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Projections of future tropical cyclone damage with a high-resolution global climate model

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Abstract High-resolution climate model simulations and a tropical cyclone damage model are used to simulate the economic damage due to tropical cyclones. The damage model produces reasonable damage estimates compared to observations. The climate model produces realistically intense tropical cyclones over a historical simulation, with significant basin scale correlation of the inter-annual variability of cyclone numbers to observed storm numbers. However, the climate model produces too many moderate tropical cyclones, particularly in the N. Pacific. Annual mean cyclone damage with simulated storms is similar to estimates with the damage model and observed storms, and with actual economic losses. Ensembles of future simulations with different mitigation scenarios and different sea surface temperatures (SSTs), as well as societal changes, are used to assess future projections of cyclone damage. Damage estimates are highly dependent on the internal variability of the coupled system. Using different ensemble members or different SSTs affects damage results by ±40 %. Experiments indicate that despite decreases in storm numbers in the future, strong landfalling storms increase in E. Asia, increasing global storm damage by ∼50 % in 2070 over 2015. Little significant benefit is seen from mitigation, but only one ensemble is available. Projected increases in vulnerable assets increase damage from simulated storms by more than threefold (∼300 %, assuming no adaptation) indicating future growth will swamp potential changes in tropical cyclones.

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1 Introduction

Tropical cyclones (TCs) are extreme natural hazards that lead to significant societal impacts in many parts of the world. TC distribution, frequency, and intensity are governed by the climate of tropical regions in which they evolve. TCs are sensitive to changes in tropical climate (Webster et al. 2005). There is an emerging literature on predicting changes to TC distribution, frequency, and intensity (see reviews by Knutson et al. (2010) and Walsh et al. (2016)). Such predictions require the use of dynamic models.

Traditionally, TCs are not resolved by global climate models with resolutions of 50–200 km (Strachan et al. 2013). Thus, some studies focus on the large-scale environmental controls on cyclones and how they might change (Knutson et al. 2010). Several metrics have been developed for relating cyclone intensity or damage to large scale fields (e.g., Emanuel 2005). These have been used recently (for example) by Reed et al. (2015) to downscale model output to estimate cyclone damage. Done et al. (2015) also develop similar metrics to project storm damage into the future.

Global climate models are now run at horizontal scales of 10–25 km where TCs can actually be resolved (e.g., Bacmeister et al. (2014)). Bacmeister et al. (2016) have recently shown skill in simulating tropical cyclones in the Community Earth System Model (CESM), and have explored how cyclones may change in the future.

Different metrics are possible to gauge the impact of tropical cyclones. Physically based measures such as storm surge and wind speed can link to estimates of vulnerability, but they are not direct measures of societal impact. One method of integrating the impact of distribution, frequency, and intensity of cyclones is to use physical estimates of TC strength coupled with a model for damage to society to estimate the direct economic damage from storms. Mendelsohn et al. (2012) applied a cyclone model and a damage model to climate model output to estimate monetary damages. Raible et al. (2012) applied a cyclone damage model similar to models used in the insurance industry to global model simulations and reanalysis, but these models did not produce realistic strength TCs.

Most studies project that TCs will change in the future and climate change may have influenced recent TC activity (Webster et al. 2005; Holland and Bruyère 2013). Future TC damages may differ depending on the climate simulation and metrics used (Mendelsohn et al. 2012; Schmidt et al. 2010). Furthermore, societal exposure to TCs will likely change in the future. Studies of past cyclone damage that normalize losses for exposure have not shown long-term trends (Pielke et al. 2008). Most of these studies use approximate metrics for storms (Done et al. 2015) rather than actual physical model outputs due to the necessity of modeling TCs with high-resolution simulations (Mendelsohn et al. 2012; Pielke et al. 2008).

In this work, we will combine a high-resolution general circulation model that represents TCs directly to a tropical cyclone damage model (a refined version of the model used by Raible et al. (2012)) to estimate how future changes in TCs may impact future TC damages. We will explore the impact of changing TCs in two different scenarios using several realizations. We will also explore the relative importance of changes in climate against changes in the built environment expected in the twenty-first century to test whether the damage changes are due to changes in climate or changes in human vulnerability (Schmidt et al. 2010). We will also assess whether different climate scenarios result in avoided TC damages. This paper is part of a larger project on the Benefits of Reducing Anthropogenic Climate changE (BRACE). The BRACE project focuses on characterizing the difference in impacts driven by climate outcomes resulting from the forcing associated with Representative Concentration Pathways (RCPs) 8.5 and 4.5 (van Vuuren et al. 2011), where RCP8.5

is considered a baseline with no mitigation, and RCP4.5 includes measures to reduce total radiative forcing.

