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Tropical Cyclones and Climate Change

Supplemental Material

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Thomas R. Knutson*[1], John L. McBride[2], Johnny Chan[3], Kerry Emanuel[4], Greg Holland[5], Chris Landsea[6], Isaac Held[1], James P. Kossin[7], A. K. Srivastava[8], and Masato Sugi[9]

[1]Geophysical Fluid Dynamics Laboratory/NOAA, 201 Forrestal Road, Princeton, NJ 08542, USA
[2]Centre for Australian Weather and Climate Research, Melbourne, Australia 3001
[3]Guy Carpenter Asia-Pacific Climate Impact Centre, City University of Hong Kong, Kowloon, Hong Kong, China
[4] Program in Atmospheres, Oceans, and Climate, Massachusetts Institute of Technology, Rm. 54-1620 MIT, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.
[5]National Center for Atmospheric Research, Boulder, CO, USA.
[6] National Hurricane Center/NWS/NOAA, 11691 SW 17th Street, Miami, FL, 33165, USA
[7] National Climatic Data Center/NOAA, 1225 W. Dayton St., Madison, WI, 53706, USA
[8] India Meteorological Department, Shivajinagar, Pune 411005, India
[9] Research Institute for Global Change, JAMSTEC, 3173-25 Showa-machi, Kanazawa-ku, Yokohama, 236-0001 Kanagawa, Japan

Contact Information:

Thomas R. Knutson
GFDL/NOAA
201 Forrestal Road
Princeton, New Jersey 08542 U.S.A.

Ph: +1-609-584-7152
Fax: +1-609-987-5063
Email: Tom.Knutson@noaa.gov

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S1. Review of tropical cyclone frequency projections.

Projections of tropical cyclone frequency changes for various climate warming scenarios have been made by counting tropical cyclone-like vortices in regional or global climate models. Table S1 summarizes the tropical cyclone frequency projections from 17 modeling studies using models having horizontal grid spacing equivalent to about 120 km or less. The top part of the table summarizes changes for storms of tropical storm intensity or greater. Globally, all of the models show a decrease in this metric, ranging from -6% to -34%, though not statistically significant in at least one case. A consistent sign of change (decrease) is also seen for the Southern Hemisphere mean frequency. For the Northern Hemisphere mean, several models show a decrease, but a few models indicate essentially no change. At the individual basin scale, especially for the Northern Hemisphere basins, the sign of the projected changes is much more variable across different models. For example, for the North Atlantic basin, 10 model experiments project an increase, and 13 a decrease. In the Northeast Pacific, three models report an increase, three models a decrease, and one essentially no change. The magnitude of the projected changes for individual basins in these studies ranges up to +/- 50% or more.

The bottom section of Table S1 presents some results for tropical cyclone frequency, considering storms of higher intensities than the minimum tropical storm intensity threshold. Eight studies report increases in the frequency of higher intensity tropical cyclones, although the specific intensity threshold considered varies, since the various models simulate storms only to certain intensity thresholds due in large part to their limited resolution. While three studies reported no change of frequency of storms at any intensity simulated, and one study (for a single basin) reported a decrease of frequency at all intensities, all of these latter four studies were conducted with relatively low resolution models (~120 km grid). We regard such lower resolution models as being less credible for simulating higher intensity categories of tropical cyclones.

To summarize the models' frequency projections, a robust decrease in tropical cyclone frequency is projected globally (-6% to -34%) and for the southern hemisphere, while the projections are much more mixed (and the uncertainty of projections is much larger) for the individual basins (projected changes up to +/-50% or more). In some cases these larger changes projected for the individual basins by downscaling or testing single model realizations[10,11,45] may be exaggerating the model's actual response to climate forcings, due to unintended influences of internal climate variability on the projections. There is a clear tendency in the models, particularly at higher resolution (60 km grid or less), to project an increase in the frequency of the stronger classes of tropical cyclones, although the actual intensity class of these strong model cyclones varies depending on the various limitations of each model. (e.g., resolution, physics).

S2. Review of intensity projections

A key issue for future projections of tropical cyclone intensity is the realism of the model or theory used in projecting the intensities of the cyclones. As of the 2008 season, the minimum horizontal grid spacing of operational numerical prediction models run at the U.S. National Centers for Environmental Prediction and used as guidance for tropical cyclone intensity predictions was about 9 km, for example, which is far finer grid resolution than currently used in typical global climate models (100-200 km). Consequently, the strongest tropical cyclones simulated using current global climate models are much weaker than the observed strongest tropical cyclones, which calls into question the reliability of current generation climate models for future projections of cyclone intensities.

