Progress Article:
Tropical Cyclones and Climate Change

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Whether the characteristics of tropical cyclones have changed or will change in a warming climate – and if so, how -- has been the subject of considerable investigation, often with conflicting results. Large amplitude fluctuations in the frequency and intensity of tropical cyclones greatly complicate both the detection of long-term trends and their attribution to rising levels of atmospheric greenhouse gases. Trend detection is further impeded by substantial limitations in the availability and quality of global historical records of tropical cyclones. Therefore, it remains uncertain whether past changes in tropical cyclone activity have exceeded the variability expected from natural causes. However, future projections based on theory and high-resolution dynamical models consistently suggest that greenhouse warming will cause the globally averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2 to 11% by 2100. Existing modeling studies also consistently project decreases in the globally averaged frequency of tropical cyclones, by 6 to 34%. Balanced against this, higher resolution modeling studies typically project substantial increases in the frequency of the most intense cyclones, and increases of the order of 20% in the precipitation rate within 100km of the storm centre. For all cyclone parameters, projected changes for individual basins show large differences among different modeling studies.

(INTRODUCTION)

The challenge for climate change detection and attribution research with regard to tropical cyclones is to determine whether an observed change in tropical cyclone activity exceeds the variability expected through natural causes, and to attribute significant changes to specific climate forcings such as greenhouse gases or aerosols. For future projections of tropical cyclone activity, the challenge is currently to develop both a reliable projection of changes in the various factors influencing tropical cyclones, both local and remote, and a means of simulating the effect of these climate changes on tropical cyclone metrics, such as storm frequency, intensity, and track distribution. This two step process is required because the coupled atmosphere-ocean models currently used to project climate on multi-decadal to centennial time scale do not themselves simulate tropical cyclones adequately.

Sea surface temperatures (SSTs) in most tropical cyclone formation regions have increased by several tenths of a degree Celsius during the past several decades[1]. The IPCC AR4[2] concluded that most of the global surface temperature increase over the past half century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations, while the U.S. CCSP 3.3 Report[3] extended this by concluding that human-induced increases greenhouse gas increases have very likely contributed to the increase in sea surface temperatures (SSTs) in the hurricane formation regions[4]. These results have raised the question of how substantial further warming, coupled with other changes in the tropical environment, would affect tropical cyclone activity.

Recent decades have seen very large increases in economic damage and disruption by tropical cyclones. Historical analyses[5] indicate that this has been caused primarily by rising coastal populations and increasing value of infrastructure in coastal areas. In developing countries, in particular, the population move to the coast is the result of social factors that are not easily countered. Climate change is hence one of several factors likely to affect the future evolution of damage from tropical cyclones.

We discuss here issues related to detection and attribution and to future projections for tropical cyclones. The future projection statements in this report are intended to apply roughly to the IPCC A1B scenario[2] as of the late 21st century. All likelihood statements follow conventions used by the IPCC[2] (Supplemental S4).

We consider new developments in the field since the 2006 WMO Expert Team statement[6], including: new satellite-based intensity analyses; improved hindcast performance of downscaling techniques; substantial new analysis of data homogeneity issues; new simulations with higher resolution global models; and analyses of the sensitivity of tropical cyclone projections to the choice of climate model being downscaled. A discussion of limitations of tropical cyclone historical data is given in Supplemental Material S5. For detection and attribution, the emphasis here is on the Atlantic basin because data records there are longer and relatively more reliable, though our assessment statements (summarized in Box 1) include consideration of all basins as appropriate. Comparisons with previous assessments and recommendations for future progress are contained in Supplemental Material S6 and S7.

STATISTICAL RELATIONS: TROPICAL CYCLONE ACTIVITY VS SST

Over the past 50 years, a significant statistical correlation exists between Atlantic tropical cyclone power dissipation (definitions in Supplemental Material S4) and SST on time scales of a few years of more[7]. A comparable large correlation exists, on all time scales down to a year, between the power dissipation and the tropical Atlantic SST relative to mean tropical SST[8]. Taken at face value, these two statistical relations lead to dramatically different inferences about late 21st century Atlantic tropical cyclone activity[9], ranging from a dramatic increase of about 300% in the first case to little change in the second (Fig. 1).

