Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2017-101
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 6 November 2017

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Changes in tropical cyclones under stabilized 1.5°C and 2.0°C global warming scenarios as simulated by the Community Atmospheric Model under the HAPPI protocols

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Abstract

The United Nations Framework Convention on Climate Change (UNFCCC) invited the scientific community to explore the impacts of a world where anthropogenic global warming is stabilized at only 1.5°C above preindustrial average temperatures. We present a projection of future tropical cyclone statistics for both 1.5°C and 2.0°C stabilized warming scenarios by direct numerical simulation using a high resolution global climate model. As in similar projections at higher warming levels, we find that even at these low warming levels the most intense tropical cyclones becomes more frequent and more intense, while simultaneously the frequency of weaker tropical storms is decreased. We also conclude that in the 1.5°C stabilization, the effect of aerosol forcing changes complicates the interpretation of greenhouse gas forcing changes.

Introduction

Changes in tropical cyclone intensity, frequency and distribution are expected as the climate warms due to anthropogenic changes in the composition of the atmosphere. While the development of a complete climate theory of tropical cyclones remains elusive (Walsh, et al. 2015), recent advances in high performance computing enables multi-decadal simulations of climate models at tropical cyclone permitting resolutions. Together with conceptual models, such numerical models are the tool of choice for investigating projected future changes in tropical cyclones (Wehner et al. 2017a).

Previous work has studied the impact of climate change on tropical storms through idealized representations of future climate through uniform increases in greenhouse gases and sea surface temperature (Walsh et al. 2015, Wehner et al. 2015) or more realistic but more extreme cases of warming using the Representative Concentration Pathways (RCP4.5 or RCP8.5) scenarios (e.g., Camargo, 2014; Knutson et al. 2015; Bacmeister et al., 2016). The United Nations Framework Convention on Climate Change (UNFCCC) invited the International Panel on Climate Change (IPCC) to explore the impacts of a world where the expected average warming remains less than or equal to 2.0°C over preindustrial levels. In particular, the UNFCCC requested an analysis of the feasibility and impacts of a target stabilized global mean temperature of 1.5°C over preindustrial levels. The Half A degree additional warming, Prognosis and Projected Impacts (HAPPI) experimental

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protocol was designed in response to this request to permit comparison of the effects of stabilizing anthropogenic global warming at 1.5°C over preindustrial levels to 2.0°C (Mitchell et al. 2017). In this paper, we present results from a high resolution atmosphere-land model forced by the HAPPI prescriptions of sea surface temperature (SST) and sea ice concentration.

The HAPPI experimental protocol consists of three parts (Mitchell et al. 2017). The "Historical" part specifies observed sea surface temperatures (SST) from the NOAA OI.v2 gridded monthly mean observational product (Reynolds et al. 2002) over the period 1996-2015. An estimate of SST and sea ice concentrations in stabilized scenarios at both 1.5° and 2.0°C are constructed from the CMIP5 (Coupled Model Intercomparison Project) multi-model database of future climate projections under the RCP2.6 and RCP4.5 forcing scenarios hereafter designated "HAPPI15" and "HAPPI20". These surface forcing functions are constructed using the observations from 2006-2015 to preserve observed interannual variations. As such, Historical year 2006 is directly comparable to HAPPI15 or HAPPI20 year 2106 as the date in the stabilized scenarios is arbitrarily increased by a century. The original design of the HAPPI protocols follows that of the "Climate of the 20th Century Plus Detection and Attribution project" (C20C+) (Stone et al. 2017a) and targets large ensembles of 50 realizations or more to quantify the differences in projections (or attribution) of extreme events in specific years. However, at the high horizontal resolutions necessary to simulate tropical cyclones, the computational costs of the climate model are too high to permit such a large number of simulations and ensemble sizes are restricted. Hence, in this study we pool results across both simulation years and the ensembles for each part of the HAPPI experiment to isolate the climate change signal, if any, from internal variability. As part of our participation in the C20C+ project, we began the Historical simulation period in 1996 extending through 2015 thus permitting a more robust estimate of present day simulated tropical cyclone statistics for comparison to the stabilized warmer climate.

This study uses the Community Atmospheric Model version 5.3 configured at a global resolution of approximately 0.25° roughly equaling a grid spacing of 28 km in tropical regions. Note that this participating model is listed as "CAM5.1.2-0.25degree" in the HAPPI documentation (http://portal.nersc.gov/c20c/data.html), but here is abbreviated to "CAM5". This configuration has been demonstrated to produce reasonable annual numbers of tropical cyclones at the global scale compared to observations (Bacmeister et al. 2014; Zarzycki et al. 2014; Wehner et al. 2014; Reed et al. 2015). The formulation of the dynamical core portion of the atmospheric model does influence tropical cyclone counts and intensities (Reed et al. 2015). The model used in this study used CAM5's finite volume based dynamical core on a latitude-longitude grid (Lin and Rood 1996; Lin and Rood 1997;Lin 2004). Storms up to category 5 on the Saffir-Simpson scale are regularly produced allowing investigation into the effects of global warming on the distribution of tropical cyclone intensity. The relationship between maximum wind speed and central pressure minima was also demonstrated to be realistic (Wehner et al. 2014). However, there are significant biases in track and cyclogenesis density, particularly

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in the Pacific Ocean with the model simulating too many storms in the central North Pacific and too few in the northwestern part of that basin.

