www.sciencemag.org/content/350/6258/320/suppl/DC1

Supplementary Materials for

The Atlantic Multidecadal Oscillation without a role for ocean circulation

Amy Clement,* Katinka Bellomo, Lisa N. Murphy, Mark A. Cane, Thorsten Mauritsen, Gaby Rädel, Bjorn Stevens

*Corresponding author. E-mail: aclement@rsmas.miami.edu

Published 16 October 2015, *Science* **350**, 320 (2015)
DOI: 10.1126/science.aab3980

This PDF file includes:

Materials and Methods

We use a hierarchy of coupled climate models with different degree of coupling with the ocean to separate the role of ocean dynamics from thermally coupled processes. We analyze 10 model simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3) archive, each of which has two versions: one in which the atmosphere is fully coupled to the ocean ("fully coupled") and another one in which the atmosphere is coupled with a 50m mixed-layer ocean model ("slab-ocean"). We supplement the CMIP3 models with fully coupled and slab-ocean model simulations of the Community Atmosphere Model version 4 (CAM4) (*35*) and of MPI-ESM-LR (*36,37*). In the CAM4 slab ocean circulation, the mixed layer depth is spatially dependent but temporally constant and is derived from the annual-mean conditions of a preindustrial control simulation of the fully coupled model. In the slab-ocean simulations, internal variability is solely driven by surface heat flux exchange between the ocean and the atmosphere. Monthly mean ocean heat transport is prescribed to yield the observed monthly mean SST climatology in the absence of surface heat flux perturbations, but does not change from year to year and does not drive internal variability. To further separate the role of atmospheric dynamics from thermal coupling with the ocean, we also analyze an atmospheric-only simulation using CAM4 ("CAM-sstClim"). In CAM4-sstClim monthly mean SST and sea ice are prescribed and do not change from year to year. All these simulations are run in pre-industrial conditions in which atmospheric concentrations of greenhouse gases and aerosols are constant in time. Of the 12 models available (summarized in Table 1), only 11 are used to compute the regressions in Fig. 1 because the GISS_E2_R model does not provide all the necessary variables. Table 1 also contains the length of each simulation and the spatial resolution of each model.

We also use an additional 39 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive. We choose all models for which both the pre-industrial and historical experiments are available and analyze one ensemble member (r1i1p1) for each model (Table S2). The pre-industrial simulations are run as described above, and we use the first 190 years for each model. Some models provide longer simulations, but we use only 190 years to maximize the number of models available. The historical simulations are forced with observed atmospheric composition and span the years from 1850 to 2005. We analyze only the years 1865-2005 to maximize the number of models available.

Surface winds and Sea Level Pressure (SLP) are from the NCEP-NCAR reanalysis (*38*), while Sea Surface Temperature (SST) are from the Extended Reconstructed SST, version 3b (ERSSTv3b) reanalysis (*39*), Hadley Centre Sea Ice and SST (HadISST) reanalysis (*40*), and Kaplan Extended SST v2 (*41*). The observed regression in Fig. 1 is computed using the years 1950-2010 in which all datasets overlap.

All data are de-trended and monthly mean anomalies are formed by subtracting the observed or simulated monthly mean climatology.

Table S1. Thirty nine fully coupled climate models that provided the first ensemble member (r1i1p1) for the preindustrial and historical experiments in the CMIP5 archive. 190 years were used in the analysis for the preindustrial simulations, while the years 1865-2005 were used for the historical simulations.

Institution	Model name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM) (Australia)	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration (China)	BCC-CSM1.1 BCC-CSM1.1(m)
Canadian Centre for Climate Modelling and Analysis (Canada)	CanESM2
National Center for Atmospheric Research (U.S.)	CCSM4
Community Earth System Model Contributors (U.S.)	CESM1(BGC) CESM1(CAM5) CESM1(FASTCHEM) CESM1(WACCM)
Euro-Mediterranean Center for Climate Change (Italy)	CMCC-CESM CMCC-CM CMCC-CMS
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (France)	CNRM-CM5 CNRM-CM5(2)
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence (Australia)	CSIRO-Mk3-6-0
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua (China)	FGOALS-g2
NOAA Geophysical Fluid Dynamics Laboratory (U.S.)	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
NASA Goddard Institute for Space Studies (U.S.)	GISS-E2-H GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC
Met Office Hadley Centre (U.K.)	HadGEM2-CC HadGEM2-ES
Institute for Numerical Mathematics (Russia)	INM-CM4
Institut Pierre-Simon Laplace (France)	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan)	MIROC-ESM MIROC-ESM-CHEM MIROC5
Max Planck Institute for Meteorology (Germany)	MPI-ESM-LR MPI-ESM-MR MPI-ESM-P
Meteorological Research Institute (Japan)	MRI-CGCM3
Norwegian Climate Centre (Norway)	NorESM1-M NorESM1-ME