Tropical Atlantic SST has increased more rapidly than tropical mean SST over the past 30 years, coincident with the positive trend over this period in the Atlantic power dissipation index (Fig. 1b). This differential warming of the Atlantic can be affected by natural multi-decadal variability, as well as by aerosol forcing, but climate models[9-13] suggest that it is not strongly influenced by greenhouse gas forcing (Fig. 1b). If the relationship between Atlantic power dissipation and this differential warming in Fig. 1b is causal, then a substantial part of the increase in Atlantic power dissipation since 1950 is likely owing to factors other than greenhouse gas-induced warming.

On the other hand, the case for the importance of local SSTs would be strengthened by observations of an increase in power dissipation in other basins, in which local warming in recent decades does not exceed the tropical mean warming. A study for the NW Pacific basin[7] shows a statistical correlation between low-frequency variability of power dissipation and local SSTs, but this correlation is considerably weaker than for the Atlantic, and other key measures of storm activity in the NW Pacific, such as the number of Category 4-5 typhoons, do not show a significant correlation with SST[14].

TROPICAL CYCLONE FREQUENCY

Detection and Attribution:

We first consider tropical Atlantic SST variability, which has been used statistically to model Atlantic tropical storm frequency changes[15-17]. Substantial multi-decadal SST variability is evident in the North Atlantic basin (Fig. 2, 2nd green series). The cause of this variability remains uncertain, with possible contributions from both internal climate variability and radiative forcing changes[16,18]. Evidence from tropical African lake sediments[19] suggests rainfall variability prior to the 20th century at least as large as that seen in the 20th century, increasing the plausibility of substantial natural climatic variability in the tropical Atlantic. The multi-decadal SST variability (evident in Fig. 2, 2nd series) complicates trend detection in this region, but model simulations indicate that substantial proportions of the observed tropical Atlantic and Northwest tropical Pacific SST increases over the past half century arise from greenhouse warming[4].

Some observational studies[15-17] report substantial century-scale increases in Atlantic tropical cyclone frequency, that can be modeled statistically by the century-scale SST increases (Fig. 2, 1st blue series vs. 2nd green series), and some of this increase has been attributed to anthropogenic forcing[15,16]. However, ref 20 finds that the statistical significance of the trends in the original storm frequency data is greatly reduced after adjustments are made[20,21] for an estimated number of missing tropical cyclones owing to limited reporting ship track density and other observational limitations in earlier years (Fig. 2, 1st red series). Further, the trend in storm count in the original data has been shown to be almost entirely due to an increase in short duration (<2 day) tropical storm[22]—a phenomenon which ref 22 interprets as likely attributable to changes in observing capabilities. There is a much smaller increasing trend in storms lasting more than 2 days (Fig. 2, 2nd red series) and after an estimated adjustment for missing storms[20,22], the resulting long-term trend is not significant ($p>0.05$).

Hurricane counts (with no adjustments for possible missing cases), show a significant increase from the late 1800s to present, but do not have a significant trend from the 1850s or 1860s to present[3]. Other studies[23] infer a substantial low-bias in early Atlantic tropical cyclone intensities (1851-1920), which, if corrected, would further reduce or possibly eliminate long-term increasing trends in basin-wide hurricane counts. U.S. landfalling tropical storm and hurricane activity shows no long-term increase (Fig. 2, orange time series)[20]. Basin-wide major hurricane counts exhibit a significant rising trend, but we judge these basin-wide data as unreliable for climate trend estimation beginning prior to aircraft reconnaissance in 1944.

A study of a 1500 year record of sediment overwash from a number of sites along the US coast and one near Puerto Rico[24] finds evidence for relatively high numbers of strong Atlantic hurricane landfalls at these sites during several periods (from around 1000-1200 AD; the early 1400s; the early 1800s; the 1950s; and in recent decades). This record is not subject to the same data errors that have made direct assessment of strong hurricane frequency from the observational record difficult, but is subject to uncertainties in interpretation of storm characteristics from geologic evidence and limited spatial coverage. Comparisons of this data set with other measures of strong landfalling tropical cyclones in the period of direct records have yet to be documented.

In terms of global tropical cyclone frequency, ref 25 concluded that there was no significant change in global tropical storm or hurricane numbers from 1970 to 2004, nor any significant change in hurricane numbers for any individual basin over that period, except for the Atlantic (discussed above). Landfall in various regions of East Asia[26] during the last 60 years and those in the Philippines[27] during the last century also do not exhibit significant trends.

Thus, considering available observational studies, and after accounting for potential errors arising from past changes in observing capabilities, it remains uncertain whether past changes in tropical cyclone frequency have exceeded the variability expected through natural causes.

