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Skilful multi-year predictions of Atlantic hurricane frequency

Doug M. Smith*, Rosie Eade, Nick J. Dunstone, David Fereday, James M. Murphy, Holger Pohlmann and Adam A. Scaife

North Atlantic hurricane activity has increased substantially since the 1970s (refs 1,2), but whether this is attributable to natural internal variability[1,3] or external forcing[4–7] has not been resolved[8]. Either way, hurricane frequency is potentially predictable, because climate models can directly simulate year-to-year variations in Atlantic tropical storm frequency, if forced by observed sea surface temperatures[9]. However, skilful predictions have been limited to lead times of one season[10], and evidence for external forcing of hurricane frequency has been indirect, relying on statistical relationships[4] or external influences on related environmental factors[5–7]. Here we extend skilful climate model predictions of hurricane frequency to lead times of several years, using decadal predictions[11] with nine variants of a general circulation model. In our experiments, the recent increase in tropical storm numbers was not caused by internal variability alone. This provides physically based model evidence of externally forced changes in hurricane frequency, albeit from a single modelling system. Initialization of the model with the observed state of the climate improves forecast skill, mainly through better predictions of tropical Pacific and North Atlantic ocean conditions, in line with previously documented teleconnections[1,3,12–15]. Our results show that predictions of hurricane frequency are viable beyond the seasonal scale, and further elucidate causes of hurricane variability.

North Atlantic hurricane activity varies substantially on decadal timescales[2,16], with relatively quiet periods from the 1900s to the 1920s and from the 1970s to the 1980s, and active periods between the 1930s and the 1960s and since 1995. On average there are 40% more hurricanes, and more than twice as many major hurricanes, in active relative to quiet periods[2]. Consequently, hurricane damage also varies from decade to decade: the average annual hurricane damage in the continental United States was approximately $20 billion (normalized to 2005 values) during the decade 1996–2005 compared with less than $4 billion for the decade 1976–1985 (ref. 17). Importantly, hurricane damage is expected to rise further if the increasing concentration of people and property in coastal regions continues[17]. There is therefore a need for skilful predictions of hurricane activity, along with improved understanding of the causes of variability, to inform potential adaptation and mitigation strategies.

Realistic simulation of the intensity of hurricanes requires models with very high spatial resolution[18]. Multi-annual prediction at such high resolution is not achievable with present computing resources. However, variations in the frequency of Atlantic tropical storms are simulated skilfully with a much lower resolution[9,10,19]. Previous studies either assumed perfect knowledge of sea surface temperatures[9,19] (SSTs) that could not be achieved in actual predictions, or made predictions limited to a single season ahead[10]. Key questions addressed here are whether Atlantic tropical storm frequency can be predicted beyond the seasonal range, and if so, what the sources of skill are.

Hurricane activity is potentially affected both by natural internal variability of the climate system[1,3,12] and by external influences (including anthropogenic greenhouse gases and aerosols[4–7] and natural variations in volcanic and solar activity). Decadal climate prediction systems[11,20–22] are potentially capable of accounting for both of these effects: in addition to specifying external influences, decadal predictions are initialized with the observed state of the climate system to predict natural internal variability and to correct errors in the model response to previous external forcing. Here we use the Met Office Decadal Climate Prediction System[11] (DePreSys, see the Methods section). We track model storms identified as coherent minima in daily sea-level pressure fields (see the Methods section). To avoid contamination by extra-tropical storms, we restrict our analysis to the Atlantic basin between 0° and 25° N. Storms forming in this region account for more than 85% of the hurricanes and intense hurricanes that made landfall on the United States between 1950 and 2005 (ref. 23). For the hurricane season (1 June–30 November), we compare the number of model storms with the observed number of tropical storms in the HURDAT database[16] that formed in this region, noting that tropical storms explain 80% of the variance in hurricane frequency[6]. To avoid spurious trends arising from recently improved capability to detect short-lived storms, we ignore observed storms shorter than two days[24]. Despite uncertainties in historical storm counts[8,16], our study period benefited from aircraft and satellite observations, and shows robust decadal variability[8].