Section 2 describes the damage model, input function, climate model, and metrics. Section 3 presents results. Discussion and Conclusions are in Section 4.

2 Methodology

Our goal is to consistently estimate the damage caused by TCs now and in the future. We will couple a cyclone damage model (Section 2.1) that uses spatially a disaggregated gross domestic product (GDP) (Section 2.2) with climate model output (Section 2.3) that tracks TCs (Section 2.4). We define assets as a spatial distribution of GDP. The cyclone damage model then projects a fractional loss of these assets based on observed or simulated storm tracks. We illustrate that for the recent past and observed storm tracks, this method provides a reasonable simulation of actual (observed) estimated losses. GDP projections can then be used to estimate future losses. We will examine the importance of those changes in different scenarios, as well as the relative importance of changes in climate and changes in the built environment, expressed through changes in GDP.

2.1 CLIMADA

The CLIMADA cyclone damage model (Bresch 2014) produces damage estimates for each year at each spatial location based on a set of probabilistic cyclone tracks derived from input cyclone tracks (locations and wind speeds). More details and previous work are described in the supplement. Wind speed is converted to a fractional loss (up to 100 % loss) for each location and storm. To get a monetary value, we then multiply this by GDP. This may not be the same as "insured losses" since it requires all GDP to be assigned to physical infrastructure. Not all GDP is physical, so as will be clear, this is a notional damage. Cyclone tracks can be from observations or simulations. CLIMADA also uses a spatial map of total societal assets (see below). Instead of dealing with the full damage statistics, e.g., an exceedance probability distribution of damage, the present paper focuses on average annual damage.

2.2 GDP estimates and projections

CLIMADA works with a spatially distributed grid of assets. Country level GDP data for present and future projections is widely available. For this analysis, a consistent spatial disaggregation method is needed to take country level data and map it at high resolution to construct a spatial distribution of assets. To spatially locate this data, we use the Nighttime Lights of the World data set (Elvidge et al. 2001; Chen and Nordhaus 2011) to distribute country level GDP data to a 10-km grid (details in the supplement). This has the advantage of a consistent mapping method everywhere on the planet, and the ability to use country level data for the present and future, albeit with caveats (Chen and Nordhaus 2011), as detailed in the supplement. For this study, we use present country level GDP data from World Bank (2015) and future projections are from the Shared Socioeconomic Pathway 5 (SSP5) described by O'Neill et al. (2013). SSP5 is most consistent with the Representative Concentration Pathway (RCP) forcing used in most of the climate experiments (O'Neill et al. 2013). We assume the same spatial distribution of assets for the future as for the present.

2.3 CESM description

For this study, we use The Community Earth System Model (CESM) version 1 simulations described in Bacmeister et al. (2016). The model is run at 25-km horizontal resolution with specified sea surface temperatures (SSTs) from observations for present day, or from CESM1 coupled model simulations at low (1° or 100 km) resolution. Future simulations are performed using different RCPs (van Vuuren et al. 2011), either a "high" emission scenario with 8.5 Wm^{-2} of radiative forcing in 2100 (RCP8.5), or a "moderate" emission scenario with with 4.5 Wm^{-2} of radiative forcing in 2100 (RCP4.5). The difference in global average temperature between these simulations in the 2060–2080 period is significant. Global average temperature in RCP8.5 is ∼4.5 K warmer than the recent past (1980–2010), while RCP4.5 is only ∼2 K warmer. (Sanderson et al. 2015).

Details of simulations are discussed by Bacmeister et al. (2016), and noted in the supplementary material (Table S1). Simulations over 1975–2013 are used for historical simulations and 19 years are used for each future simulation ensemble member. Two different methods of coupling to the surface were used in these simulations, and that requires different physical interpretation as noted in the supplement for the scaling methods. In addition, SSTs from three different ensemble members of CESM for RCP8.5, part of the CESM Large Ensemble (CESM-LE, Kay et al. (2014)) were used to explore internal variability.

2.4 Cyclone tracking and scaling algorithm

The TC tracking algorithm utilized for this analysis and that of Bacmeister et al. (2016) is described in Zhao et al. (2009) with 3-hourly output. Surface winds are adjusted following Bacmeister et al. (2014).