Projection:

Progress has been made in developing dynamical and statistical/dynamical models for seasonal tropical cyclone frequency. Such models include: global coupled climate models[13,28]; relatively high resolution atmospheric models running over observed or projected SST distributions[10,29]; regional climate model used to downscale solutions from global coupled models[12,30]; and novel statistical/dynamical techniques aimed at avoiding the limitations on intensity simulations in dynamical models[11]. Many of these models reproduce key aspects of observed past tropical cyclone variability when forced with historical variations in boundary conditions, such as SSTs or, in the case of regional models, by the SSTs and large-scale atmospheric winds, moisture, and temperature distributions from atmospheric reanalyses (Fig. 3). But such tropical cyclone frequency simulations are highly dependent on the ability of global coupled climate models to adequately simulate the changes in large-scale conditions that affect cyclone development. Care must be taken in interpreting results from regional models, as the use of small domains or spectral nudging across the regional domain constrains the model to follow the conditions imposed from the driving large-scale model.

The general convergence of frequency projections from different approaches (Table S1), in conjunction with the hindcasting tests illustrated in Fig. 3, is beginning to provide some confidence in global and hemispheric projections of tropical cyclone frequencies. However, confidence in these projections remains very low for individual basins (Table S1), owing to uncertainties in the large-scale patterns of future tropical climate change, as evident in the lack of agreement between the model projections of patterns of tropical SST changes[29] as well as remaining limitations in the downscaling strategies.

Based on existing modeling studies (Table S1) and limited existing observations, we judge that it is likely that global mean tropical cyclone frequency will either decrease or remain essentially unchanged due to greenhouse warming. Late 21st century model projections indicate decreases ranging from -6% to -34% globally, with a comparatively more robust decrease for the Southern Hemisphere (SH) mean than for the NH mean counts. Among proposed mechanisms for the decrease in global tropical cyclone frequency is a weakening of the tropical circulation[13,32] associated with a decrease in the upward mass flux accompanying deep convection[33], or an increase in the saturation deficit of the middle troposphere[11]. The more robust decrease in the SH may be due to smaller increases in SST in the SH as compared to the NH as well as areas of increased vertical shear in global model SH projections[29,34]. For individual basins, there is much more uncertainty in the tropical cyclone frequency projections, with changes of up to +/- 50% or more projected by various models.

TROPICAL CYCLONE INTENSITY

Detection and Attribution:

Future surface warming and changes in the mean thermodynamic state of the tropical atmosphere, as projected by climate models, will lead, according to theory[35,36] and modeling[10,37], to an increase in the upper limits of the distribution of tropical cyclone intensities. High resolution models project an increase in both the mean intensities (Table S2) and in the frequency of cyclones at higher intensity levels[13,38]. Such shifts are observed in the best track records of global tropical cyclone intensities, but these records are known to suffer from substantial heterogeneities, which can also manifest themselves as a shift towards stronger storms. Ref 25 reported a substantial global increase (nearly doubling) in the number of the most severe tropical cyclones (category 4 and 5 on the Saffir-Simpson scale) from 1975 to 2004. Other studies contested this finding, based on concerns about data quality[39,40] and the short record length relative to multi-decadal variability[41] in the Northwest Pacific. Analyses of globally consistent satellite-based intensity estimates since 1981 suggest that trends in the best track data are indeed inflated[42], but do support an increase globally in the intensities of the strongest tropical cyclones[43].

The new satellite-based intensity data[42,43] were designed to be more homogeneous than the existing global data, but still carry uncertainties, particularly in the Indian Ocean where the satellite record is less consistent[43]. The short time period of the data does not allow any definitive statements regarding separation of anthropogenic changes from natural decadal variability or the existence of longer-term trends and possible links to greenhouse warming. Additionally, intensity changes may result from a systematic change in storm duration, which is another route by which internal variability can affect intensity that has not been studied extensively.

The intensity changes projected by various modeling studies of the effects of warming by greenhouse gases (Table S2) are small in the sense that detection of an intensity change of a magnitude consistent with model projections should be very unlikely at this time[37,38], given data limitations and given the large interannual variability relative to the projected changes. Uncertain relationships between tropical cyclones and internal climate variability, including factors related to the SST distribution, such as vertical wind shear, also reduce our ability to confidently attribute observed intensity changes to greenhouse warming. The most significant cyclone intensity increases are found for the Atlantic basin[43], but the relative contributions to this increase from multi-decadal variability[44] (whether internal or aerosol forced) versus greenhouse-forced warming cannot yet be confidently determined.

