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Twenty-first-century projections of North Atlantic tropical storms from CMIP5 models

Gabriele Villarini[1,2]* and Gabriel A. Vecchi[3]

Assessing potential changes in North Atlantic (NA) tropical storm (TS) activity this century is of paramount societal and economic significance, and the topic of intense scientific research[1]. We explore projections of NA TS changes over the twenty-first century by applying a statistical downscaling methodology[2,3] to a suite of experiments with the latest state-of-the-art global coupled climate models[4]. We also apply a methodology[5] to partition the dominant sources of uncertainty in the TS projections. We find that over the first half of the twenty-first century radiative forcing changes act to increase NA TS frequency; this increase arises from radiative forcings other than increasing CO_2 (probably aerosols). However, NA TS trends over the entire twenty-first century are of ambiguous sign. We find that for NA TS frequency, in contrast to sea surface temperature (SST), the largest uncertainties are driven by the chaotic nature of the climate system and by the climate response to radiative forcing. These results highlight the need to better understand the processes controlling patterns of SST change in response to radiative forcing and internal climate variability to constrain estimates of future NA TS activity. Coordinated experiments isolating forcing agents in projections should improve our understanding, and would enable better assessment of future TS activity.

Recent research indicates that changes in NA seasonal TS activity are the result of (generally compensating) influences of tropical Atlantic and non-local climatic factors[6–10]. A parsimonious method to synthesize these competing influences in models and observations has been to relate TS activity to the relative SST, which represents the difference between tropical Atlantic (SST_{Atl}) and tropical-averaged SST (ref. 1–3,11; SST_{Trop}).

In Fig. 1 we show the time series of SST anomalies for SST_{Atl}, SST_{Trop} and the differences between the two (SST_{Rel}), together with the TS counts (based on a Poisson regression model in which the number of TSs depends on tropical Atlantic and tropical mean SSTs; see ref. 2 for details). These results are based on 17 climate models (see Supplementary Table S1) and three representative concentration pathways (RCPs, representing a range of plausible future radiative forcing scenarios) produced under the fifth Coupled Model Intercomparison Project[4] (CMIP5) that will be assessed as part of the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC-AR5). Tropical Atlantic and tropical mean SSTs are projected to increase over the present century. These increases are particularly large for RCP 8.5, with a mean increase of the order of 3–3.5 K by the end of this century. There are also clearly different responses depending on the RCP, in particular after the 2040s. This is not the case for relative SST, for which we do not observe any large trend or dependence on RCP. There is, however, large interannual variability, with values generally ranging from −0.5 K to 0.5 K. In all of these cases, the observations over the historical periods tend to be within the ensemble spread. The results of the TS activity are comparable to the relative SST pattern: there are no striking trends or differences among RCPs, yet there is large decade-to-decade (and year-to-year, see Supplementary Fig. S1) variability.

Over the entire twenty-first century, the projected linear trends in NA TS frequency do not show a consistent sign or a strong dependence on RCP scenario (Fig. 2, right boxplots), although individual climate models indicate trends of ±5 TS per century, a projection that is roughly similar to results using the previous generation of third Coupled Model Intercomparison Project (CMIP3) models[3]. There are, however, differences in the trends over the first and second half of the twenty-first century (Fig. 2, left and centre boxplots). The average trends in the 2006–2050 period are positive and of the order of +2 TS per century (significantly larger than zero at the 10% level for RCPs 2.6 and 4.5). In contrast, trends over the second half of the twenty-first century are weaker, with the multi-model average trends not significantly different from zero at the 10% level. These two contrasting contributions tend to offset over the entire 2006–2100 period, with a small tendency towards increasing trends (smaller than +1 TS per century, and not statistically significant).

We posit that the significant tendency for an increase across the multi-model ensemble is not due to the increases in greenhouse gases in these projections, because: the response is non-monotonic in time (greenhouse-gas changes are largely monotonic), the multi-model average is most significant over the first half of the twenty-first century (when greenhouse-gas forcing was the weakest, and most similar across the RCPs), and the increase is the largest for the two RCPs with the smallest greenhouse-gas increase. We have been able to confirm this hypothesis using the idealized climate model runs in which CO_2 increased at 1% per year, allowing an isolation of these models' sensitivity to CO_2 increase. In response to CO_2 increases in isolation, the statistical downscaling of TS frequency in these models shows a consistent tendency for decreasing trends (see Supplementary Fig. S2). It is noteworthy that the multi-model average response to CO_2 increase is quite significant, and the inter-model spread is smaller in response to CO_2 increases than to the full RCP forcings (which also include changes in aerosols and ozone).