Before considering longer timescale predictions, we test our approach in a set of seasonal hindcasts (see Methods) that start on 1 May in each year from 1960 to 2007. In agreement with previous studies[10] these hindcasts predict much of the interannual variability of tropical storm numbers (Fig. 1, anomaly correlation ACC = 0.62). This clearly demonstrates both the effectiveness of our storm tracking algorithm (see Supplementary Information), and the fact that the frequency of model storms is strongly related to the frequency of actual storms, even though the intensity of storms cannot be simulated realistically with coarse-resolution models[9].

We investigated skill beyond the seasonal range in a second set of hindcasts (see the Methods section) starting on 1 November in each year from 1960 to 2005 and extending to 10 years ahead. To gain some insight into the sources of skill we also carried out a parallel set of hindcasts (NoAssim) with exactly the same external forcing but starting in 1860 with initial conditions taken randomly from coupled model simulations of pre-industrial climate[11]. Skill in this ensemble mean arises entirely from external influences, because

Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. *e-mail: doug.smith@metoffice.gov.uk.

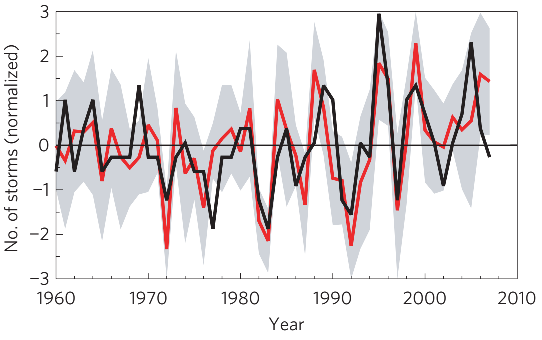

Figure 1 | Seasonal hindcasts of Atlantic tropical storm frequency. Observed (black curve) and predicted (red curve with grey shading showing the 5–95% confidence interval) normalized number of Atlantic tropical storms (see the Methods section) forming in the region 0°–25° N each year. Observations are taken from the HURDAT database[16]. Predictions are obtained by tracking model storms (see Methods) in DePreSys seasonal hindcasts starting on 1 May each year from 1960 to 2007. Both observations and predictions are for the hurricane season, 1 June–30 November.

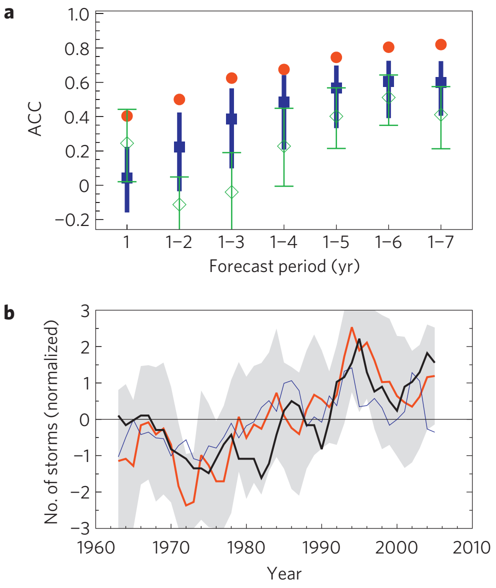

Figure 2 | Multi-annual hindcasts of Atlantic tropical storm frequency. **a**, ACC (see Supplementary Information) for predictions of the number of Atlantic tropical storms for increasing forecast periods. Forecast period '1' is the first hurricane season (months 8–13 from November hindcasts), and '1–7' is the average of years 1–7 inclusive. Initialized predictions (DePreSys, red circles) are compared with externally forced (NoAssim, blue squares) and persistence (green diamonds, see the Methods section), with the blue/green bars indicating the 5–95% confidence interval in which differences in skill from DePreSys are not significant (see Supplementary Information). **b**, The same as for Fig. 1 but for five-year rolling means. The blue curve shows NoAssim.

natural internal variations in the ensemble members are not in phase with each other or with reality.

