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Supplementary Materials for

Improved simulation of 19th- and 20th-century North Atlantic hurricane frequency after correcting historical sea surface temperatures

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This PDF file includes:

Figs. S1 to S6
References

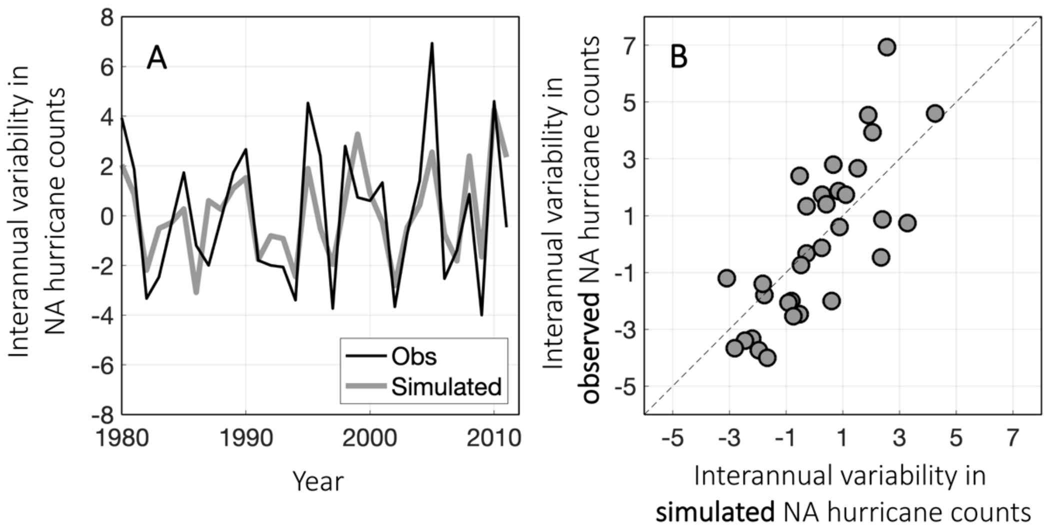

Fig. S1. Interannual variability of hurricane counts. (**A**) Interannual variability of observed (black) and simulated (gray) North Atlantic hurricane counts in the satellite era. The interannual component is the anomalies relative to 15-year running averaged hurricane counts. The simulated interannual variability (black) is the average over 16 members (eight from HadISST1-based runs and eight from HadISST1b-based runs) because groupwise bucket adjustments damp toward zero after the 1980s. (**B**) Compared with the one-to-one line (dashed gray), the simulated interannual variability of hurricane frequency is consistent with observations.