The differences between the first and second half of the twenty-first century are, therefore, not related to increases in greenhouse gases but to the models' response to non-greenhouse gases (for example, aerosol and ozone). We reason that the projected increase in NA TS frequency through the mid-twenty-first century is due to a warming of the Atlantic relative to the tropics arising at least in part from a projected reduction of anthropogenic aerosols over the NA, although non-local changes in aerosols (for example,

[1]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey 08540, USA, [2]Willis Research Network, London EC3M 7DQ, UK, [3]Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton, New Jersey 08542, USA. *e-mail: gvillari@princeton.edu.

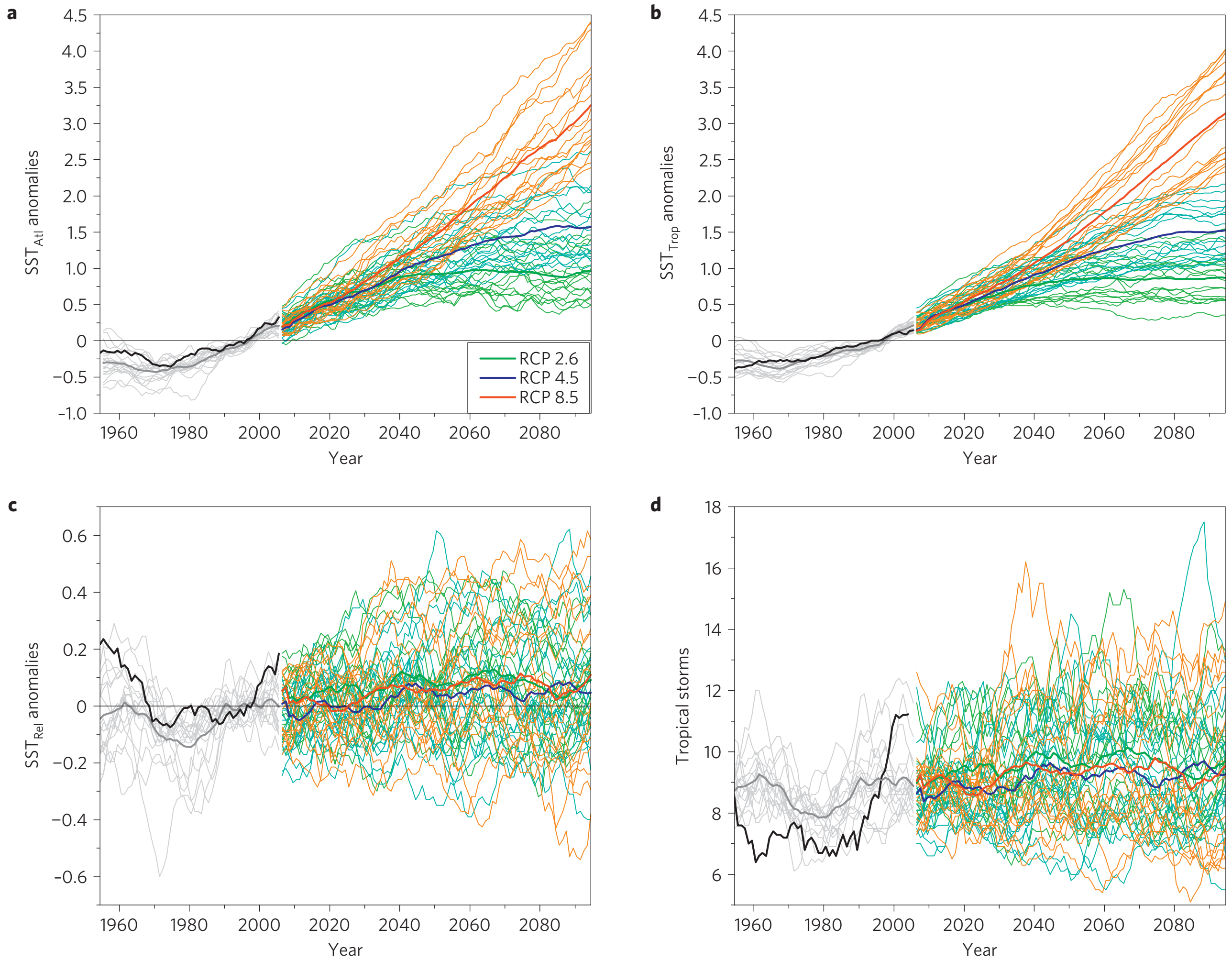

Figure 1 | Twenty-first-century projections of SST and NA TS frequency using CMIP5. a–d, Decadal averages of tropical Atlantic (**a**), tropical mean (**b**), relative SST anomalies (**c**) and TS count projections (**d**) from 17 global climate models under the CMIP5 for three scenarios. The thicker lines represent the mean from each scenario. The light grey lines (1950–2005) describe the historical runs for the 17 global climate models, and the black lines the observations (ERSSTv3b; ref. 28 for the SST, and homogenized estimates of past TS frequency based on HURDAT; refs 29,30). The SST anomalies are computed over June–November with respect to 1986–2005; seasonal TS frequency is derived with the statistical model of ref. 2.

increases over the Indian Ocean) could also be important to the projected TS changes. Using perturbation experiments with a CMIP5 climate model[12], we find evidence that aerosol changes are key to projections of increase in NA TS frequency in that model (Supplementary Figs S3 and S4). Unfortunately, we are not able to directly evaluate this conjecture across all of the CMIP5 models (in the way we explored the impact of CO_2), because idealized forcing experiments only with aerosols are not available to us at present—we think that our understanding would benefit from coordinated experiments isolating the impact of aerosols.