Nonetheless, the high-resolution CAM5 can be a informative tool to explore the change in tropical cyclone behavior in altered climates. Wehner et al. (2015) explored tropical cyclone behavior in the four idealized climate change configurations of the US CLIVAR Hurricane Working Group (Walsh et al. 2015). That project compared the combined effect of a spatially uniform 2°C increase applied to a climatological average of observed SST centered at 1990 and of a doubling of atmospheric CO_2 to a control 1990 simulation, as well as the separate effects of each factor. Their principal finding was that a lower resolution (1°) version of the CAM5 as well as methods based on the Genesis Potential Index (Emanuel and Nolan 2004) could not reproduce the sign of the change in the global number of tropical cyclones produced by the high resolution version. Under the combined effect of the uniform 2°C SST increase and CO_2 doubling, the high resolution CAM5 reduced the annual number of tropical storms (categories 0–5) from 86±4 to 70±3. However, the annual number of intense tropical cyclones (categories 4–5) increased from 10±1.7 to 12±1.7. The two separate forcing simulations revealed that most of the reduction in the total number of tropical storms of all intensities was caused by the change in the vertical temperature profile due to the CO_2 doubling while the increase in the number of intense tropical cyclones was caused solely by the increased SST. The warmer SST conditions also caused the maximum wind speeds of the most intense storms to increase and their central pressure minima to decrease while CO_2 doubling had the opposite effect. The peak of the zonally averaged tropical storm track density shifted poleward by ~2° in the Northern Hemisphere and ~4° in the Southern Hemisphere in all three perturbed US CLIVAR configurations. A small poleward shift (~1°) in Northern Hemisphere cyclogenesis origins was exhibited in the two simulations with warmer SSTs but not the CO_2 doubling only simulation, while all three perturbed simulations exhibited a similar shift in the broader Southern Hemisphere cyclogenesis distribution.

The SST and sea ice perturbations imposed by the HAPPI protocols exhibit the more realistic spatially varying SST patterns shown in Figure 1 than the uniform increase of the US CLIVAR experiments. In the HAPPI protocols, warmer configurations are produced by adding monthly climatological perturbations to the observed SSTs for each individual month, preserving the current patterns of SST variability. The SST perturbations for the 1.5°C stabilization scenario are taken directly from the multimodel mean of CMIP5 RCP2.6 simulations (which conveniently warm by approximately that amount on average above pre-industrial temperatures). Radiative forcings (greenhouse gas concentrations, burdens of various aerosol species, and ozone concentrations) are also taken directly from the RCP2.6 values. The 2.0°C scenario uses SST perturbations and CO_2 concentrations interpolated between CMIP5 RCP2.6 and RCP4.5 multi-model means, while other forcings remain the same as for the 1.5°C scenario. Sea ice concentrations are computed using an adapted version of the method described in Massey (2017) by using observations of SST and ice to establish a linear relationship between the two fields for the time

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period 1996-2015 and are consistent with the HAPPI prescribed SST fields. Details are further described in Mitchell et al. (2017). Although they represent a smaller perturbation to the climate system than does the US CLIVAR experiment, the HAPPI experiment is more physically consistent in terms of the relationship of the SST change to radiative forcing changes and in the distribution of sea ice in the high latitudes permitting the HAPPI simulations to be more widely applicable to phenomena outside of the tropics.

The CAM5 simulations performed for the HAPPI project consist of 5 realizations of the Historical period plus 6 realizations of each stabilization scenario. One of the Historical realizations is incomplete due to computer resource limitations resulting in 96 simulated years for this part of the dataset. Sixty simulated years were produced for both the 1.5 and 2.0^{o}C stabilization scenarios. Data products are freely available with further information provided at www.portal.nersc.gov/c20c. Simulated tropical cyclones are identified and tracked with the Toolkit for Extreme Climate Analysis (TECA2.) available for download and installation at https://github.com/LBL-EESA/TECA using the methods described in Knutson et al. (2007).