A number of methods exist for quantitatively evaluating a model's or theory's intensity simulation, particularly with regard to intense tropical cyclones. Examples include frequency histograms of intensities (simulated vs. observed); geographical distribution of simulated maximum intensities; scatter-plots of intensity vs. SST; measures of intensity skill if the model is used in operational forecasting; or the interannual/interdecadal variability of intensity distributions, such as the cumulative distribution functions. Some progress/examples have been reported along these lines in some studies. (See for example Figs. 3 and 5 in ref 11; Figs. 1 and 3 in ref 57; and Figs. 1 and S1 in ref 38.

On the other hand, a recent study[12] showed that even a regional model with 18km grid spacing could still be quite deficient at simulating the more intense Atlantic hurricanes, with a scatter-plot relation between intensity and SST that is not realistic for the stronger storms. A more realistic intensity distribution has been reported by downscaling the individual storms from ref 12 into a higher resolution hurricane prediction model[38]. It is recommended that further evaluations be presented in future studies to demonstrate the capabilities or deficiencies of a given model's intensity simulations.

Potential intensity theory[35,36], idealized simulations with high resolution hurricane models[37], and statistical/dynamical downscaling frameworks[11] provide means of circumventing some of the difficulties with simulating intense hurricanes that lower resolution global and regional climate models have encountered to date.

In Table S2, intensity projections from all of the above methods are presented. The potential intensity results are reported at the top of the table, followed by dynamical modeling results, which are roughly ordered from higher to lower model resolution. The main conclusion is that the intensity projections have a strong tendency to be positive for the theoretical or higher resolution models, especially when global or multi-basin aggregate results are considered. Some decreases of intensity are projected for individual basins using the statistical/dynamical downscaling frameworks[11] and for some individual models in potential intensity calculations[58], although the multi-model ensemble change reported in the latter study is positive for all basins (zero for north Atlantic). Of note is that ref 58 uses Emanuel potential intensity assuming reversible ascent. A comparison of results from potential intensity methods used in ref 37 with the Emanuel/reversible ascent potential intensity for the same models (Table S2) shows that the Emanuel/reversible has the smallest response to greenhouse warming, similar to the statistical/dynamical framework[11], while Emanuel/pseudoadiabatic is intermediate, and the Holland potential intensity is most sensitive to greenhouse warming. For the purposes of a rough comparison, we can approximate the pressure fall sensitivities as wind speed sensitivities by dividing by a factor of two (e.g., using an observed wind-pressure relation for major Atlantic hurricane intensities[60]). Using this approximation, for multi-basin averages, the Emanuel potential intensity typically projects wind speed increases of 2-4% in the studies reviewed, whereas the Holland theory projects increases of about 8%. There are large variations at the individual basin level for these theories, ranging from -8% to +21% for wind intensities.

As noted, the statistical/deterministic downscaling approach from ref 11 provides an alternate framework that has a demonstrated capability to at least statistically simulate tropical cyclones as strong as observed. Globally averaged and for most individual basins, this method produces a tendency for increasing intensity under warm climate (late 22nd century, A1B scenario). Averaged across the seven climate models they examined, the individual basin results range from about -1% to +4%. Results based on individual climate models[11], shows a wider projected range (not shown in Table S2). Of note, these individual model results are based on downscaling 20-year periods from control and warm climates without further filtering to extract the forced climate change signal. Even 20 years is a short enough period to be influenced by internal variability. With such a short period considered, those particular results from ref 11 very likely exaggerate the spread in model sensitivity to radiative forcing, owing to signal contamination by internal climate variability. Consequently we emphasize here (Table S2) the multi-model ensemble averages from ref 11 and not the individual model results. Also the use of results for the end of the 22nd century in ref 11 leads to some alteration of the signal relative to that for the late 21st century, since there is still residual warming, and possible SST pattern change, in the models during the 22nd century even though the A1B forcing is held constant at year 2100 levels.