We obtain skilful predictions of the number of Atlantic tropical storms for a range of forecast periods well beyond the seasonal timescale and out to years ahead (Fig. 2a), with DePreSys (red circles) significantly more skilful than both NoAssim (blue squares) and persistence forecasts made by persisting anomalous storm counts from previous years (green diamonds, see the Methods section, although there is a 10% chance that persistence is more skilful than DePreSys for the first year). The skill is robust to ensemble size, tracking algorithm choices and geographical region (see Supplementary Information). Furthermore, DePreSys is significantly more skilful than NoAssim even when the first year is excluded from the forecast period (Supplementary Fig. S1). As expected, persistence forecasts of the first year capture some of the high-frequency variability, and are more skilful than NoAssim.

The hindcast period is largely dominated by an increasing trend in storm frequency (Fig. 2b), which gives rise to increasing skill (and high ACCs) at longer forecast periods for all forecasts (Fig. 2a). Focusing on predictions of the average number of tropical storms in the coming five years, both DePreSys and NoAssim correctly predict below normal activity during the 1970s and enhanced activity since the 1990s (Fig. 2b). Although this signal is much stronger in DePreSys, the robust skill of NoAssim (see Supplementary Information) shows that these low-frequency variations are not caused by internal variability alone in our model, but are at least partly externally forced by a combination of anthropogenic changes in greenhouse gas, ozone and aerosol concentrations, and natural variations in solar irradiance and volcanic aerosol. This conclusion could not be drawn from the fact that persistence forecasts are skilful. We note that future increases in greenhouse gases are expected to lead to fewer storms globally[8] whereas other external factors could be more relevant to the recent increase. Further experiments with a range of models are therefore needed to assess the relative importance of different external factors.

Although NoAssim captures some of the low-frequency variability in Atlantic tropical storm frequency (Fig. 2b), DePreSys is significantly more skilful (Fig. 2a and Supplementary Fig. S1). For example, the error variance in predictions of five-year mean storm numbers is reduced by 35% ($\mathrm{ACC} = 0.75$ for DePreSys compared with 0.57 for NoAssim). We therefore investigated differences between DePreSys and NoAssim to gain further understanding of the sources of skill. North Atlantic hurricane activity is closely related to local environmental conditions, especially variations of SST, vertical wind shear and atmospheric stability[1,23,25–27]. A warmer sea surface provides additional energy from the ocean and destabilizes the atmosphere, leading to enhanced hurricane activity, whereas higher temperatures in the upper atmosphere reduce hurricane activity by increasing atmospheric stability, and increased wind shear reduces hurricane development by disrupting the organization of deep convection. Models forced by observed SSTs simulate nearly all of the interannual variations in Atlantic tropical storm numbers[9], showing that the local environmental conditions governing storm formation and development are almost entirely controlled by global SST patterns. We find that five-year mean surface temperatures are skilfully predicted by DePreSys throughout most of the globe (Fig. 3a and Supplementary Fig. S2a), with particularly high skill ($\mathrm{ACC} > 0.8$) in the hurricane main development region[1] (MDR) of the tropical North Atlantic. Interestingly however, improvements in DePreSys over NoAssim occur mainly in the North Atlantic and tropical Pacific oceans rather than the MDR (Fig. 3b and Supplementary Fig. S2b). Both of these remote regions have also been linked with Atlantic hurricane activity[1,3,12–15].

To gain further insight into how these remote regions influence hurricane formation, and to check that improved predictions of tropical storm frequency in DePreSys relative to NoAssim are consistent with plausible physical mechanisms, we examined relationships between SST in the tropical Pacific and Atlantic subpolar gyre regions (Fig. 3b), and environmental factors relevant to hurricane formation in the MDR (Fig. 4). These two regions are potentially important sources of remote influence: in multiple linear regression they account for 54% of the variance of DePreSys minus NoAssim model storms, and 44% of the observed variance in five-year mean tropical storm numbers since 1870 (see Supplementary Information).