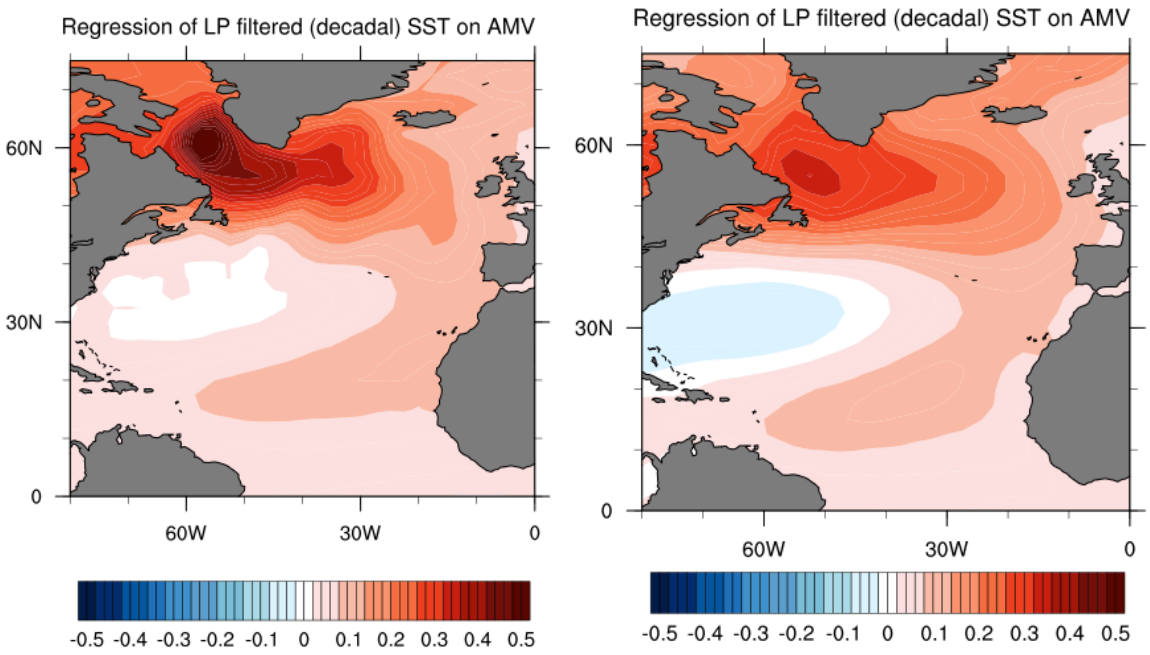

Figure S1: Regression of SST on low-pass filtered AMO index for (left panel) Multi-model mean of CMIP3 pre-industrial control fully coupled models, and (right panel) Multi-model mean of CMIP3 pre-industrial control slab-ocean models. Values are of K, per unit standard deviation of the low-pass filtered AMO index. The AMO index is filtered with a 10-year low-pass Lanczos filter.