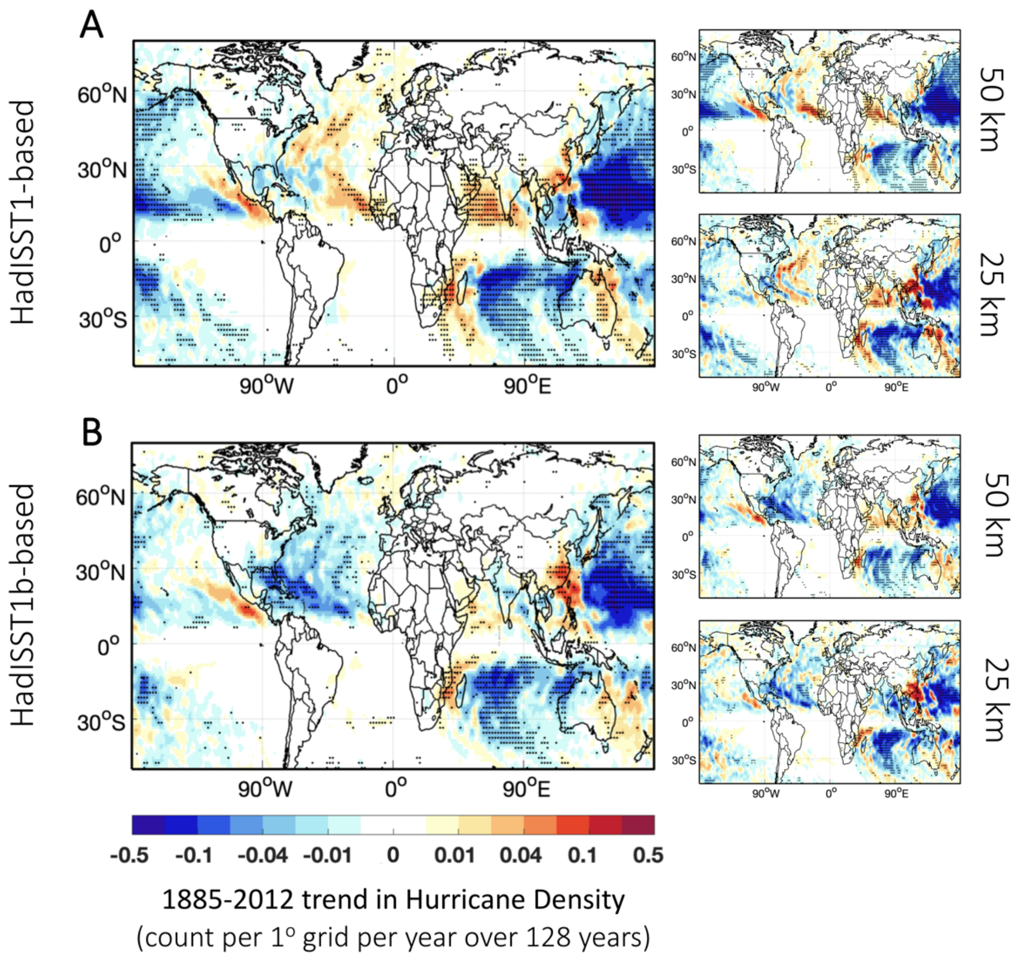

Fig. S2. Maps of 1885-2012 trends in ensemble-mean simulated hurricane track density. Individual panels are for (**A**) HadISST1-based and (**B**) HadISST1b-based simulations. Also shown are maps for HiRAM (50km) and AM2.5 (25km) simulations (smaller panels). Hurricane track density on 1° gridding is smoothed using a nine-grid 2D convolutional smoother before computing trends. Dots denote significant trends at the 95% confidence level.