CESM produces sustained winds at 10 m (derived from the lowest model level with a mid-point elevation of 60 m). This is not the same as the observations from the International Best Track Archive for Climate Stewardship (IBTRACS) observations (Knapp et al. 2010). So we need a methodology to "calibrate" the output wind from the model to match the observations (IBTRACS). To do this, we use a minimum pressure and wind speed relationship for TCs as described in the supplement. A scaling value is derived that optimizes the fit between IBTRACS sustained 10-m wind and the CESM simulated 10-m wind as a function of minimum TC surface pressure. The scaling does not adjust TC intensity (the minimum surface pressure), only the low level wind that results from that surface pressure, and it should be a constant time invariant geophysical relationship. See the supplement for more details.

3 Cyclone damage results

3.1 Evaluation of present day simulated cyclones

Bacmeister et al. (2014) found that 25-km resolution CESM1 produced realistic tropical cyclone (TC) distributions in space and in intensity. Furthermore, Wehner et al. (2014) demonstrate that the model has skill in reproducing interannual variability in TC statistics, but with slightly fewer storms than observations, a result also seen in Fig. 1 for total storm numbers. Numbers for category 3–5 storms that cause the most damage are well represented. The particular simulations used here are also used in Bacmeister et al. (2016), and details on present and future track density of TCs are shown therein.
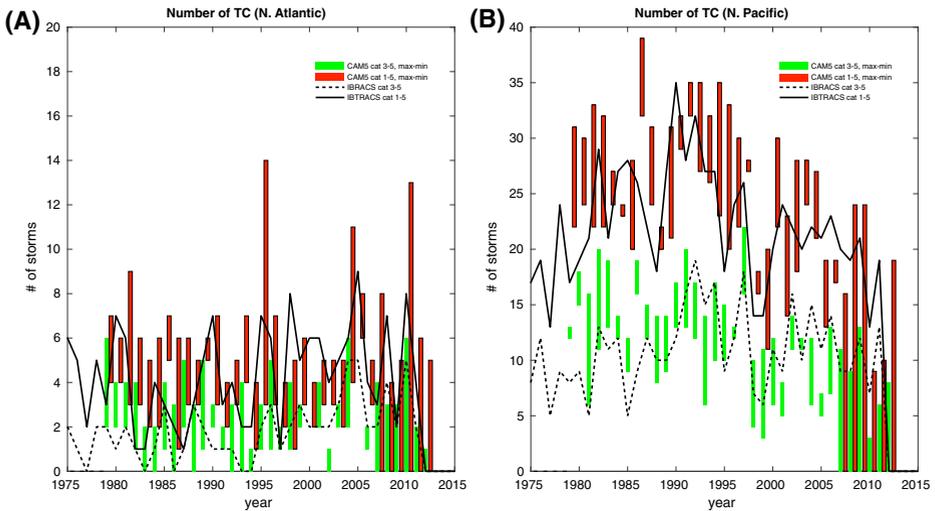
Fig. 1 Number of storms per year in the **a** Atlantic and **b** W. Pacific from IBTRACS observations (*lines*) and model simulations (*bars*). *Solid line* is all storms, *dashed line* is category 3–5 storms. *Bars* are range of simulated number of all storms (*red*) and Category 3-5 (*green*) in different CAM present day (OBS) simulations

Figure 1a, b illustrates the annual evolution of the number of storms in the North Atlantic (Fig. 1a) and North Pacific (Fig. 1b) basins from the OBS simulations after wind scaling has been applied. Figure 1b includes Eastern and Western Pacific storms. All OBS simulations use present day observed SSTs. Results indicate average number of storms for all four OBS simulations (OBSc and OBS1,2,3). More basins and global statistics are shown in the Supplement. The simulations show a good representation of the different numbers of storms between the basins and their interannual variability. The correlations with observed storm numbers for the N. Atlantic in Fig. 1a are 0.53 for USA category 3–5 and 0.35 for all storms. For the N. Pacific in Fig. 1b, correlations are 0.42 for category 3–5 and 0.56 for all storms. Next, we focus on the cyclone damage after applying CLIMADA to observed and simulated storms.

3.2 Evaluation of present day cyclone damage

Figure 2 illustrates present day simulated damages, aggregating over a basin and year from CLIMADA using simulated storms from the OBS simulations (CAM) and observed storms (IBTRACS). Figure 2a compares these results to actual insured losses over the USA from the EM-DAT data (red). The average of the CLIMADA simulated damage with IBTRACS (black) or CAM simulated storms (blue) is similar to the economic damage data (red). Note that the calibration of CLIMADA (see supplement) focuses on damage due to wind and physical infrastructure. Where damage is due to flooding or storm surge, CLIMADA results may differ from actual losses.

