North Atlantic Atmospheric Blocking and Atlantic Multidecadal Oscillation in CESM1 Large Ensemble Simulations

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ABSTRACT

Atmospheric blocking is an unusual weather phenomenon that is often associated with severe weather events such as heat waves, cold spells, and droughts. Improved understanding of the long-term variability of atmospheric blocking has important societal implication, but its mechanisms are not well understood. Multidecadal variability of winter (DJFM) atmospheric blocking in the North Atlantic, especially its relationship with multi-decadal oceanic variability represented by the Atlantic Multidecadal Oscillation (AMO), is examined using observational datasets and the Community Earth System Model version 1 Large Ensemble (CESM1LE) simulations. The CESM1LE has 30 ensemble members from 1920 to 2005 forced with the identical historical radiative forcing but slightly different initial conditions. Therefore, the internal climate variability in the 30 simulations do not necessarily exhibit identical temporal evolutions, while the externally driven variability due to the radiative forcing are likely to be coherent. The mean spatial patterns of the number of blocking days in the North Atlantic are examined in the 20th Century Reanalysis (20CR) and the 30 member CESM1LE simulations. In addition, the AMO index is examined in the Hadley Centre Sea Ice and Sea Surface Temperature data set version 1 (HadISST) and the CESM1LE. In the observations, the two primary maxima of atmospheric blocking occurrence are found over the Greenland and the British Isles. CESM1LE underestimates the mean number of blocking days in these two locations, but the time-scale of variability in these regions is comparable to that in the observations. CESM1LE also shows a reasonable AMO with similar amplitude and periodicity to the observations. In the observations, preliminary results show some correlation between the blocking in the North Atlantic and the AMO on decadal time-scales when the AMO leads the blocking by a few years. This suggests that atmospheric blocking and the associated extreme weather variability in the North Atlantic might be modulated by the multi-decadal oceanic variability associated with the AMO. In CESM1LE, the ensemble mean of AMO index and the number of blocking days show robust increasing and decreasing trends, respectively, which are likely driven by the anthropogenic radiative forcing.

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I. INTRODUCTION

Atmospheric blocking in the North Atlantic alters normal climates across Europe and Russia by shifting storm tracks. Typically associated with an anticyclone, the zonal wind pattern known as the jet stream deviates from its mean position and its westerly winds reroute north and south of the anticyclone. In addition, the normal meridional gradient of geopotential height is reversed (Fig. 1). This results in anomalous temperature and precipitation events, such as the 2010 Russian heat wave (Matsueda 2011) and cold winter extremes in west Europe (Sillmann et al. 2011). The severity of these extreme weather events and their increased frequency is a cause for concern; therefore, influences that may amplify or weaken the frequency of blocking in addition to better forecasting blocking is an ongoing scientific investigation.

One potential factor influencing blocking is the sea surface temperatures (SST). Research has been done on whether natural climate variations, anthropogenic influence, or a combination of both are causing the warming of sea surface temperatures (SST) in the North Atlantic (Ting et al. 2008). Using models and observations, it was found that the observed North Atlantic sea surface temperatures combine both the global warming forcing and a local multidecadal oscillation, most likely from internal variability (Ting et al. 2008). The Atlantic Multidecadal Oscillation (AMO), the natural variability of SST in the North Atlantic impacting regional climates across North America and the subtropics and tropics of the Northern Hemisphere (Trenberth and Shea 2005), potentially plays a significant role in the variability of blocking. This is speculated in Häkkinen et al. (2011), as the variability of blocking correlates with ocean surface temperatures and even significant Atlantic Ocean circulation changes; however, the cause and effect aspect is still unknown.

The ultimate goal of our research is to investigate the relationship blocking has with the ocean variability associated with the AMO on decadal time scales. To do so, we will eventually need a climate model to separate cause and effect between the blocking and AMO. As the first step, this paper assesses how well the Community Earth System Model 1 (CESM1) reproduces the observation in simulating the blocking and the AMO.

The models, datasets, and reanalysis products used for analysis are described in section 2. Results from the analysis are in section 3, and section 4 discusses the analysis of the blocking and AMO. Finally, conclusions from this project are in section 5.
II. METHOD AND DATASETS

1. Observational and Model Datasets

   a. 20th Century Reanalysis

      Reanalysis is a method to obtain the best estimate of the past state of the earth system for the past few decades to a century by combining a weather forecasting model and observational data for climate research. Using a forecast model with a fixed data assimilations system integrating historical observations into the system reanalysis produces a set of gridded variables varying in time in the atmosphere (and ocean in case of ocean analysis). Although the observational network is constantly changing with advances with technology, producing extraneous variability and trends in the system, reanalysis incorporates a myriad of observations that would be impossible for an individual to process and collect.