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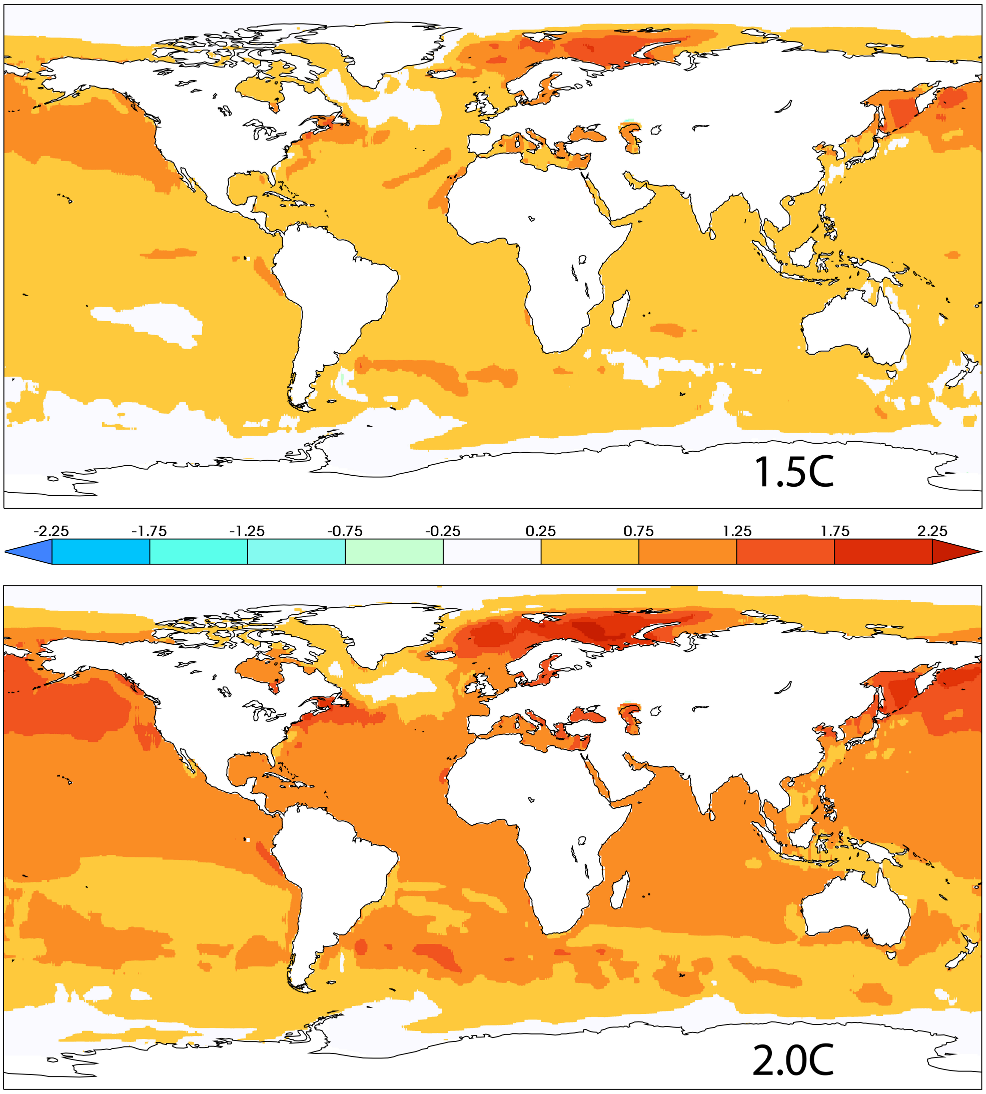

Figure 1: The temporal average of the imposed change (°C) in sea surface temperature as prescribed by the HAPPI protocols. Upper. 1.5°C stabilization. Lower: 2.0°C stabilization.

Another critical difference between the HAPPI and the US CLIVAR experimental protocols is the aerosol forcing. While the US CLIVAR protocols had no specified changes to aerosols, the HAPPI protocols set aerosol forcings to the end of the 21st century levels under the RCP2.6 scenario for both stabilization scenarios. Hence, there is a substantial reduction in the aerosol forcing in the stabilization simulations compared to the Historical simulations. Dunstone et al. (2013) indirectly found a substantial reduction in Atlantic tropical storms by varying aerosol forcing in the UK

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MetOffice climate model HadGEM2-ES at a resolution of 1.2°x1.9°. In the CAM5 simulations presented here, we used its bulk aerosol model to prescribe aerosol concentrations rather than emissions in order to reduce the computational burden (Kiehl et al., 2000). Huff et al. (2017) established that CAM5 does exhibit sensitivity to aerosol formulation in the simulated number and intensity distribution of tropical cyclones in the simulated current climate. However, the HAPPI protocol does not establish a controlled investigation of the effects of the aerosol forcing reduction in the stabilized scenarios nor have we performed such simulations yet. Figure 2 shows the percent change in total aerosol optical depth in the visible band comparing the Historical and 2.0°C stabilization simulations averaged over all years and realizations. Significant decreases are evident over most of the entire Northern Hemisphere and tropics. Results from the 1.5°C stabilization simulations are the same.

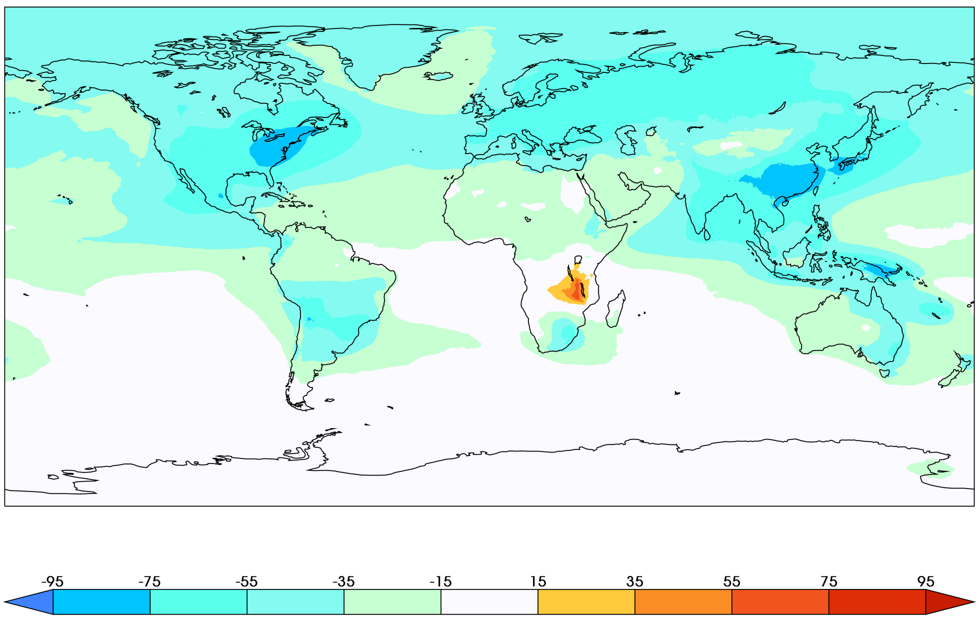

Figure 2: Percent difference between the stabilized 2°C scenario and the historical simulation of the total aerosol optical depth in the visible band.