The damage amounts are comparable between CAM OBS simulations (green for the range and blue for the mean) and damage simulated with IBTRACS (black line, single realization). There is a correlation between individual years with higher damage in
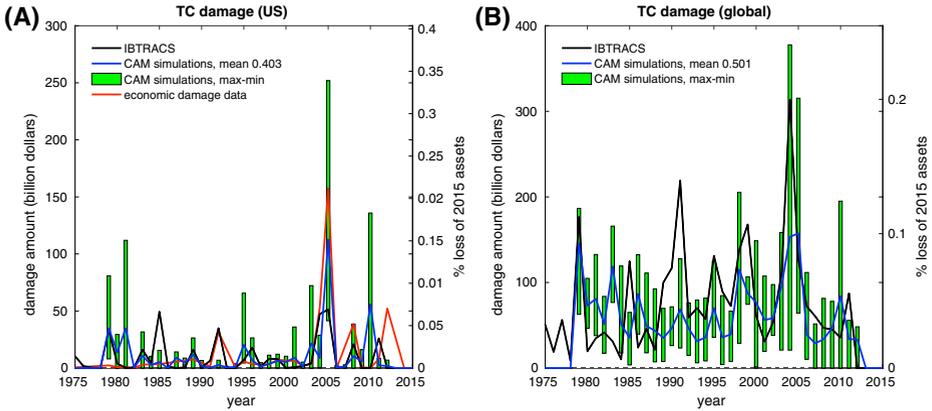
Fig. 2 Time series of annual loss from actual economic loss data (*red lines*), CAM simulation damage (*blue line*), range across CAM simulations (*green bars*) and IBTRACs (*black line*) for **a** US and **b** global. Similar to Fig. 1 but for damage in billion USD (*left scale*) and percent loss (*right scale*). Correlations printed between mean CAM and IBTRACS

observations and simulations (i.e., 2005) between all three data sets. Overall correlations between CAM and IBTRACS damage are significant at 0.40 (US) and 0.50 (global). We would not necessarily expect high correlations, except in years with strong forcing of the total number of TCs through SST anomalies (such as years with a strong El Niño). Note that because CLIMADA focuses on wind speed and does not focus on storm surge and flooding, damage for 2005 is significantly lower than estimated economic losses in Fig. 2a, because storms that year caused significant flooding in New Orleans and Houston.
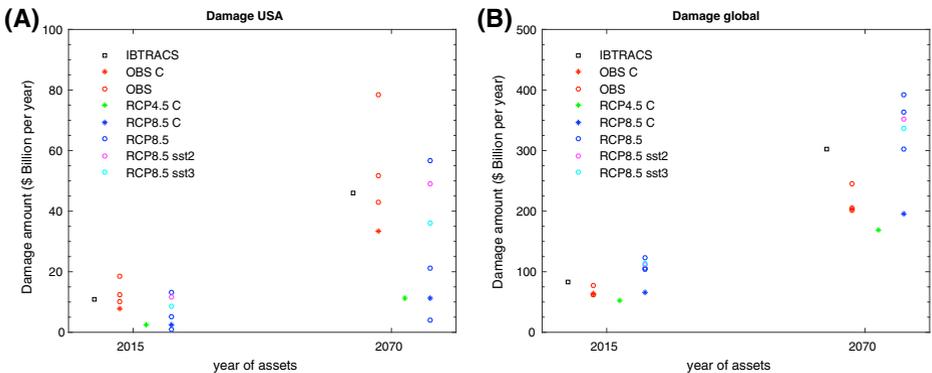

Fig. 3 **a** US and **b** global annual mean cyclone damage estimates for 2015 (*left*) and 2070 assets (*right*) for different CLIMADA simulations. Legend indicates CAM simulations: *asterisks* "c" are 1° coupling, *open circles* are 0.25° coupling simulations. Damage from observed (IBTRACS) storms as a *black square*. Different time periods are indicated by *horizontal offsets* (columns): IBTRACS on the *left*, then OBS (present day), RCP4.5 center and RCP8.5 climates right side of each time label

3.3 Annual mean damage

Figure 3 illustrates the annual mean cyclone damage for each of the simulations for the USA (Fig. 3a) and global (Fig. 3b). This is the average of the loss each year shown in Fig. 2 for each simulation. CLIMADA simulations with 2015 and 2070 assets are shown for each region. CLIMADA run with IBTRACS storms is in black. The CAM simulations for present (red), RCP4.5 (green), and RCP8.5 (blue and purple) are shown.