      The 20th Century Reanalysis (20CR) is an experimental ensemble of 56 realizations, using the NCEP Global Forecast System model. Unlike most reanalysis, only the surface pressure observations are assimilated into the model, and the observed monthly sea-surface temperature and sea-ice distributions are used as lower boundary conditions (Compo et al. 2011). The spatial resolution is 2-degrees latitude by 2-degrees longitude with output from 1871 to December of 2011 every six hours. The ensemble estimation of uncertainly makes it a well-rounded model; however, inconsistencies do occur with long-term trends (“The Climate Data Guide” 2013). The ensemble mean of 56 realizations is used for our analysis to reproduce the spatial patterns and time series of winter number of blocking days as in Häkkinen et al. (2011) Fig.2a and Fig.2b.

      20CR is available from:
      http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html

   b. Community Earth System Model

      The Community Earth System Model (CESM) is a fully coupled, global climate model that provides the state-of-the-art computer simulations of the Earth's past, present, and future climate states (NCAR CESM 2014). We used the CESM1 Large Ensemble experiment (CESM1LE), which is a 30 ensemble simulations with historical (observed) radiative forcing for 1920-2005, and RCP8.5 radiative forcing scenario for 2005-2080. In this paper, CESM1LE is used to calculate the spatial pattern of the North Atlantic blocking and AMO index time series with and without global warming forcing.

      More information about the CESM1LE is available from:
      https://wiki.ucar.edu/display/ccsm/CESM+Large+Ensemble+Planning+Page

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c. Hadley Centre Global Sea Ice and Sea Surface Temperature Version 1

The Hadley Centre Global Sea Ice and Sea Surface Temperature Version 1 (HadISST) is a combination of monthly globally complete fields of SST and sea ice concentrations, interpolated onto a regular grid. The horizontal resolution is 1-degree, and data is available from 1871-present (Rayner et al. 2003). The HadISST is one of the most often used global long-term SST dataset; however, its spatial resolution is not fine enough to see small oceanic features, e.g. eddies and fronts (“The Climate Data Guide” 2013). In this study, HadISST is used to compute the mean, standard deviation, and weighted area average sea surface temperatures in the North Atlantic Sector (0-60N, 0-80W), to calculate the AMO index time series based on Trenberth and Shea (2006).

The data set is available from:
http://www.hadobs.org/

2. Analysis Methods

a. Number of Mean Blocking Days

Atmospheric blocking statistics over the North Atlantic are calculated using the daily 500-geopotential height from the 20CR and each of the 30 members of CESM1LE. Geopotential height approximates the actual height of pressure above mean sea level. Typically, geopotential heights are higher in the tropics and lower in the poles. However, when a blocking pattern occurs in the North Atlantic, the geopotential height gradient at 500hPa to the south of the blocking center becomes abnormally positive, while the geopotential height gradient to the north becomes abnormally negative. This is called a meridional difference height inversion and is the criterion used to determine blocking in a grid cell. Calculating the meridional different height inversion, we used an algorithm used in Scherrer et al. (2006). “Meridional geopotential height gradients south (\(\nabla_s Z\)) and north (\(\nabla_n Z\)) are calculated for each grid point…with \(\phi = 2.5^\circ\) intervals as follows:

\[
\begin{align*}
(1) \ \nabla_s Z(\phi) &= Z(\phi) - Z(\phi - \phi) \\
(2) \ \nabla_n Z(\phi) &= Z(\phi + \phi) - Z(\phi)
\end{align*}
\]

A grid point is treated as a blocked situation, if the two following gradient criteria are fulfilled:

\[
(3) \ \nabla_s Z(\phi) > 0 \text{ and } \nabla_n Z(\phi) < -10 \text{ gpm/deg lat}
\]

(Scherrer et al. 2006).