<u>Projection</u>: Some increase in mean tropical cyclone maximum wind speed is likely with projected 21st century warming, although increases may not occur in all tropical regions. This conclusion has been supported by theories of potential intensity[35,36] and by further modeling studies (Supplemental Material S2; Table S2) which have more realistic simulations of intensity as model horizontal resolution is increased. Studies based on potential intensity theory and the higher resolution (<20 km) models project mean global maximum wind speed increases of +2 to +11% (roughly +3 to +21% central pressure fall (S2)) over the 21st century. At the individual basin scale, existing multi-model ensemble mean projections show a range of intensity increase of about 0 to +11%. For some

individual basins, projections based on single models can indicate increases or decreases, and projections vary over a much larger range (e.g., up to +/- 15% or more). Most of these models can say little about major hurricanes, which require higher resolution for adequate simulation. In some cases[10,11,45] the reported time slice or downscaling experiments are based on such a short record from the host climate model that the projection--particularly for individual basins--may be largely representing internal variability, rather than the forced signal of interest. Decreased potential intensity is projected from theory for some individual basins/individual model combinations, particularly using Emanuel's reversible ascent formulation of potential intensity theory, which shows a less positive sensitivity to the projected climate warming than Emanuel's pseudoadiabatic or Holland's potential intensity formulations (Section S2; Table S2).

There is a clear tendency among the models, particularly at higher resolution (60 km grid spacing or less), to project an increase in the frequency of the stronger tropical cyclones (Table S1, S2), although the actual intensity level of these strong model cyclones varies among the models, depending on model resolution and other factors. These increases are typically projected to be substantial in fractional terms. Even a relatively small shift or expansion of the intensity distribution of storms toward higher intensities can lead to a relatively large fractional increase in the occurrence rate of the strongest (rarest) tropical cyclones[12,38]. For example, a recent downscaling study[38] using an operational (9 km grid) hurricane prediction model shows a tendency toward increased frequency of Atlantic category 4-5 hurricanes over the 21st century. We judge that a substantial increase in the frequency of the most intense storms is more likely than not globally, although this may not occur in all tropical regions. Our confidence in this finding is limited, since the model-projected change results from a competition between the influence of increasing storm intensity and decreasing overall storm frequency.

While such changes were not noted in several relatively low resolution simulations, these models are less reliable for investigating the most intense cyclones. As an example, ref 13 found that, for one series of models, a resolution of ~60 km was needed before a warming-related intensification was simulated.

Further studies are needed to evaluate model projections of intensity changes, for example, by comparing model simulations of the interannual variability of intensities to observations[29]. As there is a suggestion in existing studies that climate warming-induced increases of intensity are larger in higher resolution models than in coarse-grid models[13], it is plausible that existing models may systematically underestimate future intensity trends. The future characteristics of intense tropical cyclones (category 3-5) deserve particular attention, as these storms historically have accounted for an estimated 85% of U.S. hurricane damage, despite representing only 24% of U.S. landfalling tropical cyclones[5]. Additional studies with finer resolution models hopefully will increase our confidence in future projections of tropical cyclone intensity and the frequency of very intense cyclones.

TROPICAL CYCLONE RAINFALL

Detection and Attribution:

Atmospheric moisture content has increased in recent decades in many regions[46], and climate models are unanimous that the integrated water column in the tropics will increase, on average, as the atmosphere warms. The expectation is that as the water vapor content of the tropical atmosphere increases, the moisture convergence for a given amount of mass convergence is enhanced. This should increase rainfall rates in systems (viz tropical cyclones) where moisture convergence is an important component of the water vapor budget. An increase in storm wind intensities would add to this moisture convergence. Despite this expectation, a detectable change in tropical cyclone-related rainfall has not been established by existing studies. Satellite-based studies report an increase in the occurrence of heavy rain events in general in the tropics during 1979-2003[47] and also an increase during warm periods of interannual variability[48]. A number of studies of land-based precipitation data have identified increasing trends in the frequency of very heavy precipitation events[2,3]. None of these studies isolate tropical cyclone precipitation rates.