Results

As in the US CLIVAR idealized experiments, the global number of intense tropical cyclones (category 4 and 5) is substantially increased in the warmer climates of the HAPPI stabilization scenarios with a statistical significance higher than the 1% level as shown in Figure 3. Also as in the idealized warming experiments, the number of tropical storms (category 0) is substantially decreased in a warmer climate. However, the effect on the total number of named storms of all intensities (category 0-5) is subtler in the HAPPI simulations. For this version of CAM5, the global annual

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number of category 0 to 5 storms is 73.4±0.91 in the Historical ensemble[1]. In the 1.5^{o}C stabilization scenario, this number is only reduced to 72.5±1.2, which is not significant at a 10% significance level. However, in the 2.0^{o}C stabilization scenario, a further reduction to 67.5±1.3 is realized which is significant at the 1% level. In the cooler stabilization scenario, the decrease in category 0 storms is roughly offset by the increase in intense storms leading to the insignificance of the change in the total number of storms. In the warmer scenario, the yet larger decrease in category 0 causes the change in the total number of storms to be more significant. In both stabilization scenarios, the changes from the Historical simulation in categories 1,2 and 3 storms are not statistically significant above the 5% level. Differences between the 1.5^{o}C and 2^{o}C stabilization scenarios are only highly significant in the decrease by category for the number of the weakest category of storms.
Importantly, the differences in the number of intense tropical cyclones between the two warming scenarios are not statistically significant in this study. The results presented in Figure 3 are repeated numerically in table 1.

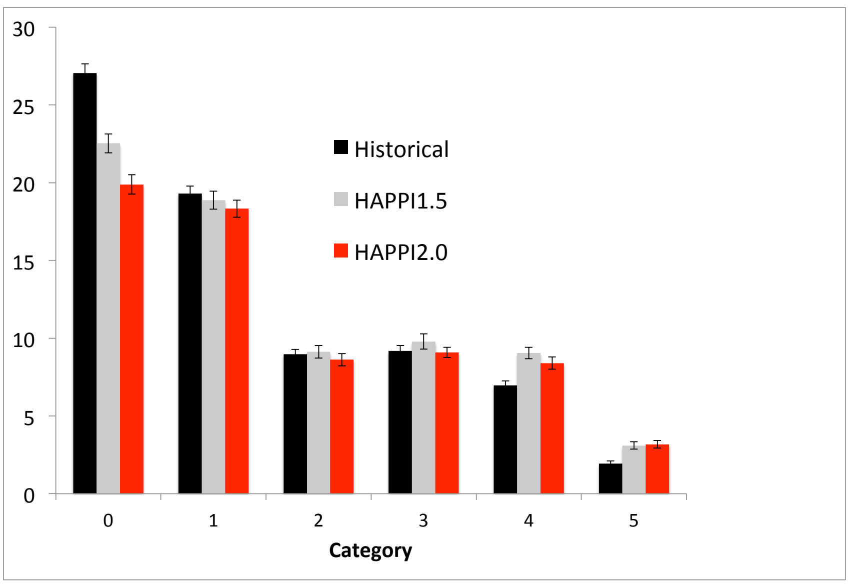

Figure 3. Global annual number of tropical cyclones by Saffir-Simpson scales for the historical (black), 1.5^{o}C stabilization scenario (gray), 2^{o}C stabilization scenario

[1] The Historical annual global tropical storm counts over all categories differs from the 1990 climatological simulations of Wehner et al. (2015) for three reasons. 1) SST are a slightly different 2) The version of CAM5 is a more recent release (CESM v1.2.2 vs. v1.0.3) 3) Subtle differences in the implementation of the tracking algorithm.

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(red). Error bars are the standard errors. Black: Historical. Gray: 1.5° Stabilization. Red: 2.0° Stabilization.

Saffir-Simpson	0-5	0	1	2	3	4	5
HAPPI15 minus Hist	**-0.9**	-4.5	-0.4	0.2	0.6	**2.1**	**1.2**
HAPPI20 minus Hist	**-5.9**	**-7.2**	*-1.0*	-0.4	-0.1	**1.4**	**1.2**
HAPPI20 minus HAPPI15	**-5.0**	**-2.6**	-0.5	-0.5	-0.7	-0.6	0.1

Table 1. Differences in CAM5 simulated global annual tropical storm counts by Saffir-Simpson scale between the two HAPPI stabilization scenarios and the Historical simulation and each other. Differences that are statistically significant at the 1% level are in bold while those at the 10% level are in italics.

Average storm track length, duration and mean translational speed are shown for the HAPPI scenarios as a function of maximum lifetime intensity on the Saffir-Simpson scale in Figure 4. Weak storms (category 0) show no substantial changes in track length, translational speed or duration between the three ensembles of CAM5 simulations and this result is consistent with the US CLIVAR experiments (Wehner et al. 2015). While these three metrics show increases for Category 2-4 storms in the 1.5°C stabilization scenario compared to the Historical simulations, those increases are attenuated in the warmer 2.0°C stabilization scenario. However, the most intense storms (category 5) exhibit consistent increases in track length and duration on average as the climate system warms. Translational speed (here averaged over the entire storm duration) increases in all three ensembles with storm intensity but the differences between scenarios is complex. Notably, while increases in average translational speed in the warmer scenarios are simulated for storms in the middle of the Saffir-Simpson scale, decreases are simulated for the most intense category. While all of the differences in Figure 4 are statistically significant well above the 1% level due to the large number of storms tracked, subtle changes in the experimental design, including changes in SST pattern or aerosol forcing might alter these results. Better quantification of this type of structural uncertainty will require further developments in high performance computing technologies to permit more diverse experiments.

