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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 indicate that greenhouse warming will cause the globally averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2–11% by 2100. Existing modelling studies also consistently project decreases in the globally averaged frequency of tropical cyclones, by 6–34%. Balanced against this, higher resolution modelling 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 100 km of the storm centre. For all cyclone parameters, projected changes for individual basins show large variations between different modelling studies.

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 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 used to project climate on a multidecadal to centennial timescale do not themselves simulate tropical cyclones adequately.

Sea surface temperatures (SSTs) in most regions of tropical cyclone formation have increased by several tenths of a degree Celsius during the past several decades[1]. The Intergovernmental Panel on Climate Change (IPCC) fourth assessment report[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, and the US Climate Change Science Program 3.3 report[3] extended this by concluding that human-induced greenhouse-gas increases have very likely contributed to the increase in sea surface temperatures (SSTs) in 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 the economic damage and disruption caused by tropical cyclones. Historical analyses[5] indicate that this has been caused primarily by rising coastal populations and the increasing value of infrastructure in coastal areas. In developing countries, in particular, the movement of the population 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 twenty-first century. All likelihood statements follow conventions used by the IPCC[2] (Supplementary Information S4).

We consider new developments in the field since the 2006 World Meteorological Organization 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 Supplementary Information S5. For detection and attribution, the emphasis here is on the Atlantic Ocean basin because the data records for this region 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 Supplementary Information S6 and S7.

Tropical cyclone activity versus sea surface temperature

Over the past 50 years, a significant statistical correlation has existed between Atlantic tropical cyclone power dissipation (definitions in Supplementary Information S4) and SST on timescales of a few years or more[7]. A comparable large correlation exists, on all

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Box 1 | Summary of detection, attribution and projection assessments.

Detection and attribution

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

Tropical cyclone projections

Frequency. It is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged owing 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 twenty-first century.

Intensity. Some increase in the mean maximum wind speed of tropical cyclones is likely (+2 to +11% globally) with projected twenty-first-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 centre.

Genesis, tracks, duration and surge flooding. We have low confidence in projected changes in tropical cyclone genesis-location, tracks, duration and 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.

timescales down to a year, between the power dissipation and the tropical Atlantic Ocean SST relative to mean tropical SST[8]. Taken at face value, these two statistical relations lead to dramatically different inferences about late-twenty-first-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 Ocean SST has increased more rapidly than tropical mean SST over the past 30 years, coincident with the positive trend in the Atlantic power dissipation index over this period (Fig. 1b). This differential warming of the Atlantic can be affected by natural multidecadal variability, as well as by aerosol forcing, but climate models[9–13] indicate 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 due 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 northwest Pacific Ocean 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 Ocean, and other key measures of storm activity in the northwest Pacific, such as the number of Category 4 and 5 typhoons, do not show a significant correlation with SST[14].

Tropical cyclone frequency

Detection and attribution. We first consider tropical Atlantic Ocean SST variability, which has been used statistically to model Atlantic changes in the frequency of tropical storms[15–17]. Substantial multidecadal SST variability is evident in the North Atlantic basin (Fig. 2, second 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] indicates that rainfall variability before the twentieth century was at least as large as that seen in the twentieth century, increasing the plausibility of substantial natural climatic variability in the tropical Atlantic Ocean. The multidecadal SST variability (evident in Fig. 2, second green series) complicates trend detection in the tropical Atlantic, 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 modelled statistically by the century-scale SST increases (Fig. 2, first blue series versus second green series), and some of this increase has been attributed to anthropogenic forcing[15,16]. However, it has been found[20] 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 a lower reporting-ship track density and other observational limitations in pre-satellite (pre-1966) years (Fig. 2, first red series). Furthermore, 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 storms[22] — a phenomenon that has been interpreted as likely being attributable to changes in observing capabilities[22]. There is a much smaller increasing trend in storms lasting more than two days (Fig. 2, second 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. Landfalling tropical storm and hurricane activity in the US shows no long-term increase (Fig. 2, orange series)[20]. Basin-wide major hurricane counts show a significant rising trend, but we judge these basin-wide data as unreliable for climate-trend estimation before aircraft reconnaissance in 1944.