Simulated intensities based on a tropical cyclone numerical prediction system (9 km grid) that is used operationally for intensity guidance[38] find that under present climate conditions, the strongest simulated storms approach the observed maximum intensities, with maximum surface winds that can exceed 70 m/s. Based on an 18-model ensemble climate change projection, this model simulates roughly a 100% increase in the frequency of Atlantic category 4-5 hurricanes by the end of the 21st century, relative to 2000 levels. A range of -66% to +138% per 100yr is projected for four individual models tested. An idealized modeling framework using an earlier version of the tropical cyclone prediction system[37] simulated intensity increases of 6% (maximum surface winds) and 14% (pressure fall) for a 1.75°C CO_2-induced tropical sea-surface warming. (These numbers are averages for climate change conditions in the Atlantic, NE Pacific and NW Pacific basins, also averaged across nine global climate model projections, and finally averaged across four variations of the hurricane model physics.) The average intensity change projection of +6% from ref 37, is about a factor of two larger that the changes projected in ref 11. A range of +1% to +10% for individual basins and individual climate models was found in ref 37 (Table S2). In addition, ref 37 used linear trend analysis to reduce contamination of the CO_2-induced signal by internal climate variability.

Using a 20 km grid global model, ref 10 reports an average intensity increase of 11% and an increase for the annual maximum intensity of 14%. Of note, their model shows substantial deficiencies at simulating very strong tropical cyclones in their control run, as does the 18 km grid regional model of ref 12. Ref 10 also reports decreases of intensity for several individual basins, but as with the individual model results from ref 11, we have concerns that their methodology may not adequately filter out internal model variability, and consequently the individual basin results from ref 10 do not receive as much weight as their global results in our summary.

Considering the progressively lower resolution studies summarized in Table S2, there is a tendency for smaller projected intensity changes or even no change. One study, limited to the NW Pacific basin, projects a decrease of intensity[32]. However, the model in this study is quite low resolution (~120 km) compared to other available studies for intensity in Table S2, and is not given a high weight here. Among the other global and regional modeling studies in Table S2, several report increases of intensity or of the number of relatively intense storms. Several others report no significant change of intensity, but among those, the grid spacing was generally relatively low (~120 km), although it was as fine as 50 km in one study[31]. However, none of the control models in these lower-resolution dynamical modeling studies simulated tropical cyclones as strong as observed, nor was the observed dependence on SST in the present climate of tropical cyclone intensity reproduced. Furthermore, ref 13 presented tropical cyclone intensity change projections using progressively higher resolution models that ranged from about 200 km grid spacing (not shown in Table S2) to about 40 km grid spacing, the latter model simulating storms with wind as intense as 80.7 m s^{-1} at 850mb. While no intensity change was projected with the lowest resolution model, a clear intensity increase was projected with the 40 km and 60 km grid spacing models[13], strongly suggesting the importance of adequate model resolution for simulating the intensity response to climate warming.

To summarize the existing intensity studies, the potential intensity theories and higher resolution (~20 km) models project a global intensity increase of +2 to +11% (or +3 to +21% in terms of central pressure fall, assuming a conversion factor of two), although some lower resolution dynamical models indicate no change. For individual basins, the existing multi-model ensemble results show a range of about -1 to +9%. For some individual basins, projections based on a single model can vary over a much larger range (e.g., up to +/- 15% or more). In some cases these larger changes projected for the individual basins by downscaling or testing single model realizations may be exaggerating the model's actual response to climate forcings, due to unintended influences of internal climate variability on the projections.

S3. Review of rainfall projections

Tropical cyclone-related rainfall projections (per storm) for climate warming scenarios are summarized in Table S3. The seven studies reporting results on this metric in Table S3 typically project substantial increases, although one model (ref 28) appears to have a distinctly lower (still positive) sensitivity of tropical cyclone rainfall to climate warming than the other models examined. The range of projections among all the studies is from +3% to +37%. The percentage increase is apparently quite sensitive to the averaging radius considered, as seen by comparing results for different radii from individual models. There is some indication that the percent increase might be smaller in the lower resolution (global) models, although further studies with additional models will be needed to assess this issue more confidently.