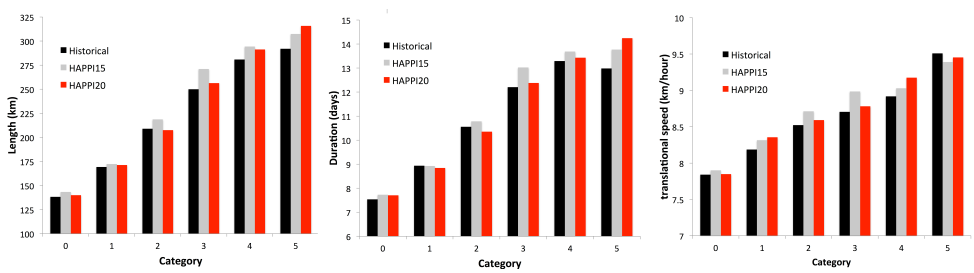

Figure 4: Left: Average tropical storm track length (km) for the HAPPI scenarios as a function of maximum intensity on the Saffir-Simpson scale. Middle: Average tropical storm track duration (days) for the HAPPI scenarios as a function of maximum intensity on the Saffir-Simpson scale. Right: Average tropical storm track speed

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(km/hour) for the HAPPI scenarios as a function of maximum intensity on the Saffir-Simpson scale. Black: Historical. Gray: 1.5° Stabilization. Red: 2.0° Stabilization.

The zonal average of the normalized density of storm tracks of all intensities for the HAPPI scenarios is shown in the left panel of Figure 5. As mentioned above, CAM5 is known to have a significant bias in the genesis location of Pacific tropical storms although the total number, both in that basin and globally is not far from observed records. More detailed but somewhat noisy maps of track density differences between the HAPPI scenarios are shown in the Appendix in Figure A1. Integrating over all longitudes, as in Figure 5, damps this noise revealing a poleward shift in the warmer HAPPI scenarios compared to the Historical simulations. In the Northern Hemisphere, there is a tendency for a substantially larger normalized density of storm tracks poleward of 25N in both the Atlantic and Pacific Ocean basins (see Figure A1). This may partially explain the increased track lengths and durations shown in Figure 4. With warmer temperatures, conditions that can sustain tropical storm wind speeds extend poleward. Although not considered here, there is potential for an anthropogenic influence on the transition to extra-tropical characteristics of storms that undergo them. In the Southern Hemisphere, Figure 5 reveals that normalized storm track density is a narrower function of latitude in the warmer HAPPI scenarios. Figure A1 reveals that this is mainly due to a change in the location of simulated tropical storms in the Southern Indian Ocean. In both hemispheres, differences between the 1.5°C and 2.0°C stabilization scenarios is smaller and noisier making any differences in track density difficult to interpret.

The zonal average of the normalized cyclogenesis density for tropical storms of all intensities is shown in the right panel of Figure 5. Again, more detailed but noisy maps of cyclogenesis density differences between the HAPPI scenarios are shown in the Appendix in Figure A2. In the Northern Hemisphere, a much smaller poleward shift than for track density starting at about 15N is simulated in the warmer HAPPI scenarios compared to the Historical simulations. Figure A2 suggests that much of this change is coming from the Atlantic Ocean but these cyclogenesis differences are not as compelling as they are for the tropical storm tracks. In the Southern Hemisphere, the cyclogenesis changes are similar to the track changes in both Figure 5 and the Appendix. Hence, we can conclude that the shifts in Southern Hemisphere tracks are mainly a result of cyclogenesis shifts that are mostly in the Southern Indian Ocean.

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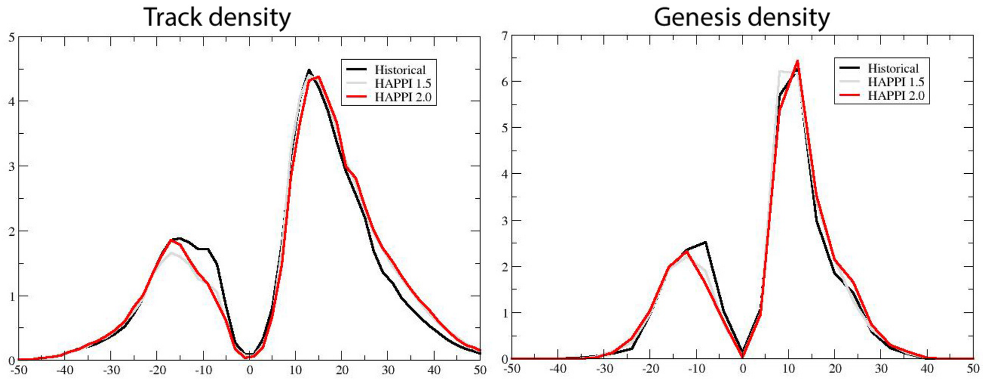

Figure 5. Left: Zonally averaged normalized tropical storm track density for the HAPPI scenarios. Right: Zonally averaged normalized tropical storm genesis density for the HAPPI scenarios. Black: Historical. Gray: 1.5° Stabilization. Red: 2.0° Stabilization.