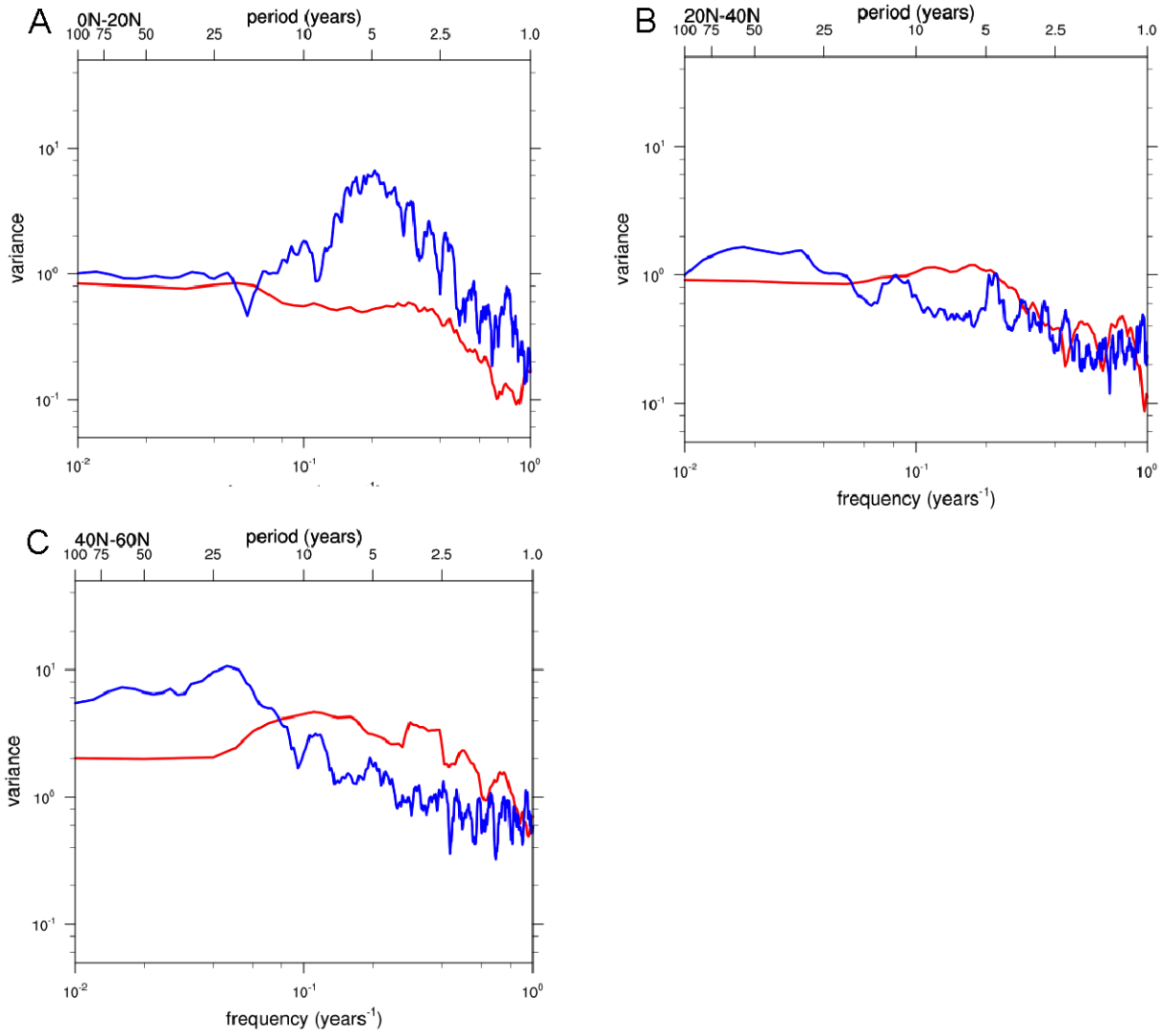

Figure S2: Power spectra of North Atlantic SST (0º-80ºW) from the GFDL_CM2_1 model in different latitude bands (A) 0º-20ºN; (B) 20ºN-40ºN; (C) 40ºN-60ºN. The blue lines are from the 500-year pre-industrial simulation with the fully coupled model, and the red lines are from the 100-year pre-industrial slab-ocean version of the model.