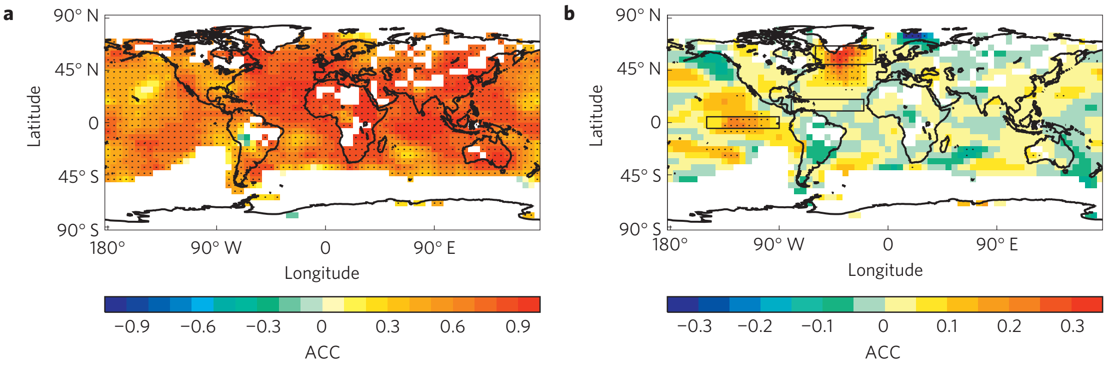

Figure 3 | Skill and impact of initialization for five-year mean surface air temperature. a, ACC between five-year mean (June–November) surface temperature predicted by DePreSys and observations from HadCRUT3 (ref. 30). Anomalies are relative to the 30-year mean preceding each hindcast start date. **b**, ACC of DePreSys minus NoAssim. Each 5° pixel represents the surrounding 15° region. The rectangles in **b** show the hurricane MDR (80°–20° W, 10°–20° N), the subpolar gyre (60°–10° W, 60°–66° N) and the Nino3 region (150°–90° W, 5° S–5° N). Stippling denotes differences between DePreSys and climatology (**a**) or NoAssim (**b**) exceeding the 5–95% confidence interval (Supplementary Information).

