mixed changes in global TC frequency. Camargo et al. (2013) finds increased global frequency in 6 of 12 CMIP5 models (RCP4.5 and RCP8.5 scenario), while Murakami et al. (2014) finds increased global frequency upon downscaling 3 of 11 climate models (RCP8.5 scenario), but in none of 11 CMIP5 models (RCP4.5 scenario). Tory et al. (2013) also examined CMIP5 model results with an alternative detection scheme and finds a decrease in global TC frequency in all eight CMIP5 models (RCP8.5 scenario). It should be noted that different studies find different (opposite sign) TC frequency changes for the same CMIP5 model in some cases (e.g., for CCSM4, 8% decrease in Tory et al. 2013 but 8% increase in Murakami et al. 2014; and for MPI-ESM-LR, 15% increase in Camargo et al. 2013, but 15% decrease in Murakami et al. 2014). This indicates that there are uncertainties in TC detection algorithms, particularly for tropical storm strength storms and for low resolution models. Therefore, projection results for tropical storms from such models have some degree of uncertainty. Another model resolution-related issue was found in Wehner et al. (2015) who simulated increased TC global frequency but only after degrading their global model resolution from 25 km grid (which has decreased global frequency) to a 100 km grid version. On the other hand, a recent study by Bhatia et al. (2018) projects an increase in global TC frequency using a global coupled model with a 25 km grid atmosphere (RCP4.5 scenario), in contrast to a decrease in global TC frequency projected by all other high resolution dynamical models that we are currently aware of.

Table 2 presents projections of the frequency of intense (Category 4–5) TCs. Owing to concern about model resolution and intensity, the entries in Table 2 are generally organized with higher resolution models located toward the top of the table and lower resolution models toward the bottom. In some cases, results from dynamical models have been statistically downscaled in an effort to achieve a more realistic distribution of TC intensities. Table 2 shows that, in contrast to overall TC frequency (Table 1), for the intense TCs an increased frequency at the global scale is projected, at least for the case of higher resolution models. Specifically, an increase in the global frequency of higher intensity TCs under climate warming was reported in eight of nine dynamical modeling studies using models with grid spacing of 28 km or finer and also for Emanuel's (2013) empirical/statistical downscaling study. For these relatively higher resolution models, the category 4+ range is often being explicitly modeled, at least in terms of maximum near-surface windspeeds of the modeled storms. In contrast, future intense TC frequency projections are much more mixed for lower resolution models, as shown by the results from the models with relatively coarser resolution (e.g., grid spacing of 50 km and larger) in Table 2.

Table 3 presents the TC intensity projections from published studies. In the table, the higher resolution model results are grouped toward the top of the table and the lower resolution model results, in which we have relatively less confidence, are grouped toward the bottom. The 15 global estimates included in Fig. 3a are all positive, with a mean increase of about 5% and a range of +1% to +10%. According to the modeled intensity projections details in Supplemental Table 3, average intensity at the global scale is projected to increase in eight of eight studies that using dynamics models with grid spacing of 60 km or finer, and an also in Emanuel et al. (2008) study with a statistical-dynamical framework. Thus, at least the relatively higher resolution models agree on an increase in global averaged TC intensity, in contrast to their general agreement on a *decrease* in global frequency as discussed earlier (Fig. 1). A few much coarser grid dynamical modeling studies (grid spacing of over 100 km) that project on change in TC intensity with climate warming are included in Supplemental Table 3, but these are not included in the summary Fig. 3.

Table 4 shows that the projected TC rainfall rate for all TC basins combined increases with climate warming in all 16 of 16 available model estimates (summarized from eight studies in which quantitative projections of a rainfall rate metric were reported). As shown in Supplemental Table 4, projections of this metric are positive even in most individual basin assessments, with only a few exceptions for some individual basin cases. The negative changes occasionally projected for individual basins have been interpreted as related to a model simulation having lower SST warming rates within that basin compared to the warming in other parts of the tropics (e.g., Knutson et al. 2015). The median of the 16 quantitative estimates is 14% for a 2^{o}C global warming.

F. Summary of projected TC track and occurrence map changes

Here we present a narrative summary of projected TC track and occurrence changes from a number of publications. Owing to the difficulty in quantitatively combining results from different studies into a common distribution, here the changes are summarized in a narrative form. These summaries are organized roughly into several broad categories representing broadly similar change features seen across multiple studies.