The annual Accumulated Cyclonic Energy (ACE) is shown in Figure 6 for the Historical and HAPPI stabilization scenarios both globally and by the major ocean basins with tropical cyclone activity. ACE is a measure of the annual kinetic energy contained in tropical storms and is obtained by squaring the maximum sustained surface wind in the system every six hours and summing it up for the year (http://www.cpc.ncep.noaa.gov/products/outlooks/background_information.shtml). Globally, ACE is mainly increased in the 1.5°C stabilization scenario by the increase in the number of intense tropical cyclones. Increases in average storm duration also lead to in the increase in ACE. However, as the total number of storms is significantly decreased in the 2.0°C stabilization scenario, ACE is decreased compared to the cooler stabilization scenario. The global changes are dominated by similar changes in the North Atlantic and Northeast Pacific. Changes in the Northwest Pacific do not exhibit large changes but CAM5 has a significant cyclogenesis location bias in the Pacific Ocean that may be relevant. While the total number of simulated north Pacific storms is a reasonable representation of observations (Wehner et al. 2014), Northwestern Pacific storms originate too far to the east causing cyclogenesis and track densities to be too high in the central Pacific and is focus of current research to be presented elsewhere. Also of note is that ACE in the Southern Indian Ocean does not change despite the cyclogenesis and track changes discussed above.

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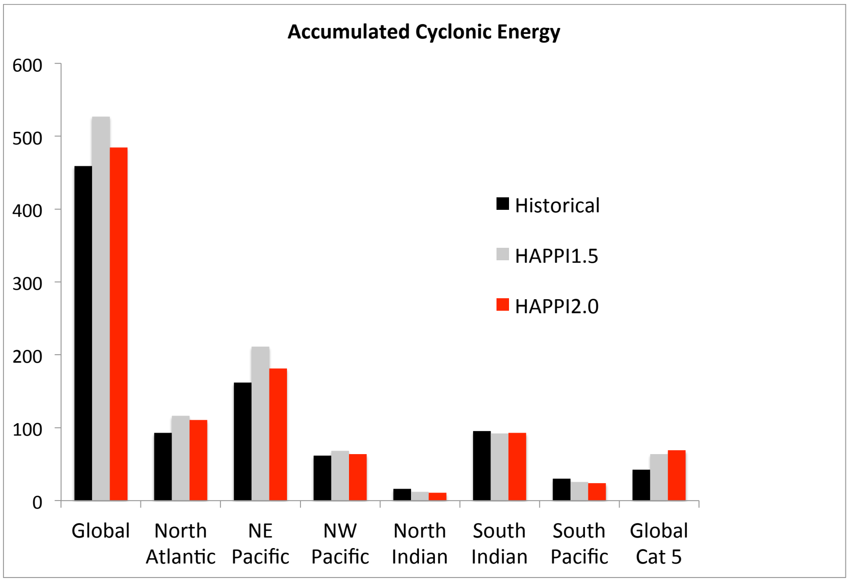

Figure 6. Average annual Accumulated Cyclonic Energy (ACE) for the Historical and HAPPI stabilization scenarios for all named storms by basin and globally for intense tropical cyclones only. Units: 1 ACE=10^4 knots. Black: Historical. Gray: 1.5^o Stabilization. Red: 2.0^o Stabilization.

Figure 7 shows the relationship between peak wind speeds and central pressure minima at the time of maximum intensity for the three HAPPI ensembles. As there are no changes to the model configuration between the simulations other than forcing conditions, this relationship does not change other than the appearance of combinations of wind speed and pressure at the very highest simulated intensities in the warmer simulations that do not occur in the Historical simulation. We conclude then that warmer temperatures do not influence the relationship between tropical storm peak wind speed and minimum central pressure. We do note however that model structural changes can influence the simulation of this relationship (Reed et al. 2015) thus requiring that evaluation of the effect of forcing changes on tropical storm statistics must be only done with simulations from the same version of the climate model.

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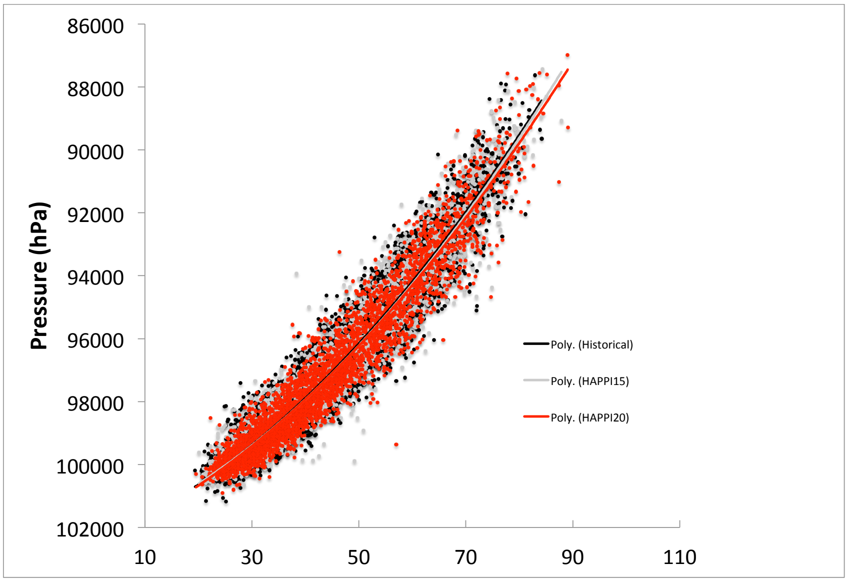

Figure 7: Scatterplot of minimum central pressure (hPa) versus maximum wind speed (m/s) at the time of maximum intensity for the HAPPI simulations. Black: Historical. Gray: 1.5° Stabilization. Red: 2.0° Stabilization. Solid lines are quadratic fits to the data.