As for the meridional difference height, inversion for each day within each grid cell is calculated using the daily 500hPa height data. The blocking events are detected at each grid cell, with the criteria that if the inversion at a grid cell occurs for five consecutive days, then the numbers of blocking days per grid cell are counted based on the method proposed by Scherrer et al. (2006) and used in Häkkinen et al. (2011). The spatial mean distribution of December-March (DJFM) blocking days in the North Atlantic (35°N-75°N, 0°W-0°E) in addition to the mean
DJFM blocking days for each decade as well as the entire period (1901-2010) are generated following Häkkinen et al (2011). A time series of the number of blocking days in DJFM in the North Atlantic sector (45°N-75°N, 70°W-10°E) is also generated following the Häkkinen et al. (2011) Fig. 2b.

b. **AMO Index**

The AMO Index is calculated using the HadISST dataset and each of the 30 members of CESM1LE as the yearly area-weighted average SST in the North Atlantic (0-60°N, 0-80°W for HadISST and 10°E-80°W for CESM1LE). Next, the SST global yearly area-weighted with a boundary of 60°N-60°S is subtracted from the average SST North Atlantic yearly weighted average, in order to remove the global warming component and separate the AMO solely due to natural variability (Trenberth and Shea 2006). In addition, 10-year smoothing is applied to both AMO time series, i.e. before and after removing the global warming component, to emphasize the multidecadal variability.

III. RESULTS/DISCUSSION

1. **North Atlantic Atmospheric Blocking**

Fig. 2. Winter (DJFM) number of blocking days averaged for 1920-2005 from the 20th Century Reanalysis (20CR, top) and one the 30 ensemble members of the Community Earth System Model Large Ensemble (CESM1LE, bottom). The red box indicates the region for the blocking day time series calculation.
The CESM1LE underestimates the mean number of blocking days for the most of the North Atlantic Sector versus the observation (Fig. 2 and Fig. 3). The CESM1LE ensemble member 13 (which is a typical case for all 30-ensemble members) does not display enhanced blocking near Greenland and Iceland. However, the member does well in the overall pattern of enhanced blocking area from the mid-Atlantic through the U.K. and Scandinavia, and to northern Siberia. Also, in comparison with the top plot in Fig. 1, a regeneration of Fig. S3 in Häkkinen et al. (2011), the CESM1LE ensemble member 13 has a high bias between 35°-45°N, longitude. Overall, all ensemble members have a high bias in the number of blocking days in the Eastern Atlantic, with the maximum that is shifted southward compared to the observations. (Fig. 2). Few members show blocking in Greenland and Iceland, but minimal compared to the observations. Finally, the ensemble member does a very good job in reproducing observed patterns of the number of blocking days in the North Pacific.
The temporal variability of the number of winter blocking days is assessed based on the time series constructed over (45°N-75°N, 70°W-10°E) (red box in Fig. 3 top panel). CESM1LE underestimates the number of blocking days throughout the entire time series versus the observation (Fig. 4) as can be expected from the mean spatial patterns. The mean blocking days in the observation is approximately 69 days, whereas nearly half of the CESM1LE members have an average in 51-53 days, with a range from 49-57 days (Fig. 5). However, the standard deviation, or variability of the mean, is comparable with the observation. The standard deviation of the observation is 16.5 days. 10 members of CESM1LE have a standard deviation from 16-17...
days, and 9 members with a standard deviation of 15-16 days. The standard deviation range is 14-19 days; therefore, the model does a well job of variability from the mean in comparison with the observation (Fig. 5). The multidecadal phase evolution of each member versus the observation are different, which is expected as each member has different internal variability by design. However, each CESM1LE ensemble member shows a dominant time scale in the variability of the number of blocking days similar to that from the observation, i.e. decadal to multi-decadal variability. Finally, CESM1LE shows a decreasing trend over time with the number of blocking days for the majority of the ensemble members as well as the composite mean of linear trends from all 30 members (Fig. 6 and 7). More than one-third of the simulations have a decreasing trend from -5 to -10 days per 100 years (Fig 6). In addition, more than two-

**Fig. 5** CESM1LE mean (left) and standard deviation (right) of the number of blocking days for 1920-2005. The maroon star on the mean plot indicates the mean value from the 20CR, 69 days. The maroon star on the standard deviation plot indicates the standard deviation from 20CR, 16.482 days.

**Fig. 6** The linear trend histogram of the number of blocking days per 100 years for all 30 ensemble members of CESM1LE. The maroon star indicates the linear trend from 20CR.
thirds of the simulations had a decreasing trend ranging from 0 to -25 days per 100 years. This could be indicative of the common response to the external forcing across all 30 ensemble members. The observation also showed a decreasing trend of about 7 days from 1920-2005; however, when the time period is changed, for example, 1900-2010, the linear trend drastically changed. This means that the linear trend is sensitive to the time frame of the observation, because of the multidecadal phases associated with blocking.