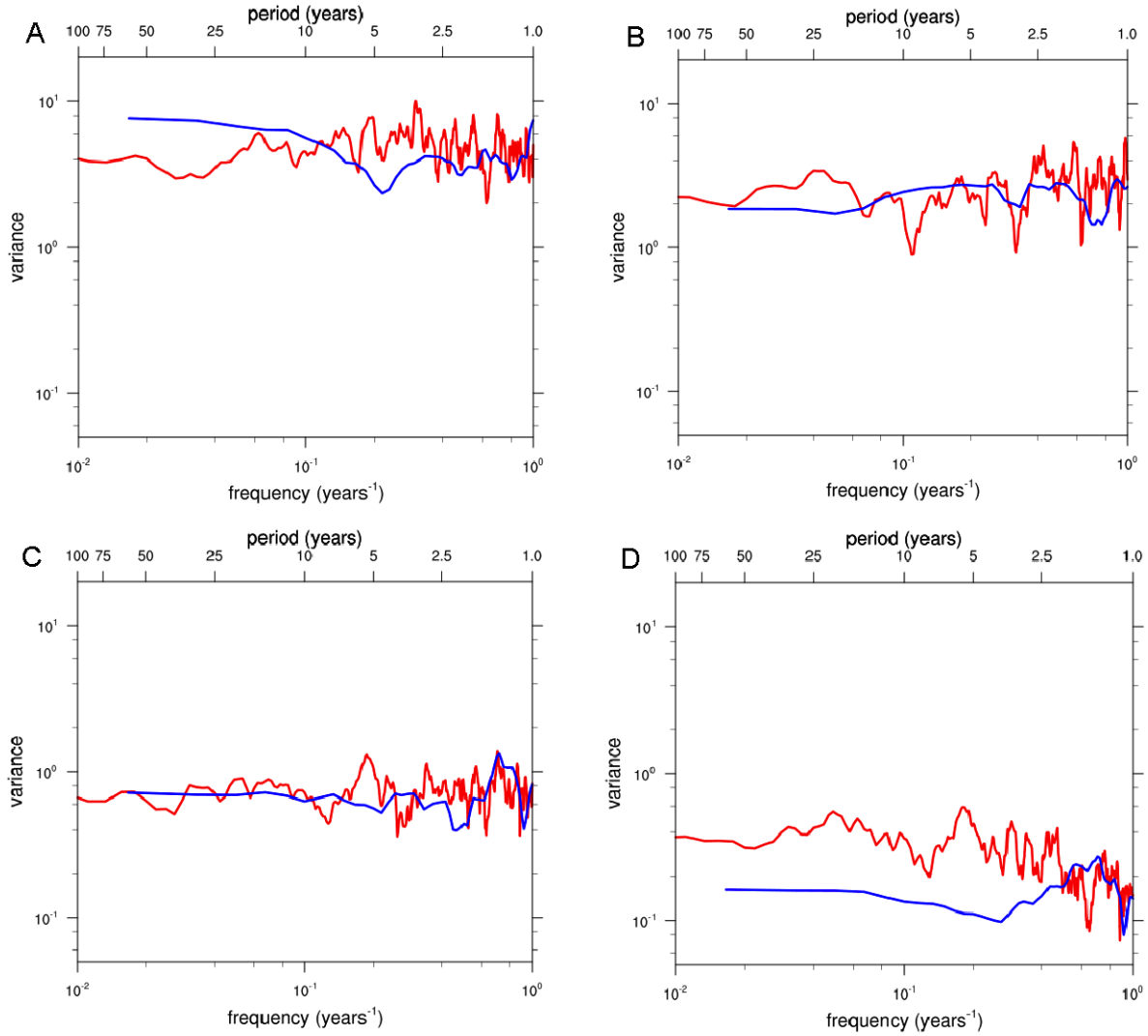

Figure S3: Power spectra of the (A) zonal and (B) meridional surface wind in the mid-latitudes over the ocean (40ºN-60ºN, 50ºW-10ºW); (C) zonal and (D) meridional surface wind in the Tropics over the ocean (10ºN-30ºN, 80ºW-15ºW) in (blue) CAM4-sstClim and (red) CAM4-slab.

REFERENCES AND NOTES

1. D. B. Enfield, A. M. Mestas-Nunez, P. J. Trimble, The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett.* **28**, 2077–2080 (2001). doi:10.1029/2000GL012745

2. R. T. Sutton, D. L. R. Hodson, Atlantic Ocean forcing of North American and European summer climate. *Science* **309**, 115–118 (2005). Medline doi:10.1126/science.1109496

3. J. R. Knight, C. K. Folland, A. A. Scaife, Climate impacts of the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.* **33**, L17706 (2006). doi:10.1029/2006GL026242

4. V. A. Semenov, M. Latif, D. Dommenget, N. S. Keenlyside, A. Strehz, T. Martin, W. Park, The impact of North Atlantic-Arctic multidecadal variability on Northern Hemisphere surface air temperature. *J. Clim.* **23**, 5668–5677 (2010). doi:10.1175/2010JCLI3347.1

5. R. Zhang, T. L. Delworth, Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes. *Geophys. Res. Lett.* **33**, L17712 (2006). doi:10.1029/2006GL026267

6. R. A. Kerr, Atlantic climate pacemaker for millennia past, decades hence? *Science* **309**, 41–43 (2005). 10.1126/science.309.5731.41 Medline doi:10.1126/science.309.5731.41

7. T. Delworth, S. Manabe, R. J. Stouffer, Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model. *J. Clim.* **6**, 1993–2011 (1993). doi:10.1175/1520-0442(1993)006<1993:IVOTTC>2.0.CO;2