Interestingly, the multi-model ensemble shows a decrease in TS frequency over the 1970s and 1980s, and a rapid rebound in the 1990s—roughly coincident in timing with a similar change in the observations (Fig. 1); such a dip and rebound is not evident in CMIP5 historical experiments forced only with past greenhouse gas or 'natural' (volcanic and solar) forcing changes (not shown). Thus, the historical simulations from CMIP5 seem to support the hypothesis[13] that a part (~25% in the multi-model average) of the observed reduction (increase) in NA TS frequency in the 1970–1980s (1990–2000s) was due to radiative forcing from changes in anthropogenic aerosols, although the small amplitude of the multi-model signal indicates that internal variability[14,15] may also have been a substantial contributor.

In addition to exploring the sign and spread of projections of NA TS frequency, it is important to assess the dominant sources of uncertainty in these projections, as doing so could help focus research to reduce this uncertainty or highlight uncertainty that may be irreducible. We use a recently developed methodology[5] to partition sources of uncertainty in projections of SST_{Atl}, SST_{Trop}, SST_{Rel} and TS into three broad classes: 'forcing uncertainty' arising from imperfect knowledge of future radiative forcing changes; 'response uncertainty' arising from imperfect knowledge of how the climate system responds to changes in radiative forcing; and 'internal variability uncertainty' arising from chaotic variations in climate and weather that are not driven by radiative forcing (Fig. 3). See Methods for further discussion of methodology.

For tropical Atlantic and tropical mean SST (Fig. 3a,b), response uncertainties dominate until about 2030, when forcing uncertainty becomes the dominant uncertainty source. The relative importance of variability to regional SST decreases rapidly after the first decade. This behaviour is similar to that exhibited by global and other regional temperatures[5].

In contrast, the dominant sources of uncertainty for projections of decadally averaged relative SST and TS frequency are fundamentally different (Fig. 3c,d), even though tropical Atlantic and tropical mean SSTs are predictors in the statistical TS model[2,3].