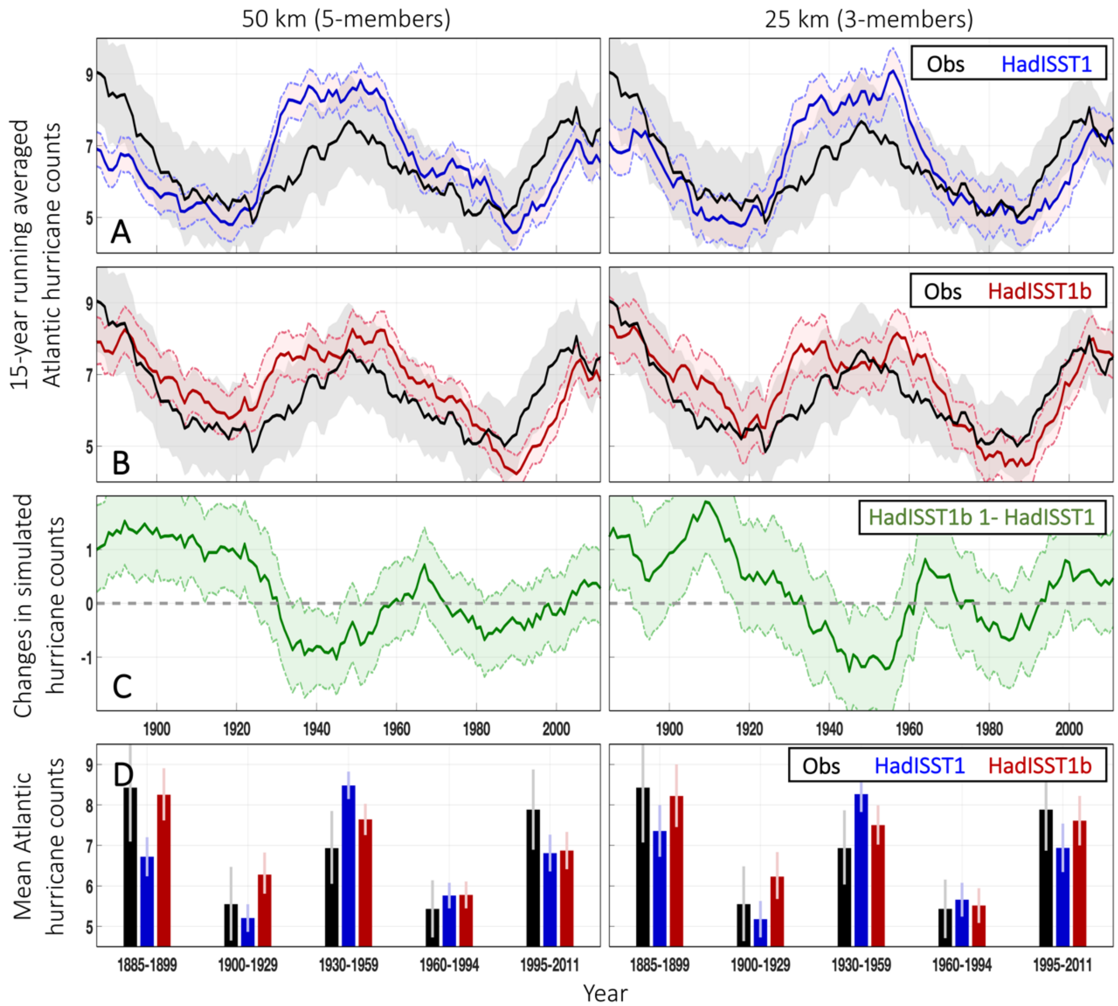

Fig. S3. Observed and simulated Atlantic hurricane counts. Panels are as those in Fig. 1 in the main text but for HiRAM simulations (left, five members) and AM2.5 simulations (right, three members). The improvement in the skill of hurricane simulations is consistent between models.

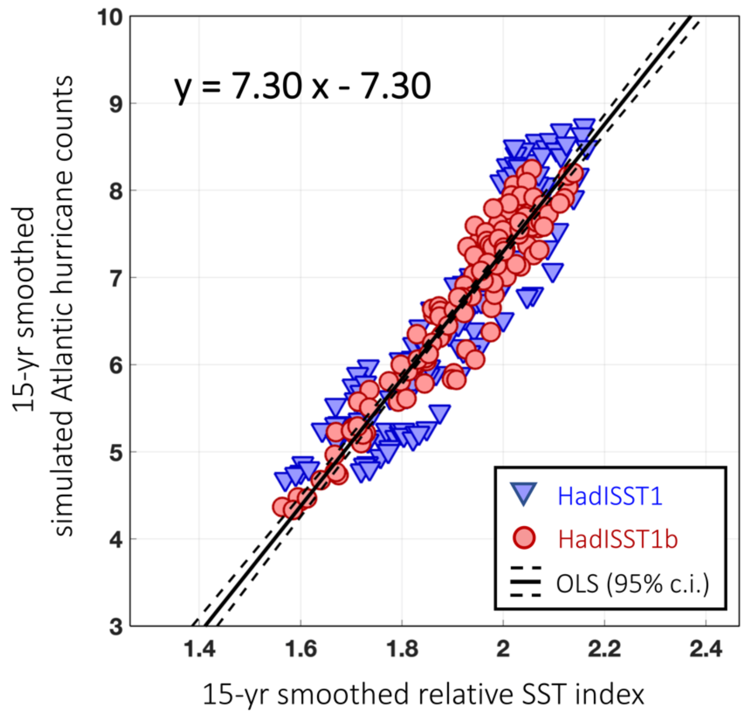

Fig. S4. Sensitivity of simulated hurricane counts to the relative SST (RSST) index. Ensemble-mean simulated hurricane counts (y-axis) using both HadISST1 (blue) and HadISST1b (red) are regressed against RSSTs from corresponding SST estimates (x-axis). A sensitivity of 7.30 hurricanes per year per °C change in RSST (black line) is estimated using an ordinary-least-square (OLS) regression. The OLS makes use of 15-year running averaged hurricane counts and RSSTs because smoothing reduces errors in both axes and alleviates the low bias in the regression slope, also known as regression dilution.