2. AMO Index

a. Before removing the Global Warming Forcing

The AMO time series based on HadISST shows multidecadal variability, i.e. in some decades, such as the 1920s to the 1960s and after 1990s exhibiting a positive phase, whereas other decades such as the 1960s to the 1990s showing a negative phase (Fig. 8). One simulation out of the 30 simulations, which is chosen subjectively as the one where the AMO best compares with the observation, does show positive and negative phases on a decadal time-scale as in observation. Most simulations indeed show a similar but slightly shorter time-scale than the observation. In addition, the year-by-year variability for CESM1LE is much greater than the observation. This is evident in the standard deviation of the AMO index as the range of those for CESM1LE is .19-.29 days, with two-thirds of the simulations in .23-.27 days (Fig. 9). The observation however had a standard deviation of approximately .18 days. Finally, both the
observation and the simulations show an increasing trend of AMO. Given the time frame, the observation had an increasing trend of about .26°C per 100 years. (Fig. 9). All simulations had increasing trends, with most of them ranging from .20-.50°C per 100 years (Fig. 9 and 10).

**Fig. 8** The HADISST (left) and CESM1 #08 (right) AMO with global forcing indexes from 1920-2005. The blue jagged line is the raw AMO data. The red line is the 10-year best smooth curve.

**Fig. 9** The standard deviation (left) and linear trend (right) of the AMO using HadISST and the CESM1LE. The navy star on the linear trend indicates where the HadISST is in reference to the CESM1LE.
b. After removing Global Warming Forcing

After removing global average SST from the observation and model AMO in order to see its natural variability, both the model and observation show an increasing trend after 1990 (Fig.11). However, this particular simulation has a higher increase during this time frame than the observation- potentially caused by the configurations associated with the model from outside forcing. Most simulations do show this increase after 1990; however, the overall trend from the simulations is not as much of an increase as shown with the global forcing. More than 1/3 of the simulations were at or near neutral (-0.5 to 0.5 degrees Celsius per 100 years) (Fig.12). With the given time frame, the observation had a decreasing trend within -.15 to -.25 degrees Celsius per 100 years. Finally, the simulations have a higher range from the mean than the observation, as shown in the standard deviation. More than ½ of the simulations had a standard deviation of plus or minus .20 to .22 degrees Celsius. The observation had a standard deviation of .177. However, the difference in standard deviation from the model and the observation is smaller than with the standard deviation of the global forcing.

Fig.10 The overall composite AMO index of the 30 members in the CESM1LE (black line) from 1920-2005. The dotted blue lines are the standard error range.
Fig 11. The AMO Index without global forcing from the observation (left) and CESM1 #08 (right). Blue line is the raw data, and the red line is the 10 year smoothing.

Fig 12. Histograms of the simulation frequency of standard deviation (left) and linear trend (right) of the AMO without global forcing index. The observation is also included with its own corresponding color.
c. Relationship of AMO and Blocking

Qualitatively, a positive correlation exists between the AMO and Blocking (Fig. 13), regenerated from Häkkinen et al. (2011). A positive phase relating to warmer ocean waters occurs with higher frequency in blocking, as shown from 1920 to 1960. A negative phase, or cooler sea surface temperatures occurs with lower frequency in blocking, as shown from 1960 to 2000. However, there does appear to be a time lag, as a change with the AMO occurs first before a response from blocking several years later. Quantitatively, the correlation between the AMO and Blocking with no shift in time lag was .2271 and .3545, with and without global forcing, respectively. When shifting the data to have the AMO lead, the highest correlation came after a six-year time lag, where the correlation was .5248 and .5652 with and without global forcing, respectively.

Fig. 13 The AMO and blocking day relationship time series from 20CR. The blue line indicates yearly mean number of blocking days. The solid black line is the 10 smoothing of the number of blocking days. The dashed pink line is the AMO index with global forcing. The solid red line is the AMO index without global forcing.
CONCLUSIONS

CESM1LE underestimates blocking in the North Atlantic Sector with a southern maximum in the Eastern Atlantic and little to no blocking in Greenland and Iceland. However, its overall scope of blocking is similar to that of the observation, in addition to doing a good job of blocking in the Northern Pacific. In addition, the standard deviation of blocking in the model is comparable with the observation. Most of the simulations have a decreasing trend with the yearly mean number of blocking days, a result potentially caused by the external forcing associated with the model. CESM1LE has higher standard deviations in the AMO with and without global forcing in comparison to the observation. Both the model and observation show an increasing trend in the AMO with global forcing, but differ without global forcing, as the model shows an increase, and the observation shows a decrease. A qualitative and quantitative correlation exists between the AMO and blocking by the observation with a time lag as AMO leads blocking. In general, the model does show similar time-scale variability with the AMO and blocking.

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