The nonlinear relation between air temperature and saturation mixing ratio would imply roughly 7% increase in precipitable water vapor content per degree C increase in SST in the models, which we assume all project relatively modest changes in tropical lower tropospheric relative humidity (though we do not at present have data from all of the models to verify this). Since a typical increase in tropical SST in these studies is on the order of 1.5- 2 degree C by 2100, this simple scaling implies about a 10-14% increase in precipitable water. Evidently the fractional increase in the storm-related precipitation rate in some models exceeds this level of change, especially for smaller averaging radii. This may be linked to enhanced low-level convergence associated with increased storm intensities in those models for the warm climate conditions. One model (ref 28) projects a fractional change in precipitation rate that is substantially less than expected by this simple scaling argument alone, for reasons that are unclear at this time.

S4. Some definitions.

Tropical cyclones are defined as warm-core non-frontal synoptic-scale cyclones, originating over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center. Throughout this paper, tropical cyclones will specifically refer to those with at least 34 kt (63 km hr^{-1}) maximum sustained surface winds.

Power Dissipation Index is an aggregate measure of tropical cyclone activity, defined as the integral over the lifetime of all storms of the surface wind speed cubed[7]. Thus the index is dependent on the frequency, intensity, and duration of tropical cyclones.

Likelihood statements: Usage in this report follows the IPCC AR4[2]: "...the following terms have been used to indicate the assessed likelihood, using expert judgment, of an outcome or a result: Virtually certain > 99% probability of occurrence, Extremely likely > 95%, Very likely > 90%, Likely > 66%, More likely than not > 50%, Unlikely < 33%, Very unlikely < 10%, Extremely unlikely < 5%."

S5. Limitations of tropical cyclone historical data

Significant limitations in historical records of tropical cyclones continue to make detection of climate trends difficult. The historical record of tropical cyclone tracks and intensities is a primarily a byproduct of real-time operations. Thus its accuracy and completeness varies throughout the record due to improvements (and occasional degradations) in data quality, including measurement methods and even analyst training[62].

Until the mid-1940s, tropical cyclone observations were limited to ships at sea (which attempted to avoid the most intense portions of tropical cyclones) and coastal weather stations. Since the mid-1940s, aircraft reconnaissance has allowed a more accurate assessment of tropical cyclones in the Atlantic and western North Pacific basins (though this was discontinued in the latter basin in 1987). In contrast to the capabilities of today's measurements, aircraft reconnaissance did not have reliable TC flight-level wind monitoring until 1990[63] and lacked comprehensive surface wind observations until the advent of the Stepped Frequency Microwave Radiometer in 2007[64]. In recent decades, estimates of tropical cyclone intensity have been highly dependent on satellite-based, pattern-recognition methods[65]. Consequently, a step-function change in ability to monitor tropical cyclone intensities globally occurred with the introduction of geosynchronous satellites in the mid to late 1970's. Even in the Atlantic basin, about 70% of the monitoring of tropical cyclones is currently done via satellite methods[64], since aircraft reconnaissance is generally not available well away from land, nor do aircraft continuously monitor cyclones within their range.

Important uncertainties in SST and atmospheric temperature historical data also complicate detection/attribution studies for tropical cyclones. For example, different historical SST data sets reconstructions have substantial differences in patterns in the century scale trends[58], and can produce substantially different regional trends in tropical cyclone counts when used to force atmospheric models (G. Vecchi, personal communication 2009). Efforts to explore past potential intensity or storm variability using theory or models that depend on observed atmospheric temperature profile may be compromised by reported inhomogeneities in radiosonde or reanalysis data[66-69]. Therefore, careful treatment of such data quality issues is essential in future tropical cyclone studies that use these data sets.

S6. Comparison with Previous Assessments

Our assessment conclusions are broadly similar to those of previous assessments of tropical cyclones and climate change[2,3,6], although there are some differences in a few areas.

IPCC AR4 concluded: "It is more likely than not that anthropogenic influence has contributed to increases in the frequency of the most intense tropical cyclones."[2]

In contrast, based in part on more recent research findings, we do not draw such an attribution conclusion in this assessment. Specifically we do not conclude that there has been a detectable change in tropical cyclone metrics relative to expected variability from natural causes, particularly owing to concerns about limitations of available observations and limited understanding of the possible role of natural climate variability in producing low frequency changes in the tropical cyclone metrics examined.

Our conclusions--that it is more likely than not that global tropical storm frequency will decrease and more likely than not that the frequency of the more intense storms will increase in some basins--are more specific than IPCC AR4 (ref 2, p. 751), which concluded that there was "…less confidence [than likely] in these projections [of a decrease in the overall number of tropical storms] and in the projected decrease of relatively weak storms in most basins, with an increase in the numbers of the most intense tropical cyclones."