In addition to the US and global, we look at a series of regions. Regions to be explored are (1) USA, (2) Central America and Caribbean, (3) Pacific Asia, and (4) Indian Ocean. The list of countries in each region is contained in the supplementary material. Supplementary Fig. S4 shows average damage for additional regions. The estimated annual mean damage and the total assets for each base year for the different regions are illustrated in Table 1. The CAM5 present includes simulations OBSc and OBS1,2,3. CAM5 future includes all future RCP8.5 simulations (R8.5c, R8.5-1,2,3 as well as R8.5-S2 and R8.5-S3) and the RCP4.5c simulation. Damages are an average of these simulations. The individual values for US and global are in Fig. 3a, b. Remaining regions are in supplementary Fig. S4.

Table 1 indicates that average annual simulated damage in present day in the US region ($12.5 billion) compares well to results from IBTRACS ($11 billion) and the EM-DAT economic loss data ($10.3 billion). CAM simulations are an average of four simulations for present day. Note the large standard deviation from year to year, larger than the value (clear from Fig. 2).

The large standard deviation highlights the role of internal climate variability and the episodic nature of damage. Even averaging over 20 years of data for each ensemble yields average values that vary significantly (Fig. 3) (see below). Observations (IBTRACS) are thus just one possible realization of this variability.

For an individual region such as the USA in Table 1, the spread in annual average damage due to ensembles of the same SST is ±40 % of the value for the present and future. The mean of $12.5 billion per year for CAM present day simulations is the mean of simulations with ranges from $8 to 18 billion. Global estimates have a narrower range from $61 to 77 billion per year (±10 %), and slightly lower than estimated with IBTRACS ($84 billion

Table 1 Average annual TC damage amount in billion US dollars from CLIMADA runs with each set of assets (2015, 2070) and each set of storms (IBTRACS, CAM present, CAM Future)

	Year	USA	C. America	E. Asia	Indian	Global
Total assets ($T)	2015	73.3	8.6	58.8	14.2	155.9
IBTRACS	2015	11.0 (15.5)	9.5 (17.8)	61.4 (53.8)	0.34 (0.68)	84.6 (63.9)
EM-DAT	2015	10.3 (28.6)				
CAM5, present	2015	12.5 (27.7)	2.6 (6.7)	50.5 (46.7)	1.2 (2.4)	67.0 (55.9)
CAM5, future	2015	7.4 (16.3)	0.9 (2.5)	85.7 (105.5)	1.3 (2.6)	96.7 (108.4)
Total assets ($T)	2070	318	46	270	170	814
IBTRACS	2070	33.4 (82.3)	20.1 (46.1)	226.7 (210.4)	5.3 (11.9)	301.8 (251.4)
CAM5, present	2070	51.7 (119.1)	6.6 (15.8)	144.7 (132.5)	10.0 (17.5)	213.8 (186.5)
CAM5, future	2070	27.1 (69.9)	2.3 (6.5)	261.4 (314.4)	9.9 (18.0)	301.9 (321.0)

Also shown are the total assets for fractional damage calculations (trillion US dollars). CAM results are averaged across 4 present and 7 future simulations (mean annual and standard deviation)

per year). This damage variability is slightly larger than Done et al. (2014) who found the internal variability of N. Atlantic TC frequency with the same SST pattern was 40 %.

When evaluated globally, the uncertainty due to different SSTs for the future falls within the spread of the ensemble with the same SST. The spread is small due to similar damage in E. Asia (Supplement Figure S4B). As discussed by Bacmeister et al. (2016), the three future SST distributions (SST1, SST2, and SST3) used in this study are characterized by different amounts of warming in the equatorial Pacific and tropical Atlantic relative to the global tropical mean SST. The SST differences are a function of variations in El Niño strength in the different ensemble SSTs. This can have significant systematic impacts on TCs in the N Atlantic and NE Pacific basins, but the spread across ensembles of a single SST is just as large in Fig. 3. It is critical to note that the observed set of storms is really only one possible state of the climate system, so comparisons to models will not be exact. The damage with observed storms (IBTRACS, black) typically falls within the range of present day simulated storms (red).