8. M. Latif, E. Roeckner, M. Botzet, E. Esch, H. Haak, S. Hagemann, J. Jungclaus, S. Legutke, S. Marsland, U. Mikolajewicz, J. Mitchell, Reconstructing, monitoring, and predicting multidecadal-scale changes in the North Atlantic thermohaline circulation with sea surface temperature. *J. Clim.* **17**, 1605–1614 (2004). doi:10.1175/1520-0442(2004)017<1605:RMAPMC>2.0.CO;2

9. T. L. Delworth, M. E. Mann, Observed and simulated multidecadal variability in the Northern Hemisphere. *Clim. Dyn.* **16**, 661–676 (2000). doi:10.1007/s003820000075

10. J. R. Knight, R. J. Allan, C. K. Folland, M. Vellinga, M. E. Mann, A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.* **32**, L20708 (2005).

11. C. Z. Wang, L. P. Zhang, Multidecadal ocean temperature and salinity variability in the tropical North Atlantic: Linking with the AMO, AMOC, and subtropical cell. *J. Clim.* **26**, 6137–6162 (2013). doi:10.1175/JCLI-D-12-00721.1

12. J. Ba, N. S. Keenlyside, M. Latif, W. Park, H. Ding, K. Lohmann, J. Mignot, M. Menary, O. H. Otterå, B. Wouters, D. Salas y Melia, A. Oka, A. Bellucci, E. Volodin, A multi-model comparison of Atlantic multidecadal variability. *Clim. Dyn.* **43**, 2333–2348 (2014). doi:10.1007/s00382-014-2056-1

13. R. Zhang, T. L. Delworth, Simulated tropical response to a substantial weakening of the Atlantic thermohaline circulation. *J. Clim.* **18**, 1853–1860 (2005). doi:10.1175/JCLI3460.1

14. N. F. Tandon, P. J. Kushnir, Does external forcing interfere with the AMOC's influence on North Atlantic sea surface temperature? *J. Clim.* **28**, 6309–6323 (2015). doi:10.1175/JCLI-D-14-00664.1

15. M. E. Mann, K. A. Emanuel, Atlantic hurricane trends linked to climate change. *Eos* **87**, 233, 238, 241 (2006).

16. B. B. Booth, N. J. Dunstone, P. R. Halloran, T. Andrews, N. Bellouin, Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability. *Nature* **484**, 228–232 (2012). Medline doi:10.1038/nature10946

17. R. Zhang, T. L. Delworth, R. Sutton, D. L. R. Hodson, K. W. Dixon, I. M. Held, Y. Kushnir, J. Marshall, Y. Ming, R. Msadek, J. Robson, A. J. Rosati, M. F. Ting, G. A. Vecchi, Have aerosols caused the observed Atlantic multidecadal variability? *J. Atmos. Sci.* **70**, 1135–1144 (2013). doi:10.1175/JAS-D-12-0331.1

18. B. Stevens, Rethinking the lower bound on aerosol radiative forcing. *J. Clim*. (2015), http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00656.1.

19. M. Klöwer, M. Latif, H. Ding, R. J. Greatbatch, W. Park, Atlantic meridional overturning circulation and the prediction of North Atlantic sea surface temperature. *Earth Planet. Sci. Lett.* **406**, 1–6 (2014). doi:10.1016/j.epsl.2014.09.001

20. C. Marini, C. Frankignoul, An attempt to deconstruct the Atlantic Multidecadal Oscillation. *Clim. Dyn.* **43**, 607–625 (2014). doi:10.1007/s00382-013-1852-3

21. D. B. Enfield, D. A. Mayer, Tropical Atlantic sea surface temperature variability and its relation to El Niño Southern Oscillation. *J. Geophys. Res.* **102**, 929–945 (1997).

22. I. M. Held, in *Large-Scale Dynamical Processes in the Atmosphere*, B. J. Hoskins, R. F. Pearce, Eds. (Academic Press, New York, 1983), pp. 127–169.