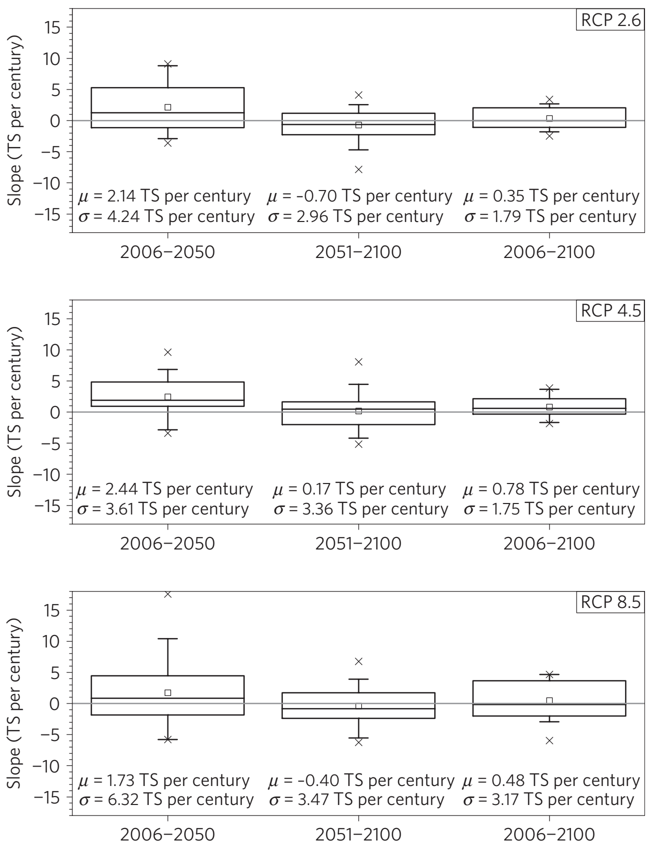

Figure 2 | Slopes of the regression lines for three periods (2006–2050, 2051–2100 and 2006–2100) for NA TS frequency derived from the SST projections using 17 global climate models and the three CMIP5 scenarios (RCP 2.6, RCP 4.5 and RCP 8.5). In the box plots, the crosses represent the minimum and maximum values, the limits of the whiskers represent the 10th and 90th percentiles, the limits of the boxes represent the 25th and 75th percentiles, and the horizontal lines and the squares inside the boxes are the median and the mean, respectively.

Internal variability uncertainty is a substantial contributor during the entire century. Response uncertainty ramps up to over 50% by the 2030s, and is dominant at the end of the century—reflecting the uncertainty in even the sign of the sensitivity of NA TS to the projected warming of the planet[1,3,16–23] (Fig. 2). Forcing uncertainty is a negligible source of uncertainty because response uncertainty is large enough to allow for both increases and decreases of NA TS frequency. Forcing uncertainty is the largest through mid-century, indicating that its contribution comes dominantly from its non-greenhouse components.

Although total uncertainty increases with lead time for both tropical Atlantic and tropical mean SST projections (Fig. 4), the warming in the models is unambiguous. On the other hand, the uncertainties in relative SST and TS counts are larger, so the sign of the change is not clear. Projected SST changes include a substantial contribution from a large relatively uniform warming in response to increasing greenhouse gases, whereas for TS frequency this uniform contribution is substantially weaker[24]—this fundamental difference between tropical Atlantic SST and TS frequency projections leads to their distinct response and uncertainty partitioning.

We note that we did not address uncertainties in projections of NA TS frequency arising from structural uncertainties in downscaling techniques. However, when applied to a previous generation of climate projections[3], our statistical technique produced results similar to a broad range of dynamical methodologies[1,16–23]. Nonetheless, given the apparent importance of non-greenhouse

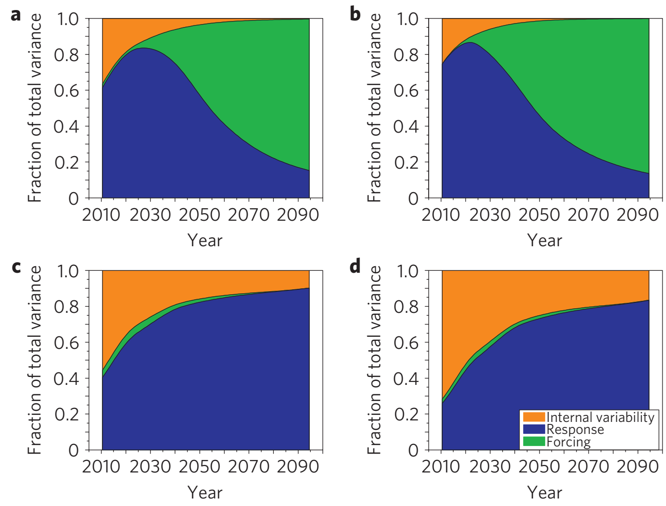

Figure 3 | Fractional contribution to uncertainties in CMIP5 projections of SST and TS frequency. a–d, Fraction of the total uncertainty in projections of decadally averaged tropical Atlantic SST (**a**), tropical mean SST (**b**), relative SST (defined as the different between tropical Atlantic and tropical mean SST; **c**) and NA TS frequency (**d**) arising from different sources. Partitioning based on the methodology of ref. 5. SST indices are computed over June–November as anomalies from 1986 to 2005; seasonal TS frequency is derived with the statistical model of ref. 2.