The most recent hurricane assessment for the North Atlantic and North Pacific by the US Climate Change Science Program[3] concluded that it is "very likely that human induced increase in greenhouse gases has contributed to the increase in sea surface temperatures in the hurricane formation regions", and that Atlantic tropical storm and hurricane destructive potential as measured by the Power Dissipation Index (which combines storm intensity, duration, and frequency) has increased. The report concludes that the power dissipation increase is substantial since about 1970, and is likely substantial since the 1950s and 60s, in association with warming Atlantic sea surface temperatures", and that "it is likely that the annual numbers of tropical storms, hurricanes and major hurricanes in the North Atlantic have increased over the past 100 years, a time in which Atlantic sea surface temperatures also increased", but that "the evidence is not compelling for significant trends beginning in the late 1800s". The report also noted substantial uncertainties. For future climate, the report concluded that "hurricane wind speeds, rainfall intensity, and storm surge levels are likely to increase", with intensity changes projected to be from 1-8% for the strongest hurricanes and rainfall from 6-18% (ranges are per °C increase in tropical SST). Also noted was that there remained substantial uncertainties arising from changing observing systems and practices and from inadequate climate models. They concluded that "confident assessment of human influence on hurricanes will require further studies using models and observations, with emphasis on distinguishing natural from human induced changes."

In the present assessment report, we do not assign a "likely" confidence level to the reported increases in annual numbers of tropical storms, hurricanes and major hurricanes counts over the past 100 years in the North Atlantic basin, nor do we conclude that the Atlantic Power Dissipation Index increase is likely substantial since the 1950s and 60s.

Some of the projected ranges for frequency, intensity and rainfall changes differ from ref 3, as more studies are available for the present report and more basins are included in the current analysis, which complicates direct quantitative comparisons.

S.7 Recommendations for Future Progress

In general, hurricane-climate research is expected to progress most rapidly though a combination of improved theory, modeling, and observations (in all basins). For future observing systems, a comprehensive analysis, including research to assess specific benefits along with a comparative cost analysis, is needed to determine the best mix of tropical cyclone observations in support of climate studies, forecasting, and other needs. For example, is a resumption or initiation of manned or unmanned aircraft reconnaissance in various basins now justifiable in terms of costs, benefits, and alternative measurement techniques? The Aerosonde has proven that small, low-cost unmanned aerial vehicles (UAVs) can monitor the near surface layer in hurricane conditions. Another promising, low-cost technique is a tethered blimp – the Aeroclipper

– that was successfully deployed into the eye of a severe tropical cyclone for several days[70]. This potentially could provide continuous central pressure measurements for tropical cyclones around the world for days at a time. A third method for greatly enhancing the analysis of tropical cyclone frequency and intensity--particularly for the majority of the globe that lacks aircraft reconnaissance--would be the XOWVM[71], a next-generation ocean vector winds mission based on polar-orbiting scatterometer. The proposed scatterometer would also have a microwave radiometer to allow for better identification of active deep convection and thus removal of the rainfall's influence on the wind signal.

A caveat is that future improvements in observing systems will lead to more discontinuities and "false climate trends" unless such biases are recognized and addressed. A related approach to the climate data homogeneity issue includes studies of how sampling can alter monitoring of frequency, intensity and duration of tropical cyclones. For example, how many of the 2005 Atlantic hurricanes would have been identified, and at what intensities, using only the monitoring capabilities available in 1970, or 1900? We recommend that reanalyses of the tropical cyclone Best Track data, along the lines of that being done in the Atlantic, be undertaken in all tropical cyclone basins. To facilitate such observational studies, researchers ideally should have access to original "raw" historical observations concerning tropical cyclones (ship, aircraft, and satellite data, etc.), along with derived quantities such as estimated tropical cyclone intensity.

A promising research frontier is paleotempestology, in which researchers use geological proxy information to infer pre-historic hurricane activity. As these techniques mature, consideration should be given to a transition from technique-development research to systematic surveys designed to produce comprehensive long-term records of tropical cyclone climatology[72].