23. R. Saravanan, Atmospheric low-frequency variability and its relationship to midlatitude SST variability: Studies using the NCAR Climate System Model*. *J. Clim.* **11**, 1386–1404 (1998). doi:10.1175/1520-0442(1998)011<1386:ALFVAI>2.0.CO;2

24. C. Wunsch, The interpretation of short climate records, with comments on the North Atlantic and Southern Oscillations. *Bull. Am. Meteorol. Soc.* **80**, 245–255 (1999). doi:10.1175/1520-0477(1999)080<0245:TIOSCR>2.0.CO;2

25. R. Seager, Y. Kushnir, M. Visbeck, N. Naik, J. Miller, G. Krahmann, H. Cullen, Causes of Atlantic Ocean climate variability between 1958 and 1998. *J. Clim.* **13**, 2845–2862 (2000). doi:10.1175/1520-0442(2000)013<2845:COAOCV>2.0.CO;2

26. S. P. Xie, A dynamic ocean-atmosphere model of the tropical Atlantic decadal variability. *J. Clim.* **12**, 64–70 (1999). doi:10.1175/1520-0442-12.1.64

27. J. C. H. Chiang, D. J. Vimont, Analogous Pacific and Atlantic meridional modes of tropical atmosphere-ocean variability. *J. Clim.* **17**, 4143–4158 (2004). doi:10.1175/JCLI4953.1

28. A. T. Evan, R. J. Allen, R. Bennartz, D. J. Vimont, The modification of sea surface temperature anomaly linear damping time scales by stratocumulus clouds. *J. Clim.* **26**, 3619–3630 (2013). doi:10.1175/JCLI-D-12-00370.1

29. X. Qu, A. Hall, S. A. Klein, P. M. Caldwell, On the spread of changes in marine low cloud cover in climate model simulations of the 21st century. *Clim. Dyn.* **42**, 2603–2626 (2014).

30. M. Brueck, L. Nuijens, B. Stevens, On the seasonal and synoptic time-scale variability of the North Atlantic trade wind region and its low-level clouds. *J. Atmos. Sci*. **72**, 1428–1446 (2015).

31. K. Bellomo, A. Clement, T. Mauritsen, G. Rädel, B. Stevens, the influence of cloud feedbacks on equatorial Atlantic variability. *J. Clim.* **28**, 2725–2744 (2015). doi:10.1175/JCLI-D-14-00495.1

32. T. L. Delworth, R. J. Greatbatch, *J. Clim*. **13**, 1481-1495 (2000).

33. M. Visbeck, H. Cullen, G. Krahmann, N. H. Naik, An ocean model's response to North Atlantic Oscillation-like wind forcing. *Geophys. Res. Lett.* **25**, 4521–4524 (1998). doi:10.1029/1998GL900162

34. G. D. McCarthy, I. D. Haigh, J. J. Hirschi, J. P. Grist, D. A. Smeed, Ocean impact on decadal Atlantic climate variability revealed by sea-level observations. *Nature* **521**, 508–510 (2015). Medline doi:10.1038/nature14491

35. P. Gent, G. Danabasoglu, L. J. Donner, M. M. Holland, E. C. Hunke, S. R. Jayne, D. M. Lawrence, R. B. Neale, P. J. Rasch, M. Vertenstein, P. H. Worley, Z.-L. Yang, M. Zhang, The Community Climate System Model version 4. *J. Clim.* **24**, 4973–4991 (2011). doi:10.1175/2011JCLI4083.1

36. B. Stevens, M. Giorgetta, M. Esch, T. Mauritsen, T. Crueger, S. Rast, M. Salzmann, H. Schmidt, J. Bader, K. Block, R. Brokopf, I. Fast, S. Kinne, L. Kornblueh, U. Lohmann, R. Pincus, T. Reichler, E. Roeckner, The atmospheric component of the MPI-M Earth system model: ECHAM6. *J. Adv. Model. Earth Syst.* **5**, 146–172 (2013). doi:10.1002/jame.20015

37. K. Bellomo, A. C. Clement, T. Mauritsen, G. Rädel, B. Stevens, Simulating the role of subtropical stratocumulus clouds in driving Pacific climate variability. *J. Clim.* **27**, 5119–5131 (2014). doi:10.1175/JCLI-D-13-00548.1

38. E. Kalnay, M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, A. Leetmaa, R. Reynolds, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, R. Jenne, D. Joseph, The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Am. Meteorol. Soc.* **77**, 437–471 (1996). doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

39. T. M. Smith, R. W. Reynolds, T. C. Peterson, J. Lawrimore, Improvements to NOAA's historical merged land–ocean surface temperature analysis (1880–2006). *J. Clim.* **21**, 2283–2296 (2008). doi:10.1175/2007JCLI2100.1

40. N. A. Rayner *et al*., Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**, 4407 (2003). doi:10.1029/2002JD002670

41. A. Kaplan, M. Cane, Y. Kushnir, A. Clement, M. Blumenthal, B. Rajagopalan, Analyses of global sea surface temperature 1856-1991. *J. Geophys. Res.* **103**, 18567–18589 (1998). doi:10.1029/97JC01736