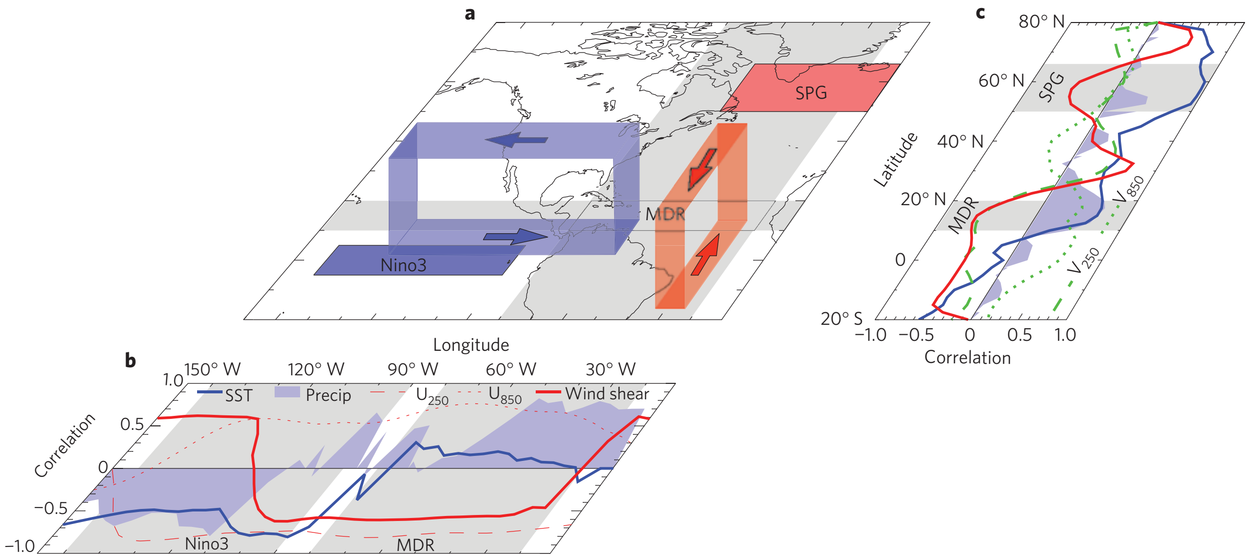

Figure 4 | Remote influences on hurricanes. a, Schematic showing anomalous atmospheric circulations associated with cold Nino3 (blue) and warm subpolar gyre (SPG) (red). **b**, Longitudinal cross-section through the MDR showing correlations between the first five-year mean (June–November) DePreSys minus NoAssim Nino3 SST and meridional mean (10°–20° N) SST (blue line), precipitation (blue shading), upper (250 hPa, red dashed line) and lower (850 hPa, red dotted line) zonal winds, and zonal wind shear (solid red line, upper minus lower zonal wind). **c**, The same as in **b** but for a latitudinal cross-section showing correlations between subpolar gyre SST and zonal means (80°–20° W), including upper (250 hPa, green dashed line) and lower (850 hPa, green dotted line) meridional winds.

In our experiments, a cooler tropical Pacific is associated with reduced wind shear and increased precipitation in the MDR. This is shown in Fig. 4b with negative wind shear (solid red line) and positive precipitation (blue shading) correlations in the MDR (80°–20° W). This is consistent with an anomalous atmospheric zonal (Walker) circulation (Fig. 4a, blue arrows) with atmospheric descent in the tropical Pacific, upper-level westward winds (Fig. 4b, negative red dashed line) and ascent occurring in the tropical Atlantic. The resulting reduced wind shear[13] and upper tropospheric cooling[14] both favour hurricane formation.

On the other hand, a warmer subpolar gyre is associated with reduced wind shear and increased precipitation in the MDR (Fig. 4c, negative red solid line and positive blue shading, 10°–20° N), both of which favour increased hurricane activity. This is consistent with a reduced temperature gradient between the Equator and the subpolar gyre, reduced atmospheric northward heat transport[28] and a build-up of anomalously warm SST north of the Equator including the MDR, (Fig. 4c, positive blue line, 10°–20° N). This drives an anomalous tropical meridional (Hadley) circulation[29] (Fig. 4a, red arrows) with increased lower-level southerly and upper-level northerly winds (Fig. 4c, positive green dotted line and negative green dashed line, 10°–20° N) and a northward shift of the rainfall in the intertropical convergence zone[28,29] (Fig. 4c, positive blue shading, 10°–20° N). Consistent with these mechanisms, we also find significantly improved predictions of MDR wind shear in DePreSys relative to NoAssim (see Supplementary Fig. S3). Correlation does not prove causality, but the fact that improved predictions of SST in the tropical Pacific and North Atlantic are compatible with improved predictions of environmental factors in the MDR, and occur through plausible physical mechanisms[13,14,28,29] in our hindcasts, increases our confidence in the improved predictions of tropical storm frequency and provides further evidence of remote ocean forcing[1,3,12–15].

By assessing tropical storms directly simulated by our model we have shown that present-generation climate models can skilfully predict Atlantic average tropical storm numbers for the coming few years. Further improvements are likely with continued model development, sustained ocean observations and future higher resolution models that simulate hurricanes more realistically. The skill is increased by initialization, mainly through improved predictions of ocean temperatures in the tropical Pacific and North Atlantic that influence the hurricane development region by means of anomalous atmospheric circulations. It is not surprising that initialization improves skill through these regions as natural internal variability is believed to be important there[3,12,22]. However, initialization may also improve skill by correcting the simulated response to external forcing. Either way, our results indicate that some of the recent increase in Atlantic tropical storm numbers was externally forced, at least in our model. Our study demonstrates that multi-annual hurricane predictions are viable, and paves the way for future experiments to disentangle the role of different natural and anthropogenic external forcing factors. This will be important for predicting future hurricane numbers, especially in the coming years.