A study of a 1,500-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 AD 1000–1200; 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 geological 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, it was concluded[25] 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

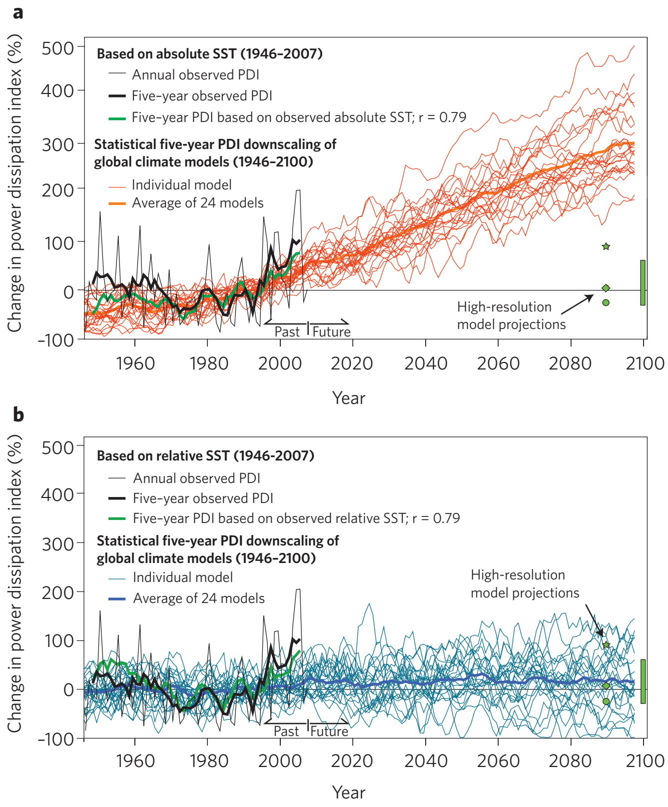

Figure 1 | Past and extrapolated changes in Atlantic hurricane power dissipation index (PDI). Anomalies are regressed onto **a**, tropical Atlantic SST or **b**, tropical Atlantic SST relative to tropical mean SST (1946–2007), and these regression models are used to statistically estimate the PDI from several climate models. Anomalies are per-cent change relative to 1981–2000 average (2.13 x 10^{11} m^3 s^{-2}). The green bar denotes approximate range of the PDI anomaly predicted by the statistical/dynamical calculations of ref. 11. The green circle, star and diamond denote approximate values suggested by high-resolution dynamical models (refs 12, 10 and 13 respectively). SST region is 20° W–70° W, 7.5° N–22.5° N. Figure reproduced with permission from ref. 9 (© 2008 AAAS).

