The North Atlantic Oscillation as a driver of rapid climate change in the Northern Hemisphere

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Details on resampling used to generate the distributions in Figure 4

As described in the Methods section, we have five-member ensembles of simulations using the FLOR model that are forced by radiative forcing changes over the period 1951-2015 (this set of experiments is called FLOR_HIST). We have an additional five-member ensemble of simulations using the FLOR model that are forced by radiative forcing changes as well as the NAO surface heat flux anomalies (called FLOR_HIST+NAO) over 1951-2015.

For each season and each model simulation we calculate the number of North Atlantic tropical storms. To construct the black curve in Figure 4 we do the following: we use the five ensemble members from FLOR_HIST, and note that for the period 1965-1994 we have 150 realizations of the number of tropical storms in a season (5 ensemble members times 30 years). We call this population A. For the period 1995-2014 we have a total of 100 realizations (5 ensemble members times 20 years). We call this population B. We randomly select 30 members from population A and 20 members from population B. We calculate the percentage change in the mean number of tropical storms in population B versus population A, and define this as a single estimate of the percentage difference in tropical storm activity between the two periods. We repeat this process 10,000 times, and plot the histogram from these 10,000 samples as the black line in Figure 4. This is an estimate of the histogram of the percentage change in tropical storm activity between the two periods solely in response to radiative forcing changes.

We repeat this process using the FLOR_HIST+NAO experiments and plot the red curve. This is an estimate of the histogram of the percentage change in tropical storm activity between the two periods in response to both radiative forcing changes and the NAO flux forcing. The fact that the black curve is symmetric around zero indicates that this model simulates no change in tropical storm activity between these two periods for the case of only radiative forcing changes. The red curve is shifted to the right, indicating an increase of tropical storm activity after 1995 when the NAO heat flux forcing is taken into account.
Figure S1 Spatial pattern of the heat flux anomalies (W m⁻²) used as anomalous flux forcing in the HIST+NAO experiments. Regions with negative values indicate a flux of heat from the ocean to the atmosphere. The fluxes are derived from the ECMWF-Interim reanalysis, and are the fluxes over December-March that correspond to a positive one standard deviation anomaly of the North Atlantic Oscillation. The fluxes were applied over the North Atlantic from the Equator to 80°N, including the Greenland Sea and Barents Sea but not the interior Arctic. The fluxes were adjusted such that their areal integral is zero for the region over which they are applied. Therefore, this flux addition does not systematically add or subtract heat from the ocean.
**Figure S2** Schematic of some of the impacts of the North Atlantic Oscillation (NAO) on the ocean. A positive phase of the NAO has stronger westerly winds over the subpolar gyre, thereby extracting more heat from the Labrador Sea and subpolar gyre. This leads to increasing density of water in the Northwest Atlantic, thereby increasing the west-east density gradient across the North Atlantic and leading to a strengthening of the Atlantic Meridional Overturning Circulation (AMOC). The increased AMOC results in strengthened poleward heat transport in the North Atlantic extending into the Barents Sea and Arctic Ocean.
Figure S3 Spatial pattern of changes in sea ice extent, calculated as mean over the period 2000-2010 minus the mean over 1979-1993. Left column: Results using March data. Right column: Results using September data. Top row: Observations (obtained from National Snow and Ice Data Center, http://nsidc.org/data). Second row: Ensemble mean from three models (CM2.1, FLOR, CM3). Third row: Results using only CM2.1. Fourth row: Results using only FLOR. Fifth row: Results using only CM3.
Figure S4 Spatial pattern of the annual mean surface air temperature response to the NAO flux anomalies applied to the ocean. The temperature response is calculated as the multi-model mean surface air temperature in the HIST+NAO simulations minus the multi-model mean in the HIST simulations. The map is for the time-mean over 1996-2005. Areas without stippling are significant at the 95% level using a Students-t test.
Figure S5 Time series of the response of the vertical shear of the zonal wind over to NAO flux anomalies averaged over the main development region for tropical storms in the Atlantic (10°N-25°N, 70°W-20°W). The shear is computed as the differences in seasonal mean (July-October) zonal wind at 250 hPa minus 850 hPa. The time series plotted indicates the shear in the HIST+NAO simulations minus the shear in the HIST simulations. The black diamonds indicate the mean response from all three models, while the shaded bars denote the range of the ensemble mean response in the three models. A five point running mean was applied to the time series before plotting (so that data begins in 1953 and ends in 2013 due to end effects).
Figure S6 Differences in vertical shear of the zonal wind. The shear is computed as the seasonal mean (July-October) zonal wind at 250 hPa minus 850 hPa. Due to differing lengths of some reanalysis products, multiple products were used in (a) and (b). Stippling indicates statistical significance at the 95% level using a Student’s t test. (a) – (c) Results from reanalyses. (d) Shear computed from HIST simulations. (e) Shear from HIST+NAO simulations. (f) Difference in shear computed as HIST+NAO minus HIST, representing the influence of the NAO forcing on the shear differences between the two periods. Note the different values for the color shading in the left and right columns.
Figure S7  AMOC response (50°N) to NAO related flux anomalies. (a) Heat flux anomalies only. (b) Heat flux and wind stress anomalies. The flux anomalies are applied over the North Atlantic from the Equator to approximately 80°N, including the Greenland and Barents Sea, but excluding the Arctic Ocean. Constant seasonal anomalies were applied over the December through March period, with no anomalies applied the rest of the year.
**Figure S8** Predictions of AMOC anomalies (relative to 1990-2010 time-mean) using the GFDL CM2.1 (top) and FLOR (bottom) models. The various colored lines represent the ensemble mean of sets of decadal predictions initialized on January 1st from years 2011, 2012, 2013, 2014, 2015, and 2016. The values plotted indicate the anomaly of the maximum value of the AMOC streamfunction over the domain 20°N-60°N in the North Atlantic, and below 500m. The prediction models were initialized from observations and forced with changing radiative forcing. The consensus of the predictions is for an AMOC that is weaker than its’ mean from the 1990-2010 period.