Methods

Experimental design. We employed a version of DePreSys (ref. 11) updated to sample modelling uncertainties by using nine variants of the third Hadley Centre coupled global climate model (HadCM3) obtained by perturbing poorly constrained atmospheric and surface parameters (see Supplementary Information). HadCM3 was also updated with a fully interactive sulphur cycle, and flux adjustments to restrict the development of regional SST and surface salinity biases. We assessed skill in two sets of hindcasts (forecasts made retrospectively but using only data that would have been available at the time): (1) seasonal (seven-month-long) hindcasts starting from 1 May in every year from 1960 to 2007, and (2) ten-year-long hindcasts starting from 1 November in every year from 1960 to 2005. Hindcasts consisted of nine ensemble members each using a different model variant. The ensemble size for the decadal hindcasts was further increased by combining with those starting in the previous two years, giving 27 ensemble members (out to eight years ahead, see Supplementary Information).

Tracking model storms. We assessed the number of Atlantic storms directly simulated by HadCM3 by tracking model storms identified in daily fields of mean sea-level pressure (MSLP). Local minima in the tropical Atlantic/Caribbean basin (within the latitudes 0°–25° N) are identified as gridboxes with lower MSLP than any of the surrounding eight gridboxes. Minima within 800 km of one another on successive days are assumed to form storm tracks. Each MSLP minimum can belong to only one storm track, and each storm track must contain minima from at least two successive days. Results are robust to different thresholds and regions (see Supplementary Information). As a result of model errors, we present normalized anomalies, obtained by removing the mean and dividing by the standard deviation. This was achieved by a cross-validation approach in which each forecast period was excluded from its calibration. To enable a direct comparison both DePreSys and NoAssim were normalized by the DePreSys standard deviation.

Persistence. Persistence is computed as the anomaly averaged over the n years preceding the hindcast start, where n is the length (years) of the forecast period. For example, for a hindcast starting in November 1970, persistence for forecast periods 1 and 1–2 is the June–November mean anomalies from 1970, and the average of 1969 and 1970, respectively.