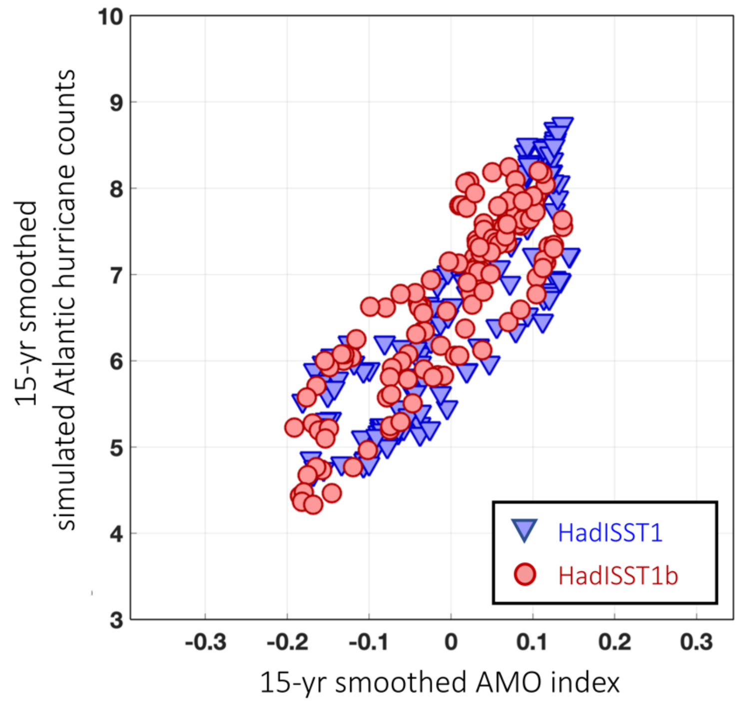

Fig. S5. Sensitivity of simulated hurricane counts to the AMO index. Similar to Fig. S4 but against the Atlantic Multidecadal Oscillation index in respective SST estimates. AMO is defined as the annual SST anomalies over the North Atlantic (0--80°W, 0--65°N) relative to global-mean SST anomalies (*52*).