A feature seen in a number of projection studies is a shift in TC activity in the northwest Pacific basin from the South China Sea region to the East China Sea region. For example, this is projected under future climate change forcing experiments by selected subsets of CMIP3 and CMIP5 models (Wang et al. 2011; Wang and Wu 2015; Kossin et al. 2016). There is, however, a considerable range of results across different projection studies for such a change, with results being sensitive to the particular set of climate models used for these projections. Among other TC-climate studies projecting an eastward shift in TC tracks in the western North Pacific are the following: Yokoi and Takayabu (2009) report an eastward shift in TC genesis locations as projected by CMIP5 models under the IPCC A1B scenario. Murakami et al. (2011) project an eastward shift in western North Pacific TC tracks using a 20-km mesh AGCM. Both of the above studies infer that the projected eastward shift is related to a projected eastward shift in the monsoon trough due to the dynamical atmospheric response to an SST warming pattern that is greater in the eastern Pacific than in the western Pacific (i.e., an El Niño-like change pattern). Yokoi et al. (2012) report that an eastward shift in TC tracks in the basin is projected by the CMIP5 models. Using a regional model downscaling technique, Lok and Chan (2017) project a poleward shift of TC activity in the western North Pacific, leading to fewer landfalling TCs in South China, but higher projected intensities for the TCs making landfall there.

Another common feature in several published TC track/occurrence projections is an increase in TC activity in the central Pacific and near Hawaii. Murakami et al. (2013a) project a significant increase in TC tracks near Hawaii using 20-km-mesh high-resolution AGCM. Yoshida et al. (2017) also project a poleward expansion of TC activity in the NE Pacific including near Hawaii along with some poleward expansion in the far eastern North Atlantic; decreased occurrence is projected elsewhere. They project no significant regions of expansion and decreased occurrence in the NE Pacific. Li et al. (2010) analyzed the GFDL HiRAM2.1 and ECHAM5 T319 models (IPCC AR4, A1B scenario) and found that both models projected increased TC genesis frequency in the north central Pacific but decreased TC genesis frequency elsewhere in the North Pacific. Zhang et al. (2017), analyzing projections for the North Pacific based on the Emanuel (2013) framework, project increased TC occurrence over most of the North Pacific, but especially in the central North Pacific. Other studies projecting increased TC frequency in the central North Pacific include Knutson et al. (2015), Murakami et al. (2017a), and Bhatia et al. (2018).

A number of other features are seen in published TC track/occurrence projections. Roberts et al. (2015) project a poleward expansion in the NE Pacific and in the eastern part of the NW Pacific basin, along with a slight increase in the N. Indian Ocean, and decreases elsewhere. Kim et al (2014) find in a 2xCO2 experiment decreased occurrence in most regions, but with slight increases near Hawaii and in the eastern SW Pacific. Manganello (2014) focused on the NW Pacific only, and project a poleward expansion of TC occurrence (A1B scenario time slice) using a 16 km-grid global model time slice experiment, but did not simulate such a change using a 125 km grid version of the model. Sugi et al. (2016) project essentially no significant expansion of overall tropical storm occurrence. Wehner et al. (2015) project a poleward expansion of TC occurrence in their 2xCO2 & +2K uniform SST warming timeslice experiments using a ~25 km grid global model. Park et al. (2017) project a decrease in TC occurrence over the North Atlantic (Gulf of Mexico) but an increase over the northwest Pacific (particularly near Korea and Japan). Yamada et al. (2017), using a 14 km grid global nonhydrostatic model, project decreased TC occurrence in the eastern North Pacific, but generally only small (nonsignificant) changes elsewhere in the tropics. Two TC projection studies showing an eastward shift in TC tracks in the North Atlantic include Murakami and Wang (2010) and Colbert et al. (2013).

Regarding behavior of very intense TCs, four studies provide global maps of projected changes in geographical distribution of very intense (Category 4-5 or Category 5) TC occurrence that have some broadly similar characteristics over several basins (Murakami et al. 2012b, Fig. 12; Knutson et al. 2015, Fig. 9; Sugi et al. 2016, Fig.3; and Yoshida et al. 2017, Fig. 2f). According to each of these studies, the occurrence frequency of Cat 4-5 TCs will increase in northern part of the tropical North Pacific TC basins but decrease in the southwestern part of the Northwest Pacific, in the South Pacific and in the South Indian Ocean near Australia. On the other hand, Bhatia et al. (2018) project that the occurrence of Category 3-5 TCs will increase in most TC regions, although areas with the most pronounced statistical significance include the Atlantic, western North Pacific, central and eastern North Pacific, and the southwest Pacific, including near northeast Australia. Also, Ogata et al. (2016) commented that the increase in Cat4-5 occurrence frequency in the northern part of the western North Pacific reported by Sugi et al. (2016) could be overestimated due to lack in air-sea interaction in their model simulations.

G. Author Responses to Elicitation on Confidence Levels

(See Supplemental Table 5 in separate file)

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