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References

1. Goldenberg, S. B., Landsea, C. W., Mestas-Nunez, A. M. & Gray, W. M. The recent increase in Atlantic hurricane activity: Causes and implications. *Science* **293,** 474–479 (2001).
2. Klotzbach, P. J. & Gray, W. M. Multidecadal variability in North Atlantic tropical cyclone activity. *J. Clim.* **21,** 3929–3935 (2008).
3. Zhang, R. & Delwoth, T. L. Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophys. Res. Lett.* **33,** L17712 (2006).
4. Mann, M. E. & Emanuel, K. A. Atlantic hurricane trends linked to climate change. *Eos, Trans. Am. Geophys. Union* **87,** 233–244 (2006).
5. Trenberth, K. E. & Shea, D. J. Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.* **33,** L12704 (2006).
6. Holland, G. J. & Webster, P. J. Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philos. Trans. R. Soc. Lond.* **365,** 2695–2716 (2007).
7. Gillett, N. P., Stott, P. A. & Santer, B. D. Attribution of cyclogenesis region sea surface temperature change to anthropogenic influence. *Geophys. Res. Lett.* **35,** L09707 (2008).
8. Knutson, T. R. *et al.* Tropical cyclones and climate change. *Nature Geosci.* **3,** 157–163 (2010).
9. Zhao, M., Held, I. M., Lin, S-J. & Vecchi, G. A. Simulations of global hurricane climatology, interannual variability, and response to global warming using a 50 km resolution GCM. *J. Clim.* **22,** 6653–6678 (2009).
10. Vitart, F. *et al.* Dynamically-based seasonal forecasts of Atlantic tropical storm activity issued in June by EUROSIP. *Geophys. Res. Lett.* **34,** L16815 (2007).
11. Smith, D. M. *et al.* Improved surface temperature prediction for the coming decade from a global climate model. *Science* **317,** 796–799 (2007).
12. Knight, J. R., Folland, C. K. & Scaife, A. A. Climate impacts of the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.* **33,** L17706 (2006).
13. Goldenberg, S. B. & Shapiro, L. J. Physical mechanisms for the association of El Nino and West African rainfall with Atlantic major hurricane activity. *J. Clim.* **9,** 1169–1187 (1996).
14. Tang, B. H. & Neelin, J. D. ENSO influence on Atlantic hurricanes via tropospheric warming. *Geophys. Res. Lett.* **31,** L24204 (2004).
15. Vimont, D. J. & Kossin, P. The Atlantic meridional mode and hurricane activity. *Geophys. Res. Lett.* **34,** L07709 (2007).
16. Landsea, C. W. Counting Atlantic tropical cyclones back to 1900. *Eos, Trans. Am. Geophys. Union* **88,** 197–208 (2007).
17. Pielke, R. A. *et al.* Normalized hurricane damage in the United States: 1900–2005. *Nat. Hazards Rev.* **9,** 29–42 (2008).
18. Bender, M. A. *et al.* Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. *Science* **327,** 454–458 (2010).
19. LaRow, T. E., Lim, Y-K., Shin, D. W., Chassignet, E. P. & Cocke, S. Atlantic basin seasonal hurricane simulations. *J. Clim.* **21,** 3191–3206 (2008).
20. Keenlyside, N. S., Latif, M., Jungclaus, J., Kornblueh, L. & Roeckner, E. Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature* **453,** 84–88 (2008).
21. Pohlmann, H., Jungclaus, J., Köhl, A., Stammer, D. & Marotzke, J. Initializing decadal climate predictions with the GECCO oceanic synthesis: Effects on the North Atlantic. *J. Clim.* **22,** 3926–3938 (2009).
22. Mochizuki, T. *et al.* Pacific decadal oscillation hindcasts relevant to near-term climate prediction. *Proc. Natl Acad. Sci. USA* **107,** 1833–1837 (2009).
23. Saunders, M. A. & Lea, A. S. Large contribution of sea surface warming to recent increase in Atlantic hurricane activity. *Nature* **451,** 557–561 (2008).
24. Landsea, C. W., Vecchi, G. A., Bengtsson, L. & Knutson, T. R. Impact of duration threshold on Atlantic tropical cyclone counts. *J. Clim.* **23,** 2508–2519 (2010).
25. Emanuel, K. Environmental factors affecting tropical cyclone power dissipation. *J. Clim.* **20,** 5497–5509 (2007).
26. Latif, M., Keenlyside, N. & Bader, J. Tropical sea surface temperature, vertical wind shear, and hurricane development. *Geophys. Res. Lett.* **34,** L01710 (2007).
27. Garner, S. T., Held, I. M., Knutson, T. & Sirutis, J. The roles of wind shear and thermal stratification in past and projected changes of Atlantic tropical cyclone activity. *J. Clim.* **22,** 4723–4734 (2009).
28. Kang, S. M., Held, I. M., Frierson, D. M. W. & Zhao, M. The response of the ITCZ to extratropical thermal forcing: Idealized slab-ocean experiments with a GCM. *J. Clim.* **21,** 3521–3532 (2008).
29. Mantsis, D. F. & Clement, A. C. Simulated variability in the mean atmospheric meridional circulation over the 20th century. *Geophys. Res. Lett.* **36,** L06704 (2009).
30. Brohan, P., Kennedy, J., Harris, I., Tett, S. F. B. & Jones, P. D. Uncertainty estimates in regional and global observed temperature changes: A new dataset from 1850. *J. Geophys. Res.* **111,** D12106 (2006).

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Author contributions

D.M.S. led the analysis and interpretation. D.F. developed the storm tracking algorithm, which R.E. used to analyse storm counts. D.M.S., R.E., H.P. and N.J.D. conducted the analysis. D.M.S. and J.M.M. developed DePreSys and designed the experiments. D.M.S. and A.A.S. wrote the paper with contributions from all authors.

Additional information

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