A definition of the physical size of tropical storms has recently been developed by Chavas et al. (2016) by defining an approximate radius at specified wind speeds. Figure 8 shows average Chavas radii for the Historical and HAPPI stabilization scenarios. Radii are calculated every three hours over the duration of every tracked storm for the threshold wind speeds defining the Saffir-Simpson categories as well as for the storms' maximum wind speed. Each relevant radius is calculated for a given storm. For instance, we calculate 6 radii for a category 5 storm (1 for each Saffir-Simpson threshold) but only a single radius for a category 0 storm. The CAM5 HAPPI simulations exhibit about a 5% increase in category 0 storm size and a smaller (2-3%) increase in category 1 storm size in the warmer stabilized climates. Little change in storm size is simulated for more intense tropical cyclones except for category 5 storms in the 2°C stabilization scenario that experience an 8% increase in Chavas radius. The increase in weak storm size may be due to the change in the track density discussed above. The increased fraction of tracked tropical storms at higher latitudes are likely to be in the lower categories and may be starting their extra-tropical transition but maintaining high winds. The increase in category 5 storm size in only the warmer of the two HAPPI stabilizations currently lacks an explanation. Planned simulations of this version of CAM5 with the so-called unHAPPI protocols (stabilized at 3° and 4°C above preindustrial levels) may provide some insight into these aspects of change in storm structure.

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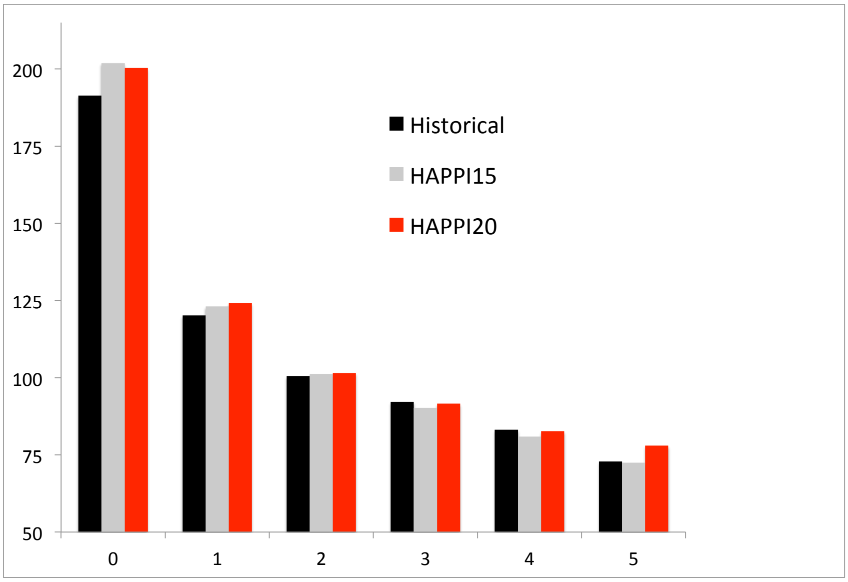

Figure 8. Chavas radii at different wind speeds selected as the definitions of the Saffir-Simpson categories (km) for the HAPPI simulations. Black: Historical. Gray: 1.5° Stabilization. Red: 2.0° Stabilization.

Conclusion

The Half A degree additional warming, Prognosis and Projected Impacts (HAPPI) experimental protocol was designed to rapidly inform the Intergovernmental Panel on Climate Change about the differences between stabilized climate at 1.5°C and 2.0°C above preindustrial global temperatures. However, it does not isolate all of the effects of forcing changes required to stabilize the climate from the present day conditions. In particular, the effect of sulfate aerosol reductions in the atmosphere has a non-local effect in the HAPPI simulations and has been demonstrated to be important to assessing changes in tropical cyclones (Huff et al. 2017) and heat waves (Wehner et al. 2017b). As the radiative forcing changes due to CO_2 between the historical and 1.5°C scenarios may be smaller than the forcing changes due to aerosols, the CO_2 effects in tropical storms may be comparable or even smaller by the aerosol effects at this stabilization level.

It is fair to say that the simulated differences tropical cyclone statistics between the 1.5°C and 2.0°C stabilization scenarios as defined by the HAPPI protocols are small. Indeed, both warmer climates produce fewer tropical storms over all intensities in the global sense and the reduction increases as the sea surface temperature (SST) becomes warmer. Also, the most intense storms become more intense in both warmer SST configurations with the highest peak wind speeds and lowest central pressure minima simulated in the warmer of two stabilizations.

Given the similarities between the two HAPPI scenarios and the importance of aerosol forcings, a more complete understanding of tropical storm frequency in aggressively stabilized climates requires detailed descriptions of the changes in those forcings. This would be particularly critical in geoengineering schemes relying on solar radiation management. However, as found by Bacmeister et al. (2016) in their comparison of RCP4.5 to RCP8.5, major uncertainties in the pattern of SST changes also pose a significant challenge in accurately projecting future tropical storm frequency.