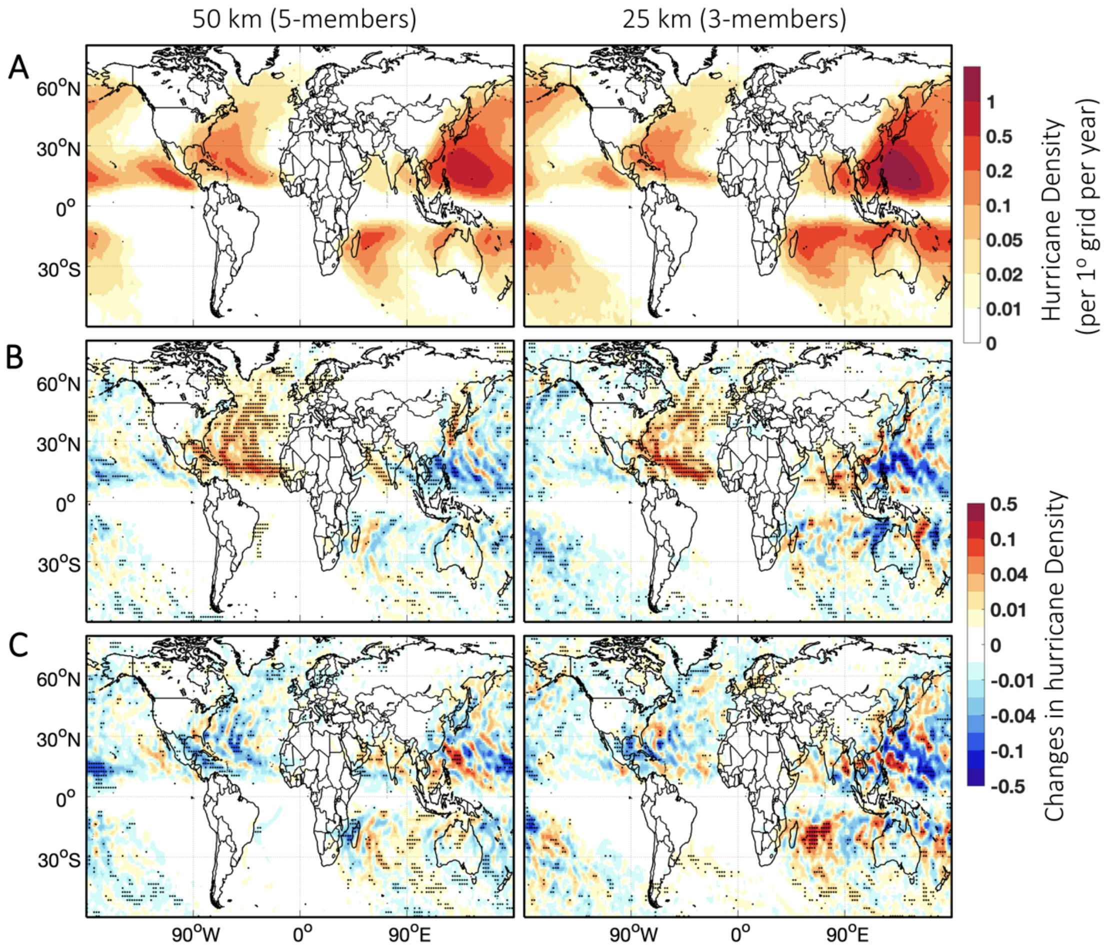

Fig. S6. Maps of hurricane track density. Panels are as those in Fig. 3 in the main text but for HiRAM simulations (left, five members) and AM2.5 simulations (right, three members). The pattern of changes in hurricane density is consistent between models.

REFERENCES AND NOTES

1. T. Knutson, S. J. Camargo, J. C. Chan, K. Emanuel, C.-H. Ho, J. Kossin, M. Mohapatra, M. Satoh, M. Sugi, K. Walsh, L. Wu, Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bull. Am. Meteorol. Soc.* **101**, E303–E322 (2020).
2. E. J. Cha, T. R. Knutson, T.-C. Lee, M. Ying, T. Nakaegawa, Third assessment on impacts of climate change on tropical cyclones in the typhoon committee region—Part II: Future projections. *Trop. Cyclone Res. Rev.* **9**, 75–86 (2020).
3. R. A. Pielke Jr., J. Gratz, C. W. Landsea, D. Collins, M. A. Saunders, R. Musulin, Normalized hurricane damage in the United States: 1900–2005. *Nat. Hazards Rev.* **9**, 29–42 (2008).
4. K. Emanuel, Global warming effects on U.S. hurricane damage. *Weather Clim. Soc.* **3**, 261–268 (2011).
5. G. A. Vecchi, T. R. Knutson, Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878–1965) using ship track density. *J. Clim.* **24**, 1736–1746 (2011).
6. L.-P. Caron, L. Hermanson, A. Dobbin, J. Imbers, L. Lledó, G. A. Vecchi, How skillful are the multiannual forecasts of Atlantic hurricane activity? *Bull. Am. Meteorol. Soc.* **99**, 403–413 (2018).
7. G. A. Vecchi, T. R. Knutson, On estimates of historical North Atlantic tropical cyclone activity. *J. Clim.* **21**, 3580–3600 (2008).
8. G. A. Vecchi, R. Msadek, W. Anderson, Y.-S. Chang, T. Delworth, K. Dixon, R. Gudgel, A. Rosati, B. Stern, G. Villarini, A. Wittenberg, X. Yang, F. Zeng, R. Zhang, S. Zhang, Multiyear predictions of North Atlantic hurricane frequency: Promise and limitations. *J. Clim.* **26**, 5337–5357 (2013).
9. M. Zhao, I. M. Held, S.-J. Lin, G. A. Vecchi, 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. T. Knutson, J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. Srivastava, M. Sugi, Tropical cyclones and climate change. *Nat. Geosci.* **3**, 157–163 (2010).
11. K. Emanuel, The maximum intensity of hurricanes. *J. Atmos. Sci.* **45**, 1143–1155 (1988).
12. A. H. Sobel, J. Nilsson, L. M. Polvani, The weak temperature gradient approximation and balanced tropical moisture waves. *J. Atmos. Sci.* **58**, 3650–3665 (2001).
13. G. A. Vecchi, B. J. Soden, Effect of remote sea surface temperature change on tropical cyclone potential intensity. *Nature* **450**, 1066–1070 (2007).

14. N. A. Rayner, D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, A. Kaplan, Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res. Atmos.* **108**, D14 (2003).

15. C. W. Landsea, S. Feuer, A. Hagen, D. A. Glenn, J. Sims, R. Perez, M. Chenoweth, N. Anderson, A reanalysis of the 1921–30 Atlantic hurricane database. *J. Clim.* **25**, 865–885 (2012).

16. K. Emanuel, S. Solomon, D. Folini, S. Davis, C. Cagnazzo, Influence of tropical tropopause layer cooling on Atlantic hurricane activity. *J. Clim.* **26**, 2288–2301 (2013).

17. I. M. Held, M. Zhao, The response of tropical cyclone statistics to an increase in CO2 with fixed sea surface temperatures. *J. Clim.* **24**, 5353–5364 (2011).