Tropical cyclone/climate modeling studies will benefit from ongoing efforts to improve global climate models. Higher resolution global models with improved physics are being developed and refined, and future global and regional climate models will increasingly use two-way nesting or variable resolution techniques that will better resolve tropical cyclone-like vortices. Some studies suggest that whereas a climate model with horizontal grid spacing of 20 km may be adequate for tropical cyclone frequency and track simulations, model grid spacing of 1 km or less may be needed to realistically simulate the highest wind speeds in the eyewall region[73]. Diagnosis of changes in the full tropical cyclone structural life cycle and related impacts (e.g., winds, precipitation, and storm surge) from genesis through to extratropical transition or dissipation is recommended. In general, there is a need to improve understanding of the physical mechanisms producing the climate-induced changes in tropical cyclones in the models, and to increase use of statistical significance testing and multi-model experiments to identify robust modeling results.

Empirical approaches that estimate tropical cyclone potential intensity, frequency, etc. based on large-scale environmental measures[74] may also be useful for projections of tropical cyclone activity under climate change. However, caution must be exercised in applying empirical approaches to climate change scenarios, as the statistical relations developed for the present climate, such as SST thresholds for tropical cyclone genesis, may not apply in the case of greenhouse gas-driven climate warming[12].

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TABLE S1. TC Frequency Projections												
Reference	Model/type	Resolution/	Experiment	Basin								
				Global	NH	SH	N Atl.	NW Pac.	NE Pac.	N Ind.	S. Ind.	SW Pac.
Tropical Storm Frequency Changes (%)												
Sugi et al. 2002 (ref 32)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	**-34**	**-28**	**-39**	**+61**	**-66**	-67	+9	**-57**	**-31**
McDonald et al. 2005 (ref 50)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	**-6**	-3	**-10**	**-30**	**-30**	**+80**	**+42**	+10	**-18**
Hasegawa and Emori 2005 (ref 51)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					-4				
Yoshimura et al. 2006 (ref 52)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	**-15**								
Oouchi et al. 2006 (ref 10)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	**-30**	**-28**	**-32**	**+34**	**-38**	**-34**	**-52**	**-28**	**-43**
Chauvin et al. 2006 (ref 31)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2				**+18** **-25**					
Stowasser et al. 2007 (ref 53)	IPRC Regional		Downscale NCAR CCSM2, 6xCO2					+19				
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		-13		-8	-20	+4	-26		
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		-19		-13	-28	+7	-51		
Emanuel et al. 2008 (ref 11)	Statistical-deterministic	---	Downscale 7 CMIP3 mods.: A1B, 2180-2200 Average over 7 models	-7	+2	-13	+4	+6	-5	-7	-12	-15
Knutson et al. 2008 (ref 12)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100				-27					
Leslie et al. 2007 (ref 54)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)									~0
Gualdi et al. 2008 (ref 28)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	**-16** (2x) **-44** (4x)			-14	-20	-3	-13	-14	**-22**
Semmler et al. 2008 (ref 55)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100				-13					
Zhao et al. 2009 (ref 29)	GFDL HIRAM timeslice	50 km	Downscale A1B:									
			CMIP3 n=18 ens.	**-20**	**-14**	**-32**	**-39**	**-29**	+15	-2	**-30**	**-32**
			GFDL CM2.1	**-20**	**-14**	**-33**	-5	-5	**-23**	**-43**	**-33**	**-31**
			HadCM3	**-11**	+5	**-42**	**-62**	**-12**	**+61**	-2	**-41**	**-42**
			ECHAM5	**-20**	**-17**	**-27**	-1	**-52**	**+35**	-25	**-13**	**-48**
Sugi et al. 2009 (ref 45)	JMA/MRI global AGCM timeslice		Downscale A1B:									
		20 km	MRI CGCM2.3	**-29**	**-31**	**-27**	+22	**-36**	**-39**	**-39**	**-28**	**-22**
		20 km	MRI CGCM2.3	**-25**	**-25**	**-25**	+23	**-29**	**-30**	-29	**-25**	**-27**
		20 km	MIROC-H	**-27**	**-15**	**-42**	-18	**+28**	**-50**	+32	**-24**	**-90**
		20 km	CMIP3 n=18 ens.	**-20**	**-21**	**-19**	+5	**-26**	**-25**	-15	-5	**-42**
		60 km	MRI CGCM2.3	**-20**	**-21**	**-17**	**+58**	**-36**	**-31**	-12	**-22**	-8
		60 km	MIROC-H	-6	0	**-16**	+6	**+64**	**-42**	**+79**	+10	**-69**
		60 km	CMIP3 n=18 ens.	**-21**	**-19**	**-25**	+4	-14	**-33**	+33	-18	**-36**
		60 km	CSIRO	**-22**	**-29**	-11	**-37**	+13	**-49**	-7	**-22**	+10
Higher Intensity TC Frequency Changes												
Bender et al. 2010 (ref 38)	GFDL Hurricane model	9 km	Downscale TCs from ref 22 18-mod ensemble: (range over 4 indiv. models)				Cat 4-5 TC freq: +100% (-66 to +138%)					
Knutson et al. 2008 (ref 12)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100				+140% (12 vs 5) # w/ V_{sfc}>45					