Projection: Tropical cyclone-related rainfall rates are likely to increase with greenhouse warming. This is a robust projection in model simulations of tropical cyclones in a warmer climate: all seven available studies report substantial increases in storm-centered rainfall rates (Supplemental Material S3, Table S3). The range of projections for the late 21st century among existing studies is +3% to +37%. The percentage increase is apparently quite sensitive to the averaging radius considered, with the larger (smaller) sensitivities reported for the smaller (larger) averaging radii. Typical projected changes are about +20% within 100 km of the storm center. However, model resolution and complex physical processes near the storm center place a level of uncertainty on such projections that is not easily quantified. Annually averaged rainfall from tropical cyclones could decrease if the impact of decreased frequency of storms exceeds that of increased rainfall rates in individual storms, although this effect has not yet been quantified.

TROPICAL CYCLONE GENESIS, TRACKS, DURATION, AND SURGE FLOODING

Detection and Attribution:

There is no conclusive evidence that any observed changes in tropical cyclone genesis, tracks, duration, or surge flooding exceed the variability expected from natural causes. There are suggestions of observed storm track and/or genesis location changes in the Atlantic, and these have been offered as providing an explanation for the lack of increasing trends in U.S. and Gulf Coast landfalling storms. Century scale trend analyses of Atlantic tropical cyclone track density suggests a decrease in storm track density in the western part of the basin and near major landfalling regions, and an increase in the middle and eastern regions of the basin[20,49]. However, according to recent studies of ship track density[20] and storm occurrence by duration class[22], at least some of the increases in the eastern Atlantic are likely attributable to observing system changes; it is unlikely that the reduced numbers in the western region are strongly affected by such observing system changes. A long-term (century-scale) decrease in average tropical cyclone duration has been reported in the Atlantic basin[20], associated with a strong upward trend in short duration (<2 day) storms coupled with little change in longer-lived (>2 day) storms[22]. But the observed increase in short-lived storms was interpreted by ref 22 as likely attributable largely to observing system changes, rather than climate change.

Sea level has risen globally by about 0.17 m during the 20th century[2], and sea level changes have important regional differences due to various factors, both climate change-related and otherwise. There also has been marked degradation of coastal wetlands and local variations in land subsidence arising from coastal development. However, a detectable increase in storm surge flooding from tropical cyclones has not been established.

Projection:

We have low confidence in projections of changes in tropical cyclone genesis location, tracks, duration, or areas of impacts, and existing model projections do not show dramatic large-scale changes in these features. The vulnerability of coastal regions to tropical cyclone storm surge flooding is expected to increase with future sea level rise and coastal development, although this vulnerability will also depend on future storm characteristics.

Substantial impacts can occur in higher latitudes from tropical cyclones that have undergone extratropical transition. Downscaled model projections[11] suggest that no significant increase or decrease of tropical cyclone duration should be expected to occur. Projections for the expansion of the subtropics in climate models[2] suggests some potential for the poleward movement of the average latitude of transition, but no dynamical modeling studies have focused on this issue and we place low confidence in any assessments concerning extratropical transition at this point.

Changes in tropical cyclone storm surge potential depend on future projections of sea level rise--which are uncertain both at the global scale[2] and in regional structure^{--}as well as on storm characteristics. Even assuming no future changes in tropical cyclone behavior, storm surge incidence from tropical cyclones, the most damaging aspect of tropical cyclone impacts in coastal regions, would be expected to increase because of highly confident predictions that at least some future increase in sea level will occur[2].

INFLUENCE OF UNCERTAINTY IN LARGE-SCALE TROPICAL PROJECTIONS

Uncertainties in model projections of future tropical cyclone activity arise due to both uncertainties in how the large-scale tropical climate will change and uncertainties in the implications of these changes for tropical cyclone activity. Both of these uncertainties will need to be addressed to increase confidence in regional and global tropical cyclone projections.

As an example of the large uncertainty remaining in tropical cyclone projections regionally due to differences among global climate model projections used to force the downscaling models, Fig. 4 (top) shows results from downscaling experiments[29], in which a single global atmospheric model is forced with SST change projections from several global climate models. While each of the global climate models projects a substantial increase in tropical SSTs during the 21st century, important differences exist in the regional-scale details of their projections, which lead to marked differences in the downscaled regional projections of tropical cyclone activity. Similarly sensitive results have been reported with other tropical cyclone downscaling approaches[11,30,38] (e.g., Fig. 4 bottom and Supplemental Material S1, S2). The uncertainty in climate model-projected SSTs and related variables can affect even the sign of the projected tropical cyclone activity change in a given region.