18. M. Sugi, J. Yoshimura, Decreasing trend of tropical cyclone frequency in 228-year high-resolution AGCM simulations. *Geophys. Res. Lett.* **39**, L19805 (2012).

19. G. A. Vecchi, T. L. Delworth, H. Murakami, S. D. Underwood, A. T. Wittenberg, F. Zeng, W. Zhang, J. W. Baldwin, K. T. Bhatia, W. Cooke, J. He, S. B. Kapnick, T. R. Knutson, G. Villarini, K. van der Wiel, W. Anderson, V. Balaji, J. Chen, K. W. Dixon, R. Gudgel, L. M. Harris, L. Jia, N. C. Johnson, S.-J. Lin, M. Liu, C. H. J. Ng, A. Rosati, J. A. Smith, X. Yang, Tropical cyclone sensitivities to CO2 doubling: Roles of atmospheric resolution, synoptic variability and background climate changes. *Clim. Dyn.* **53**, 5999–6033 (2019).

20. S. Woodruff, H. Diaz, J. Elms, S. Worley, COADS Release 2 data and metadata enhancements for improvements of marine surface flux fields. *Phys. Chem. Earth* **23**, 517–526 (1998).

21. S. J. Worley, S. D. Woodruff, R. W. Reynolds, S. J. Lubker, N. Lott, ICOADS release 2.1 data and products. *Int. J. Climatol.* **25**, 823–842 (2005).

22. E. Freeman, S. D. Woodruff, S. J. Worley, S. J. Lubker, E. C. Kent, W. E. Angel, D. I. Berry, P. Brohan, R. Eastman, L. Gates, W. Gloeden, Z. Ji, J. Lawrimore, N. A. Rayner, G. Rosenhagen, S. R. Smith, ICOADS Release 3.0: A major update to the historical marine climate record. *Int. J. Climatol.* **37**, 2211–2232 (2017).

23. C. Folland, D. Parker, Correction of instrumental biases in historical sea surface temperature data. *Q. J. R. Meteorol. Soc.* **121**, 319–367 (1995).

24. E. C. Kent, J. J. Kennedy, T. M. Smith, S. Hirahara, B. Huang, A. Kaplan, D. E. Parker, C. P. Atkinson, D. I. Berry, G. Carella, Y. Fukuda, M. Ishii, P. D. Jones, F. Lindgren, C. J. Merchant, S. Morak-Bozzo, N. A. Rayner, V. Venema, S. Yasui, H.-M. Zhang, A call for new approaches to

quantifying biases in observations of sea surface temperature. *Bull. Am. Meteorol. Soc.* **98**, 1601–1616 (2017).

25. E. C. Kent, N. A. Rayner, D. I. Berry, R. Eastman, V. Grigorieva, B. Huang, J. J. Kennedy, S. R. Smith, K. M. Willett, Observing requirements for long-term climate records at the ocean surface. *Front. Mar. Sci.* **6**, 441 (2019).
26. J. J. Kennedy, N. A. Rayner, R. O. Smith, D. E. Parker, M. Saunby, Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2. biases and homogenization. *J. Geophys. Res. Atmos.* **116**, D14104 (2011).
27. J. J. Kennedy, N. A. Rayner, C. P. Atkinson, R. E. Killick, An ensemble data set of sea surface temperature change from 1850: The Met Office Hadley Centre HadSST. 4.0.0.0 data set. *J. Geophys. Res. Atmos.* **124**, 7719–7763 (2019).
28. G. Carella, J. Kennedy, D. Berry, S. Hirahara, C. J. Merchant, S. Morak-Bozzo, E. Kent, Estimating sea surface temperature measurement methods using characteristic differences in the diurnal cycle. *Geophys. Res. Lett.* **45**, 363–371 (2018).
29. S.-P. Xie, C. Deser, G. A. Vecchi, J. Ma, H. Teng, A. T. Wittenberg, Global warming pattern formation: Sea surface temperature and rainfall. *J. Clim.* **23**, 966–986 (2010).
30. G. A. Vecchi, M. Zhao, H. Wang, G. Villarini, A. Rosati, A. Kumar, I. M. Held, R. Gudgel, Statistical–dynamical predictions of seasonal North Atlantic hurricane activity. *Mon. Weather Rev.* **139**, 1070–1082 (2011).
31. G. Villarini, G. A. Vecchi, Twenty-first-century projections of North Atlantic tropical storms from CMIP5 models. *Nat. Clim. Chang.* **2**, 604–607 (2012).
32. D. Chan, P. Huybers, Systematic differences in bucket sea surface temperature measurements among nations identified using a linear-mixed-effect method. *J. Clim.* **32**, 2569–2589 (2019).
33. D. Chan, E. C. Kent, D. I. Berry, P. Huybers, Correcting datasets leads to more homogeneous early-twentieth-century sea surface warming. *Nature* **571**, 393–397 (2019).
34. D. Chan, P. Huybers, Systematic differences in bucket sea surface temperatures caused by misclassification of engine room intake measurements. *J. Clim.* **33**, 7735–7753 (2020).
35. D. Chan, P. Huybers, Correcting observational biases in sea-surface temperature observations removes anomalous warmth during World War II. *J. Clim.* 1–44 (2021).
36. K. Cowtan, R. Rohde, Z. Hausfather, Evaluating biases in sea surface temperature records using coastal weather stations. *Q. J. R. Meteorol. Soc.* **144**, 670–681 (2018).