							m/s					
Oouchi et al. 2006 (ref 10) (Average intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	**Signif. Increase, # V_{850} of 55-60 m/s**								
Walsh et al. 2004 (ref 56)	CSIRO DARLAM regional model	30 km	3xCO2; 2061-2090 minus 1961-1990									+26% P<970 mb
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		+42%, #>50m/s							
Stowasser et al. 2007 (ref 53)	IPRC Regional	~50 km	Downscale NCAR CCSM2, 6xCO2					Increase intensity PDI : +50%				
Leslie et al. 2007 (ref 54)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)									+100 % #>30 m/s by 2050
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		+32%, #>50m/s							
McDonald et al. 2005 (ref 50)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	Increase in strong tropical cyclones (vort > 24-30 x 10^{-5}/s)								
Sugi et al. 2002 (ref 32)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	~0								
Gualdi et al. 2008 (ref 28)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	~0								
Hasegawa and Emori 2005 (ref 51)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					Decrease (all intensity)				
Yoshimura et al. 2006 (ref 52)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	~0								

Table S1. Projections of TC Frequency. Projected change in frequency of tropical cyclones in warm climate runs relative to control run in percent. The top section presents results for tropical storms. The bottom section presents results for higher intensity tropical cyclones from studies that reported such results. The higher intensity results in the bottom section are ordered from top to bottom generally in order of decreasing model horizontal resolution. Red and blue numbers/text denote projected increases and decreases, respectively. Bold text denotes where a statistical significance test was reported that showed significance. The frequency projections from ref 11 been computed slightly differently from those shown in Fig. 8 of the original paper in order to facilitate intercomparison with projection results from other studies.