PROGRESS SUMMARY AND OUTLOOK

We have assessed recent research on tropical cyclones and climate change and find substantial progress in several areas since the previous WMO expert team assessment[6]. These include ; i) substantial new analyses of global intensity data and several important studies of Atlantic tropical cyclone data quality issues, which strongly affect conclusions about climate change detection; ii) important progress in higher resolution global modeling that provides improved projections of global storm frequencies, and confirmation of theoretical expectations for a globally-averaged increase in tropical cyclone intensity and rainfall: and iii) improved dynamical and statistical/dynamical downscaling tools for tropical cyclone activity, and more convincing evaluations of these tools.

This progress in the science has encouraged us to raise our confidence levels concerning several aspects of cyclone activity projections. These include our assessment that tropical cyclone frequency will likely either decrease or remain essentially the same. Despite this lack of an increase in total storm count, we assess the projection of an increase in the globally averaged frequency of the strongest tropical cyclones as more likely than not—a higher confidence level than our previous assessment[6].

An important finding is that while some statistical methods project very large (~300%) increases by the late 21st century in aggregate Atlantic hurricane activity (power dissipation), such dramatic projected increases are not supported by existing downscaling models or by alternative statistical methods[9]. Moreover, despite some suggestive observational studies, we cannot at this time conclusively identify anthropogenic signals in past tropical cyclone data. A substantial human influence on future tropical cyclone activity cannot be ruled out, however, and could arise from several mechanisms (including oceanic warming, sea level rise, and circulation changes). In the absence of a detectable change, we are dependent on a combination of observational, theoretical and modeling studies to assess future climate changes in tropical cyclone activity. These studies are growing progressively more credible but still have many limitations, as discussed in this report.

Given the important societal impacts of tropical cyclones and the apparent sensitivity of these storms to details of regional and tropical climate, further research is strongly recommended to enhance climate-relevant observations, theory, and modeling of tropical cyclones and related regional climate changes. We provide specific recommendations for further research and observational activities in Supplemental Material S7. Going forward, models with increasingly fine spatial resolution and new approaches for improving past tropical cyclone records hold substantial promise for reducing uncertainties in both the understanding of causes of past changes and future projections of tropical cyclone activity.

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ADDITIONAL INFORMATION

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FIGURE LEGENDS

Fig. 1. Past and extrapolated changes in Atlantic hurricane power dissipation index (PDI)[9]. Anomalies are regressed onto: a) tropical Atlantic SST or b) tropical Atlantic SST relative to tropical mean SST (1946 to 2007), and these regression models are used to statistically estimate PDI from several climate models. Anomalies are percent change relative to 1981-2000 average (2.13×10^{11} m^3 s^{-2}). Green bar denotes approximate range of PDI anomaly predicted by the statistical/dynamical calculations of ref 11. Other green symbols denote approximate values suggested by high-resolution dynamical models: circle (12), star (10) and diamond (13). SST region is 20^o-70^oW, 7.5^o-22.5^oN.

Fig. 2. Tropical Atlantic indices (5-yr means, 1878-2008, solid black) and linear trends[20,22]. Green-shaded curves depict global mean temperature (HadCRUT3) and Aug.-Oct. Main Development Region (MDR: 10°–20°N, 80°–20°W) SST anomalies (HadISST). Blue-shaded curves represent unadjusted tropical storm counts. Red curves include time-dependent adjustments for missing storms based on ship track density[20,22]. Curves labeled "> 2-day" depict storms with duration of at least 2 days[22]. Orange curves depict U.S. landfalling tropical storms and hurricanes (no adjustments). Vertical axis tics represent one standard deviation. Series normalized to unit standard deviation. Only the top three series have significant linear trends ($p=0.05$).

Fig. 3. Simulated vs. observed Atlantic tropical cyclone interannual variability (approximately 1980-2006) using several methods: a) tropical storm counts using a

statistical/dynamical downscaling method[11]; b) hurricane counts (Aug.-Oct.) using a regional climate model downscaling method[12]; c) tropical storm counts using a ~100 km grid global model[31]; and d) hurricane counts using a 50 km grid global model[29]. Methods: (a) uses NCEP reanalyses and observed SSTs as input; (b) uses observed SSTs and interior spectral nudging to NCEP reanalyses; and (c, d) use only observed SSTs. Future projections of tropical storm frequency using methods (a, b, d) included in Table S1.

Fig. 4. Sensitivity of future projected tropical cyclone activity to different climate models providing downscaling conditions. Top: projected fractional changes Atlantic hurricanes (late 21st century) using a global atmospheric model to downscale SST projections from three individual climate models or from an 18-model ensemble[29]. The two projections for each case (red, blue) used different controls based on different observed SST data. The vertical bars denote 90% confidence intervals. Bottom: approximate percentage change in power dissipation in various tropical storm basins projected for the late 22nd century using a statistical/dynamical downscaling framework forced with climate change statistics from seven global models[11].