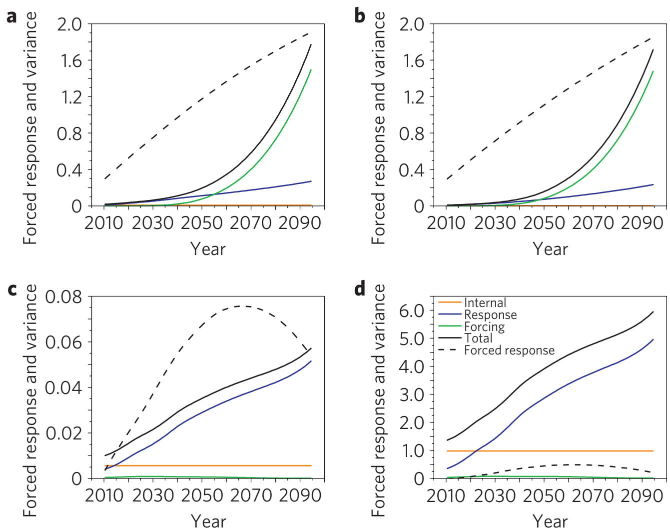

Figure 4 | Total uncertainty in CMIP5 projections of SST and TS frequency. a–d, Time-series plots of the signal, individual components and the total uncertainties for projections of decadal-mean tropical Atlantic SST (**a**), tropical mean SST (**b**), relative SST (defined as the different between tropical Atlantic and tropical mean SST; **c**) and NA TS frequency (**d**). Partitioning based on the methodology of ref. 5. SST indices are computed over June–November as anomalies from 1986 to 2005; seasonal TS frequency is derived with the statistical model of ref. 2.

forcing to the projected changes in NA TS frequency, future work should explore the potential for direct radiative heating to impact TS activity through free-atmospheric temperatures[25], a process that our statistical downscaling technique cannot address. Moreover, although this study is limited to NA TS frequency, it is crucial that future studies explore the relative roles of greenhouse and non-greenhouse forcing in future TS activity in other basins and on that of the strongest cyclones (projections of which may differ from those on overall frequency)[17,20].

Although, at present, we do not know with confidence the sign of expected changes in NA TS frequency over the coming century, the dominant sources of uncertainty identified here signal a way forward. On the basis of this suite of global climate model projections, response and variability uncertainties represent present dominant limitations in our ability to confidently project NA TS activity, a situation similar to that for regional precipitation[26]. Therefore, better characterization and reduction (where possible) of these uncertainties should be a focus of efforts to glean the likely course of NA TS activity over the present century. For the response uncertainty, it is key to better understand and model the processes that control patterns of SST change in response to likely future radiative forcing[27]: should we expect the NA to warm more or less than the global tropics over the present century? Enhanced understanding and representation of climatic processes, including improved representation of clouds and their interactions with aerosols, atmospheric convection, oceanic processes and high-resolution climate modelling, should lead to improvements in our ability to project decadal NA TS activity. Although a substantial component of internal variability uncertainty may prove irreducible, efforts should continue to build the observational, theoretical and modelling basis to understand (and exploit) sources of predictability of decadal climate variations.

Methods

The methodology used to create the projected NA TS time series is based on ref. 2, in which the number of NA TS is modelled by a conditional Poisson distribution with the logarithm of the rate of occurrence parameter that depends linearly on tropical Atlantic and mean tropical SSTs.

We followed the methodology described in ref. 5 to separate the contribution from the different sources of uncertainties, with the following differences: we used 17 climate models available for the CMIP5 project (see Supplementary Table S1 for a list); each individual prediction was fitted with a loess function over the period 1955–2095, rather than a fourth-order polynomial; the reference period is 1986–2005; models are assumed to be independent and received the same weight[26]; for the NA TS counts, the internal variability uncertainty comprises the internal variability as described in ref. 5 and 'weather uncertainty', representing the inherently unpredictable variations in TS activity that are unconstrained by SST. Weather uncertainties are computed as the difference between the 95th and 5th percentiles obtained from a conditional Poisson distribution, in which the rate of occurrence is a linear function of tropical Atlantic and tropical mean SSTs (based on ref. 2). Their contribution is estimated independently of RCPs and lead time, similarly to what was done for the internal variability in ref. 5. Consult Supplementary Fig. S5 to see the relative contribution of these two sources of internal variability.

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Author contributions

Both authors contributed extensively to the work presented in this paper and to the writing.

Additional information

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