Table S2. Intensity Projections: **Metric/ Reference**	**Technique/ Model**	**Resolution/ Metric type**	**Climate Change scenario**	**Global**	**NH**	**SH**	**NAtl, NW Pac, NE Pac**	**N Atl.**	**NW Pac.**	**NE Pac.**	**N Ind.**	**S. Ind.**	**SW Pac.**
Potential intensity or stat/dynamical projections (% Change)								Avg (low, high)					
Vecchi and Soden 2007 (adapted from ref 58)	Emanuel PI, reversible w/ diss. heating	Max Wind speed (%)	CMIP3 18-model A1B (100yr trend)	2.6	2.7	2.4	2.1	0.05 (-8.0, 4.6)	2.9 (-3.1, 12.6)	3.5 (-6.4 16.1)	4.4 (-3.3, 16.0)	3.7 (-7.6, 17.1)	0.99 (-8.6, 8.6)
Knutson and Tuleya 2004 (adapted from ref 37)	Potential Intensity Emanuel, reversible	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				5.0	2.6 (-5.6, 12.6)	7.0 (-1.0, 19.6)	5.4 (-5.0, 21.9)			
Knutson and Tuleya 2004 (ref 37)	Potential Intensity, Emanuel, pseudoadiabatic	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				7.6	6.0 (1.6, 13.2)	8.5 (2.8, 25.2)	8.2 (-3.3, 28.0)			
Knutson and Tuleya 2004 (ref 37)	Potential Intensity, Holland	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				15.2	12.4 (-4.0, 28.9)	17.3 (9.4, 30.6)	15.8 (3.4, 42.5)			
Emanuel et al., 2008 (ref 11)	Stat./Dyn. Model	Max Wind speed (%)	CMIP3 7-model A1B (2181-2200 minus 1981-2000)	1.7	3.1	0.2	3.3	2.0	4.1	-0.1	0.2	0.5	-0.8
Dynamical Model Projections (Max wind speed % change or frequency change as noted)													
Bender et al. 2010 (ref 38)	GFDL Hurricane model	9 km	Downscale TCs from ref 22 18-mod ensemble: (range over 4 indiv. models)					Cat 4-5 TC freq. +100% (-66 to +138%)					
Knutson and Tuleya 2004 (ref 37)	GFDL Hurricane Model	9 km grid inner nest	CMIP2+ +1%/yr CO2 80-yr trend				5.9	5.5 (1.5, 8.1)	5.4 (3.3, 6.7)	6.6 (1.1, 10.1)			
Knutson and Tuleya 2004 (Pressure fall) (ref 37)	GFDL Hurricane Model	9 km grid inner nest; Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				13.8	13.0 (3.2, 21.6)	13.6 (8.0, 16.5)	14.8 (3.6, 25.0)			
Knutson et al. 2001 (ref 12)	GFDL Hurricane Model	18 km grid w./ ocean coupling	GFDL R30 downscale, +1%/yr CO2 yr 71-120 avg	6									
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100					+2.9					
Oouchi et al. 2006 (ref 10) (Average intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	10.7	8.5	14.1		11.2	4.2	0.6	-12.8	17.3	-2.0
Oouchi et al. 2006 (ref 10) (Average annual maximum intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	13.7	15.5	6.9		20.1	-2.0	-5.0	-16.7	8.2	-22.5
Semmler et al. 2008 (ref 55)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100					+4					
Walsh et al. 2004 (ref 56)	CSIRO DARLAM regional model	30 km	3xCO2; 2061-2090 minus 1961-1990										+26% P<970 mb
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		+42%, #>50m/s								
Chauvin et al. 2006 (ref 31)	ARPEGE Climat Timeslice	~50 km	Downscale - CNRM B2 - Hadley A2					~0 ~0					
Stowasser et al. 2007 (ref 53)	IPRC Regional	~50 km	Downscale NCAR CCSM2, 6xCO2						+50% in PDI, incr. intensity				
Leslie et al. 2007 (ref 54)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)										+100% #>30 m/s
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		+32%, #>50m/s								
McDonald et al. 2005 (ref 50)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	Increase in strong tropical									

				cyclones (vort > 24-30 x 10^{-5}/s)									
Sugi et al. 2002 (ref 32)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	~0									
Gualdi et al. 2008 (ref 28)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	~0									
Hasegawa and Emori 2005 (ref 51)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2						De-crease				
Yoshimura et al. 2006 (ref 52)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	~0									

Table S2. Tropical cyclone intensity change projections (percent change in maximum wind speed or central pressure fall, except as noted in the table. The dynamical model projections are ordered from top to bottom in order of decreasing model horizontal resolution. Red and blue colors denote increases and decreases, respectively. Pairs of numbers in parentheses denote ranges obtained using different models as input to a downscaling model or theory. The potential intensity change projections from refs 11, 37, and 58 in the table include some unpublished supplemental results (personal communication from the authors) such as results for individual basins, ranges of results across models, and results for additional or modified calculations that are adapted from the original papers but have been modified in order to facilitate intercomparison of methods and projection results from different studies.

Table S3. TC Precipitation Projections						
Reference	Model/type	Resolution/	Experiment	Basins	Radius around storm center	Percent Change
Hasegawa and Emori 2005 (ref 51)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2	NW Pacific	1000 km	+8.4
Yoshimura et al. 2006 (ref 52)	JMA GSM8911 Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	Global	300 km	+10 (Arakawa-Schubert) +15 (Kuo)
Chauvin et al. 2006 (ref 31)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2	Atlantic	n/a	Substantial increase
Bengtsson et al. 2007 (ref 13)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B	Northern Hemisphere	550 km Accum. Along path	+21 (all TCs) +30 (TC > 33 m/s intensity)
Knutson et al. 2008 (ref 12)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100	Atlantic	50 km 100 km 400 km	+37 +23 +10
Knutson and Tuleya 2008 (ref 61)	GFDL Hurricane Model (idealized)	9 km inner nest	CMIP2+ +1%/yr CO2 80-yr trend	Atlantic, NE Pacific, NW Pacific	~100 km	+22
Gualdi et al. 2008 (ref 28)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	Global	100 km 400 km	+6.1 +2.8

Table S3. Tropical Cyclone-related precipitation projected changes (%) for the late 21st century (relative to present day). Results from Gualdi et al. are from ref 28 and personal communication (2009).