Text Box. Summary of detection, attribution, and projection assessments.

SUMMARY ASSESSMENT:

Detection and Attribution:

It remains uncertain whether past changes in any tropical cyclone activity (frequency, intensity, rainfall, etc.) exceed the variability expected through natural causes, after accounting for changes over time in observing capabilities.

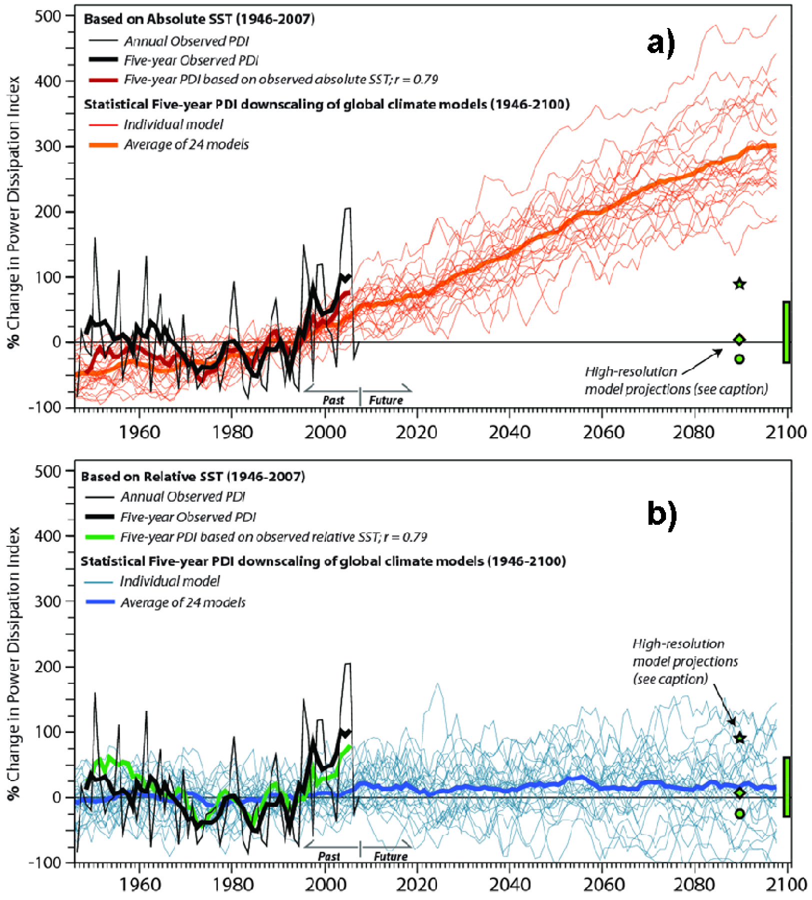
Tropical Cylone Projections:

Frequency: It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged due to greenhouse warming. We have very low confidence in projected changes in individual basins. Current models project changes ranging from -6 to -34% globally, and up to ± 50% or more in individual basins by the late 21st century.

Intensity: Some increase in mean tropical cyclone maximum wind speed is likely (+2 to +11% globally) with projected 21st century warming, although increases may not occur in all tropical regions. The frequency of the most intense (rare/high-impact) storms will more likely than not increase by a substantially larger percentage in some basins.

Rainfall: Rainfall rates are likely to increase. The projected magnitude is on the order of +20% within 100 km of the tropical cyclone center.

Genesis, Tracks, Duration, Surge Flooding: We have low confidence in projected changes in genesis location, tracks, duration, or areas of impact. Existing model projections do not show dramatic large-scale changes in these features. The vulnerability of coastal regions to storm surge flooding is expected to increase with future sea level rise and coastal development, although this vulnerability will also depend on future storm characteristics.