Globally, future storms (blue) increase global average damage (Fig. 3b), but this varies by region, with the USA seeing a decrease in damage with future storms (Fig. 3a). There is wide spread across the ensembles however. The different coupling (OBSc, R4.5c, R8.5c, indicated by the asterisk in Fig. 3) does change the conclusion that global damage increases with future TCs (but the same assets) as the R8.5c has similar global damage to present. All three simulations with different coupling have similar global damage, with slightly lower damage for RCP4.5c (Fig. 3b). But given the spread across the other ensembles, it is not clear this is a significant difference. Note that the number of storms noted by Bacmeister et al. (2016) in these simulations is HIGHER in R4.5 than R8.5, but there is LESS damage, indicating either weaker storms and/or fewer landfalling storms.

We can estimate of the relative effect on damages between future changes in TCs and future changes in assets. The mean damage increases with future TCs and the same assets globally and in E. Asia while it decreases in other regions (Table 1). Globally, the change in mean annual damage with constant assets due to future storms is a ∼+45 % or $30 billion ($67 to 97 billion, Table 1). However, the change in damage due to a change in assets globally (with present TCs) is ∼+300 % ($67 to 214 billion, Table 1), similar for future TCs ($97 to 302 billion). There are differences by region. Damage for the USA increases entirely due to changes in assets, not changes in TCs (Fig. 3a), while for E. Asia (the other larger region of damages), the damage increase due to TCs is similar to (and dominates) the global average.

4 Discussion and conclusions

Simulated and observed TCs are applied to the CLIMADA damage model. Storm intensities defined by wind speed or central pressure are realistic compared to observations. Inter-annual variability in TCs is reproduced. CLIMADA produces reasonable damage with observed (IBTRACs) storms. CAM simulated storms for present day also have similar annual mean damage to that with observed storms and damage estimates.

There is a wide range of estimated damage amounts for present and future across ensemble simulations. Damage amounts are estimated based on average annual estimated damages. Ensemble simulations with the same SSTs (OBS, R8.5) show large spread. Globally, the spread in damage across three different ensemble members for present and future is about ±40 % of the estimated damage amount. Estimated damage is thus strongly dependent on internal variability of the climate system. Spread results from atmospheric variability of

storms (ensembles with the same SST) and induced by coupled modes of variability (ensembles with different SST: SST2, SST3). CAM and CLIMADA simulations do not indicate clear benefits to mitigation (RCP4.5c v. RCP8.5c). Regional variability is higher than global variability, and the global values are dominated by results in East Asia due to a large number of stronger Pacific storms. Despite an overall decrease in future storms, the track density of W. Pacific category 4 and 5 simulated storms increases, likely driving the increase in damage (Bacmeister et al. 2016, Fig. 2). This seems pretty robust across ensembles, but simulations with other models will be necessary to define how robust these results are.

Thus, the societal impact from intense and landfalling storms may not have the same trend as some TC metrics (e.g., total storm numbers). There may also be regional differences in TC damage trends. Results indicate that metrics for adaptation and mitigation (economic damage as a measure of societal impact) may yield different conclusions than traditional geophysical metrics (cyclone numbers).

Changes in simulated cyclone damage can be separated between increases in damage due to storms and increases in damage due to changes in future assets. Globally, there is a larger effect on damage from changes in assets (∼300 %) than from changes in storms (∼50 %) between present and 2070–2090. However, this does differ by region, with the USA seeing no increase from changes in storms (all due to changes in assets) while E. Asia has a larger effect of changes in storms than changes in assets. It is worth noting that the effect from changes in assets is dependent on GDP growth assumptions, and if these are incorrect, then the value will be different. However, basic conclusion that changes in assets matter more than changes in storms will still hold.

We do not account for adaptation in our estimates of future damage, i.e., that societies will adjust their built environment to better handle tropical cyclones. Evidence indicates that societies do adapt to cyclones and reduce their exposure (Bakkensen and Mendelsohn 2016). The large effect of asset increases without adaptation should be simply a baseline estimate that if anything argues strongly that adaptation is necessary, even without any impact of climate change.

With these caveats, CLIMADA simulates cyclone damage similar to observed, and CAM simulations produce similar storm damage to observed storms for the present. Future simulations indicate that TC damage increases in the future even as the total TC density goes down because of increases in the number of most intense storms. Due to large internal variability in TCs (Done et al. 2014; Bacmeister et al. 2016), the generality of these results will need to be tested on a larger ensemble size (for both a given SST and for multiple SSTs), and with different modeling frameworks. Further work should also focus on local and regional impacts and the need for regional impact studies to identify locally appropriate risk reduction (adaptation) measures.

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