Changes in other important characteristics of tropical cyclone behavior are subtler. Both warmer climate conditions considered here project significant changes in the poleward density of tropical storm tracks compared to the Historical simulations but the differences between them is not likely to be highly significant. Also, changes in Accumulated Cyclonic Energy (ACE), storm duration, track length and translational speed are complex with the differences clearly evident for only the most intense storms. Finally, some properties of tropical cyclones are not significantly altered in warmer climates, most notably the robust relationship between maximum wind speeds and central pressure minima.

Acknowledgement

The work at LBNL was supported by the Department of Energy's Office of Science under contract number DE-AC02-05CH11231. This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Work at Stonybrook University was supported by the Department of Energy's Office of Science under contract number DE-SC0016605.

These simulations were performed using resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy, also under Contract No. DE-AC02-05CH11231.

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Appendix

Figures A1 and A2 show the differences between HAPPI scenarios for the tropical storm track and cyclogenesis densities. The top panels show the differences for each warmer stabilized scenario minus the Historical simulation individually. The lower left panels show the difference between the 2.0°C and 1.5°C stabilized scenarios. The

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lower right panels show the difference between the average of the two stabilized scenarios minus the Historical simulation.

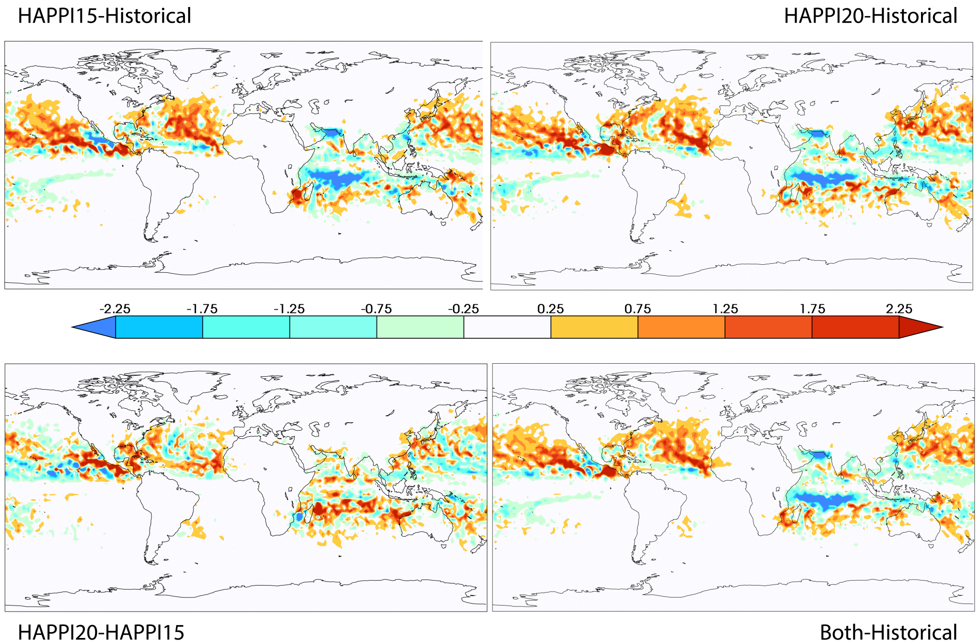

Figure A1. Percent difference of normalized tropical cyclone track density for the HAPPI simulations.

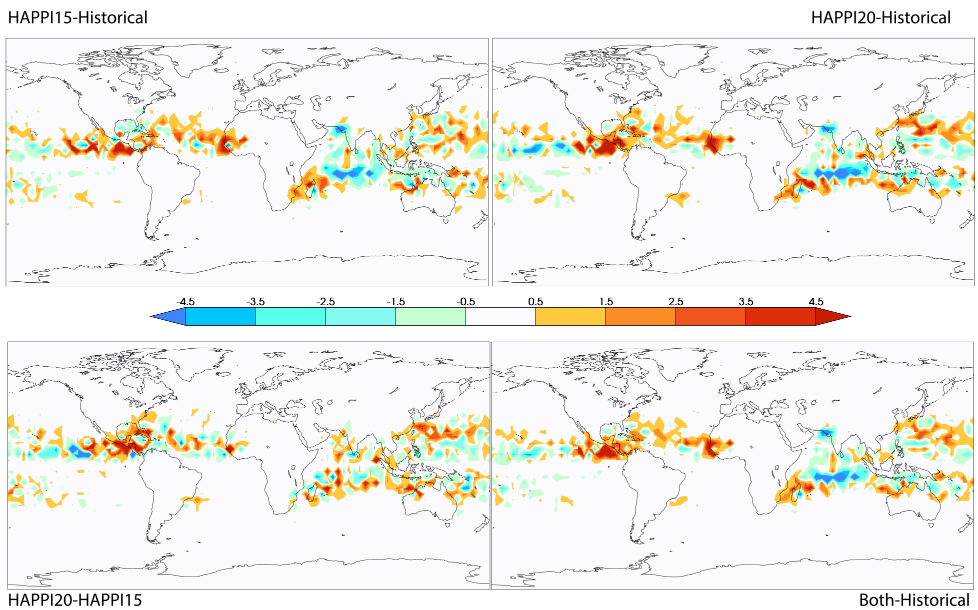

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Figure A2. Percent difference of normalized tropical cyclogenesis density for the HAPPI simulations.