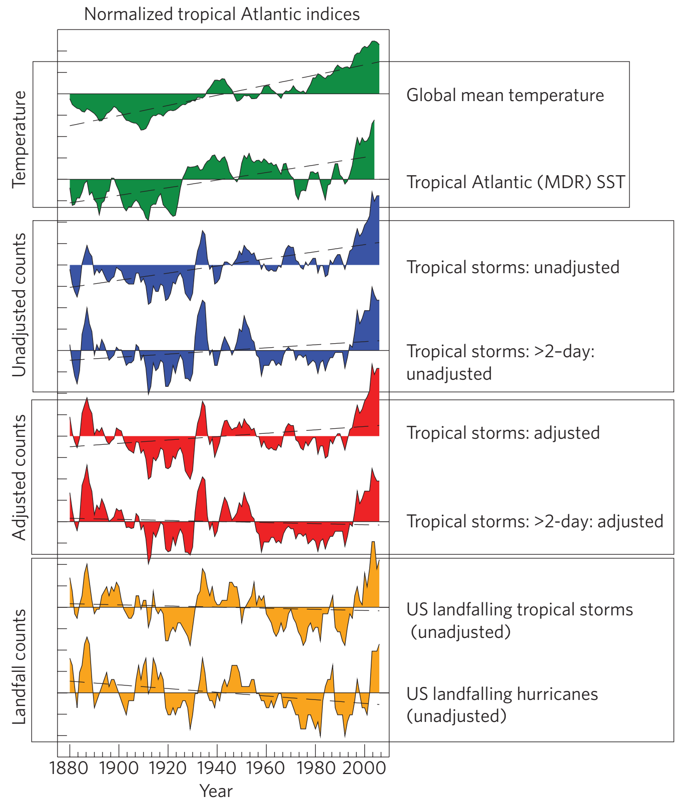

Figure 2 | Tropical Atlantic indices. Green-shaded curves depict global mean temperature (HadCRUT3 data set) and August–October main development region (MDR; 10° N–20° N, 80° W–20° W) SST anomalies (HadISST data set). Blue-shaded curves represent unadjusted tropical storm counts. Red-shaded curves include time-dependent adjustments for missing storms based on ship-track density[20,22]. The curve labelled '>2-day' depicts storms with a duration greater than 2.0 days[22]. Orange-shaded curves depict US landfalling tropical storms and hurricanes (no adjustments). Solid black lines are five-year means (1878–2008); dashed black lines are linear trends. Vertical axis ticks represent one standard deviation. Series normalized to unit standard deviation. Only the top three series have significant linear trends (p = 0.05). Figure reproduced with permission from refs 20 (© 2008 AMS) and 22 (© 2009 AMS).

for the Atlantic (discussed above). Landfall in various regions of East Asia[26] during the past 60 years, and those in the Philippines[27] during the past century, also do not show 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[10,29,30]; regional climate models used to downscale solutions from global coupled models[12,31]; and new 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 (Supplementary 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 (Supplementary 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 modelling studies (Supplementary 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 owing to greenhouse warming. Late-twenty-first-century model projections indicate decreases ranging from −6 to −34% globally, with a comparatively more robust

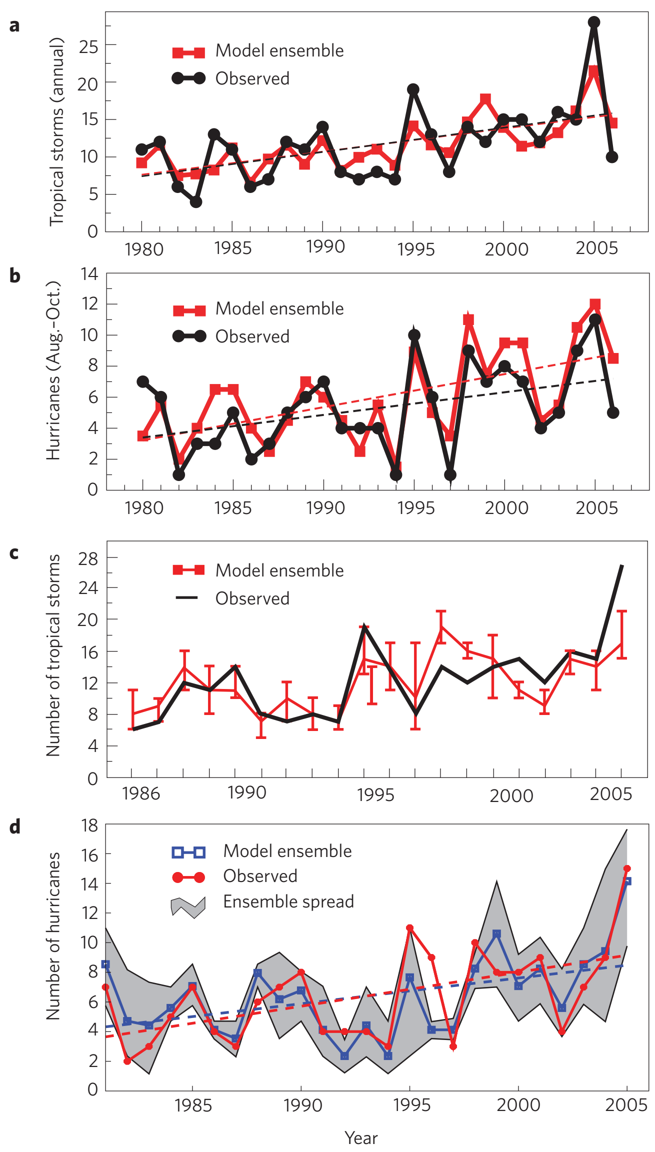

Figure 3 | Simulated versus observed Atlantic tropical cyclone interannual variability (approximately 1980–2006) using several methods. a, Tropical storm counts using a statistical/dynamical downscaling method and atmospheric reanalyses and observed SSTs as input. Reproduced with permission from ref. 11 (© 2008 AMS). **b**, Hurricane counts (August–October) using a regional climate-model downscaling method and data from observed SSTs and interior spectral nudging to atmospheric reanalyses. Reproduced from ref. 12 (© 2008 NPG). **c**, Tropical storm counts using an ~100-km grid global model and only observed SSTs. Reproduced with permission from ref. 30 (© 2008 AMS). **d**, Hurricane counts using a 50-km grid global model and only observed SSTs. Reproduced with permission from ref. 29 (© 2009 AMS). Dashed lines (**a**,**b**,**d**) are linear trends (colour-matched to time series). Future projections of tropical storm frequency using methods **a**, **b** and **d** are included in Supplementary Table S1.