37. M. Pfeiffer, J. Zinke, W.-C. Dullo, D. Garbe-Schönberg, M. Latif, M. E. Weber, Indian Ocean corals reveal crucial role of World War II bias for twentieth century warming estimates. *Sci. Rep.* **7**, 14434 (2017).
38. H. Murakami, G. A. Vecchi, S. Underwood, T. L. Delworth, A. T. Wittenberg, W. G. Anderson, J.-H. Chen, R. G. Gudgel, L. M. Harris, S.-J. Lin, F. Zeng, Simulation and prediction of category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model. *J. Clim.* **28**, 9058–9079 (2015).
39. M. Zhao, I. M. Held, G. A. Vecchi, Retrospective forecasts of the hurricane season using a global atmospheric model assuming persistence of SST anomalies. *Mon. Weather Rev.* **138**, 3858–3868 (2010).
40. M. E. Schlesinger, N. Ramankutty, An oscillation in the global climate system of period 65–70 years. *Nature* **367**, 723–726 (1994).
41. K. E. Taylor, R. J. Stouffer, G. A. Meehl, An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **93**, 485–498 (2012).
42. E. Kent, D. Berry, Assessment of the marine observing system (ASMOS): Final report (2008).
43. J. Kennedy, R. Smith, N. Rayner, Using AATSR data to assess the quality of in situ sea-surface temperature observations for climate studies. *Remote Sens. Environ.* **116**, 79–92 (2012).
44. C.-Y. Lee, S. J. Camargo, A. H. Sobel, M. K. Tippett, Statistical–dynamical downscaling projections of tropical cyclone activity in a warming climate: Two diverging genesis scenarios. *J. Clim.* **33**, 4815–4834 (2020).
45. G. Villarini, G. A. Vecchi, Projected increases in North Atlantic tropical cyclone intensity from CMIP5 models. *J. Clim.* **26**, 3231–3240 (2013).
46. C. W. Landsea, J. L. Franklin, Atlantic hurricane database uncertainty and presentation of a new database format. *Mon. Weather Rev.* **141**, 3576–3592 (2013).
47. M. Zhao, I. M. Held, S.-J. Lin, Some counterintuitive dependencies of tropical cyclone frequency on parameters in a GCM. *J. Atmos. Sci.* **69**, 2272–2283 (2012).
48. T. M. Merlis, M. Zhao, I. M. Held, The sensitivity of hurricane frequency to ITCZ changes and radiatively forced warming in aquaplanet simulations. *Geophys. Res. Lett.* **40**, 4109–4114 (2013).
49. T. Knutson, J. Sirutis, M. Zhao, R. E. Tuleya, M. Bender, G. A. Vecchi, G. Villarini, D. Chavas, Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. *J. Clim.* **28**, 7203–7224 (2015).

50. L. M. Harris, S.-J. Lin, C. Tu, High-resolution climate simulations using GFDL HiRAM with a stretched global grid. *J. Clim.* **29**, 4293–4314 (2016).
51. K. Bhatia, G. Vecchi, H. Murakami, S. Underwood, J. Kossin, Projected response of tropical cyclone intensity and intensification in a global climate model. *J. Clim.* **31**, 8281–8303 (2018).
52. K. E. Trenberth, D. J. Shea, Atlantic hurricanes and natural variability in 2005. *Geophys. Res. Lett.* **33** (2006).