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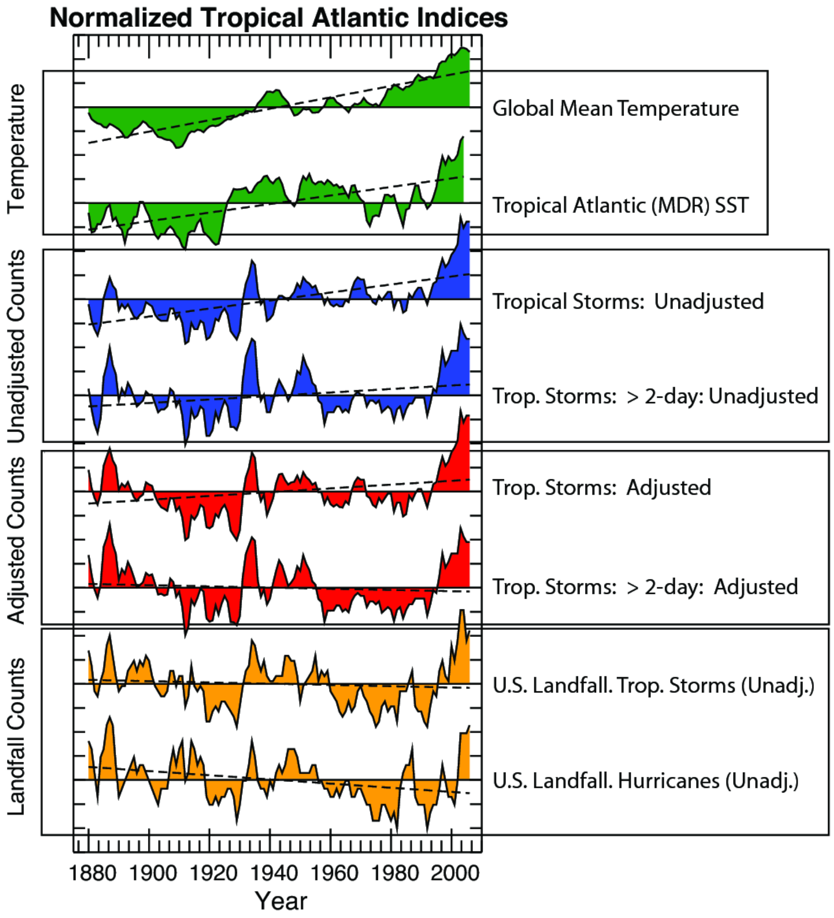

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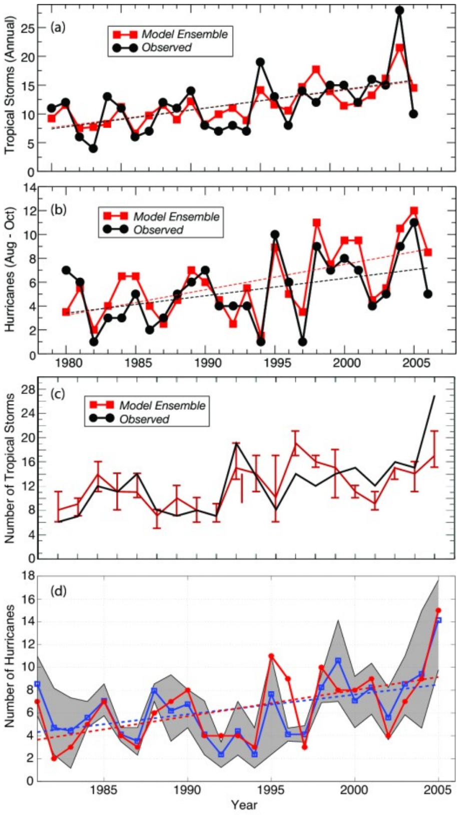

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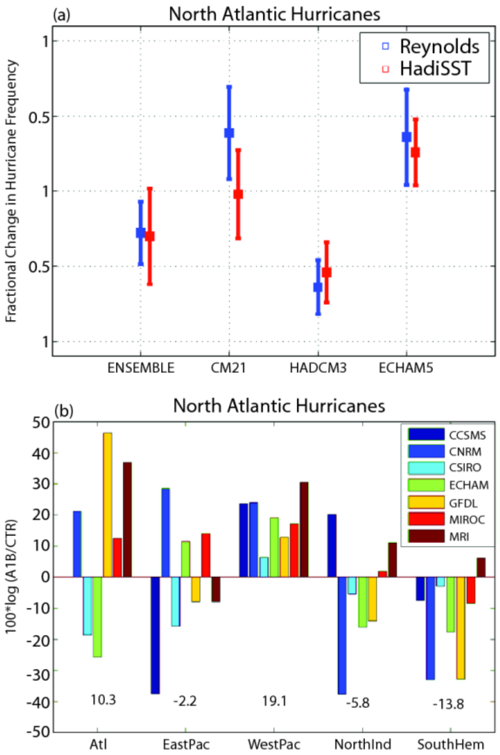

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