decrease for the Southern Hemisphere mean counts than for the Northern Hemisphere mean counts. Among the 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 Southern Hemisphere may be due to smaller increases in SST compared with the Northern Hemisphere as well as areas of increased vertical shear in global model Southern Hemisphere projections[29,34]. For individual basins, there is much more uncertainty in projections of tropical cyclone frequency, 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 modelling[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 (Supplementary 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 have substantial heterogeneities, which can also manifest themselves as a shift towards stronger storms. A substantial global increase (nearly doubling) in the number of the most severe tropical cyclones (Category 4 and 5 on the Saffir–Simpson scale) has been reported[25] from 1975 to 2004. Other studies contested this finding, based on concerns about data quality[39,40] and the short record-length relative to multidecadal variability[41] in the northwest Pacific. Analyses of globally consistent satellite-based intensity estimates since 1981 indicate 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. Furthermore, intensity changes may result from a systematic change in storm duration, which is another route by which the storm environment can affect intensity that has not been studied extensively.

The intensity changes projected by various modelling studies of the effects of greenhouse-gas-induced warming (Supplementary 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 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 Ocean basin[43], but the relative contributions to this increase from multidecadal variability[44] (whether internal or aerosol forced) versus greenhouse-forced warming cannot yet be confidently determined.

Projection. Some increase in the mean maximum wind speed of tropical cyclones is likely with projected twenty-first 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 modelling studies (Supplementary Information S2 and Supplementary Table S2) that have more realistic simulations of intensity as the horizontal resolution of the model is increased. Studies based on potential intensity theory and the higher resolution (<20-km grid) models project mean global maximum wind speed increases of +2 to +11% (roughly +3 to +21% central pressure fall; Supplementary Information S2) over the twenty-first century. At the individual basin scale, existing multimodel ensemble mean projections show a range of intensity changes from about −1 to +9%. For some individual basins, projections based on single models can indicate larger increases or decreases, and projections vary over a range of the order of ±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 (Supplementary Information S2 and Supplementary 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 (Supplementary Tables S1 and S2), although the actual intensity level of these strong model cyclones varies between 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 towards 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 towards increased frequency of Atlantic Category 4 and 5 hurricanes over the twenty-first 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.

Although 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, it was found that, for one series of models, a resolution of ~60 km was needed before a warming-related intensification was simulated[13].

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[38]. 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 US hurricane damage, despite representing only 24% of US landfalling tropical cyclones[5]. Further studies with finer resolution models hopefully will increase our confidence in future projections of tropical cyclone intensity and the frequency of very intense cyclones.

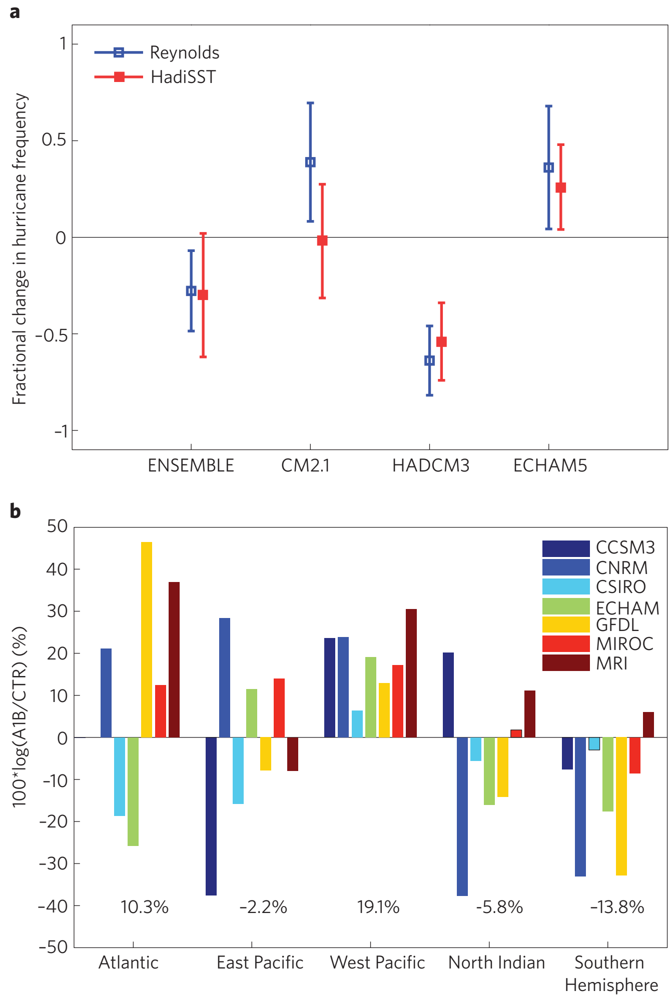

Figure 4 | Sensitivity of projected tropical cyclone activity to different climate models providing downscaling conditions. a, Projected fractional change in North Atlantic hurricanes (late twenty-first century) using a global atmospheric model to downscale SST projections from three individual climate models or from an 18-model ensemble. The two projections for each case (red and blue) used different controls based on different observed SST data. The vertical bars denote 90% confidence intervals. Reproduced with permission from ref. 29 (© 2009 AMS). **b**, Approximate percentage change in tropical cyclone power dissipation in various tropical storm basins projected for the late twenty-second century using a statistical/dynamical downscaling framework forced with climate change statistics from seven global models. The change here is given as 100 multiplied by the logarithm of the ratio of the twenty-second- (A1B) and twentieth-century power dissipation (see ref. 11). Reproduced with permission from ref. 11 (© 2008 AMS).

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-vapour 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 (such as tropical cyclones) where moisture convergence is an important component of the water-vapour 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, generally in the tropics during 1979–2003 (ref. 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-centred rainfall rates (Supplementary Information S3 and Supplementary Table S3). The range of projections for the late twenty-first century between 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 centre. However, model resolution and complex physical processes near the storm centre 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.

Genesis, tracks, duration and surge flooding

Detection and attribution. There is no conclusive evidence that any observed changes in tropical cyclone genesis, tracks, duration and surge flooding exceed the variability expected from natural causes. There are suggestions of observed storm-track and/or genesis-location changes in the Atlantic Ocean, and these have been offered as providing an explanation for the lack of increasing trends in US and Gulf Coast landfalling storms. Century-scale trend analyses of Atlantic tropical-cyclone-track density indicates 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[22] as being likely attributable largely to observing-system changes, rather than climate change.

Sea level has risen globally by about 0.17 m during the twentieth century[2], and sea-level changes have important regional differences owing 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] indicate some potential for the poleward movement of the average latitude of transition, but no dynamical modelling 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 at the global scale[2] and in regional structure — as well as on storm characteristics. Even assuming no future changes in tropical cyclone behaviour, 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 projections

Uncertainties in model projections of future tropical cyclone activity arise owing 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 between global climate model projections used to force the downscaling models — Fig. 4a shows results from downscaling experiments[29], in which a single global atmospheric model is forced with projections of SST change from several global climate models. Although each of the global climate models project a substantial increase in tropical SSTs during the twenty-first 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[11,31,38] (for example, Fig. 4b and Supplementary Information S1and 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

Since the previous World Meteorological Organization expert-team assessment of research on tropical cyclones and climate change[6], substantial progress has been achieved. Specific advances include new analyses of global data on hurricane intensity, and several important studies of data quality issues in Atlantic tropical cyclone records, which strongly affect conclusions about climate change detection. Moreover, important progress has been made in higher resolution global modelling that provides improved simulations of global storm frequencies and further support for theoretical expectations for a globally averaged increase in tropical cyclone intensity and rainfall. Finally, dynamical and statistical/dynamical downscaling tools for tropical cyclone activity have improved, and evaluations of these tools have become more convincing.

These improvements have encouraged us to raise our confidence levels concerning several aspects of cyclone-activity projections. These include our assessment that tropical cyclone frequency is likely to either decrease or remain essentially the same. Despite this lack of an increase in total storm count, we project that a future increase in the globally averaged frequency of the strongest tropical cyclones is more likely than not — a higher confidence level than possible at our previous assessment[6].

Importantly, although some statistical methods project very large increases of about 300% by the late twenty-first 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 modelling 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 review.

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 modelling of tropical cyclones and related regional climate changes (see Supplementary Information S7 for specific recommendations for further research and observational activities). 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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