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Atlantic meridional overturning circulation and the prediction of North Atlantic sea surface temperature

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ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC), a major current system in the Atlantic Ocean, is thought to be an important driver of climate variability, both regionally and globally and on a large range of time scales from decadal to centennial and even longer. Measurements to monitor the AMOC strength have only started in 2004, which is too short to investigate its link to long-term climate variability. Here the surface heat flux-driven part of the AMOC during 1900–2010 is reconstructed from the history of the North Atlantic Oscillation, the most energetic mode of internal atmospheric variability in the Atlantic sector. The decadal variations of the AMOC obtained in that way are shown to precede the observed decadal variations in basin-wide North Atlantic sea surface temperature (SST), known as the Atlantic Multidecadal Oscillation (AMO) which strongly impacts societally important quantities such as Atlantic hurricane activity and Sahel rainfall. The future evolution of the AMO is forecast using the AMOC reconstructed up to 2010. The present warm phase of the AMO is predicted to continue until the end of the next decade, but with a negative tendency.

1. Introduction

The AMOC (Dickson and Brown, 1994; Ganachaud and Wunsch, 2003; Srokoz et al., 2012) is characterized by a northward flow of warm, salty water in the upper layers of the Atlantic, and a southward return flow of colder water in the deep Atlantic. It transports a substantial amount of heat from the tropics and Southern Hemisphere toward the North Atlantic, where the heat is then transferred to the atmosphere. The mild climate of Northern Europe is a consequence of this heat supply. Changes in the AMOC are thought to have a profound impact on many aspects of the global climate system. For example, the AMO, a coherent pattern of multidecadal variability in surface temperature centered on the North Atlantic Ocean, is linked to the AMOC in climate models (Knight et al., 2005; Zhang and Delworth, 2006). Observed decadal variability in the air–sea heat exchange over the North Atlantic (Gulev et al., 2013), continental summertime climate of both North America and Western Europe (Sutton and Hodson, 2005), Atlantic hurricane activity, Sahel rainfall or the Indian summer monsoon (Zhang and Delworth, 2006) have been also hypothesized to be related to the AMOC.

The cause of AMOC variability at time scales of decadal and longer is poorly understood. Measurements to estimate the AMOC strength at 26.5°N have only started in 2004, consisting of three elements: transport through the Florida Straits, flow induced by the interaction between wind and the ocean surface (Ekman transport), and transport related to the difference in sea water density between the American and African continents (Kanzow et al., 2007; Willis, 2010; Send et al., 2011; Fischer et al., 2010). Longer reconstructions covering several decades from hydrographic data (Bryden et al., 2005) or Atlantic SST (Latif et al., 2004, 2006) are subject to large uncertainties. A way out of this dilemma could be to use climate models, but care is required because the models suffer from large biases and suggest different competing mechanisms for the generation of AMOC variability (Latif and Keenlyside, 2011; Liu, 2012). Here we propose an innovative method to reconstruct the heat flux-forced AMOC variability during 1900–2010. The approach (Supplement) is an extension of a previously employed method (Eden and Jung, 2001) based on the variability of the North Atlantic Oscillation (NAO) (Hurrell, 1995), a large-scale seesaw in atmospheric mass between the Azores high and the Icelandic low. Variations of the NAO are associated with changes in the air–sea heat exchange over the subpolar North Atlantic. A persistent high NAO phase, for example, favors deep convection in the Labrador Sea which is followed by an anomalously strong AMOC in ocean general circulation models (OGCMs) (e.g.,

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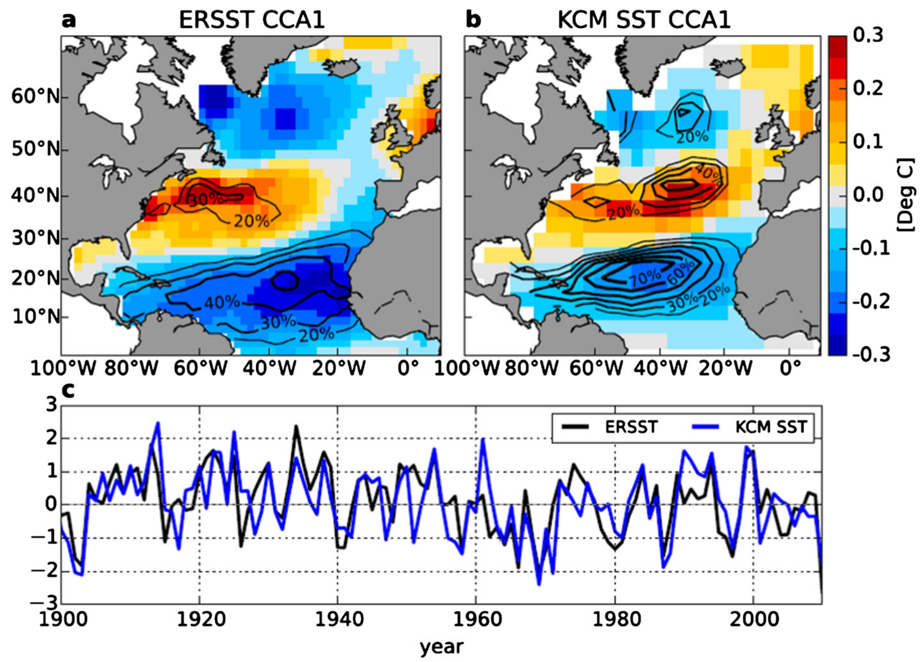

Fig. 1. The leading CCA mode between model and observed SST 1865–2010 at zero lag. (a) "Observed" pattern, (b) model pattern, and (c) time series associated with the two patterns. Color shading in (a) and (b) denote the loadings, contours the explained variances with respect to annual means. The data were linearly de-trended prior to the analysis. The time series are dimensionless.

Eden and Jung, 2001; Alvarez-Garcia et al., 2008). The power spectrum of the NAO index is almost white, so that a stochastic scenario (Hasselmann, 1976; Delworth and Greatbatch, 2000) may apply, in which the low-frequency portion of the NAO variability drives low-frequency variability of the AMOC. This has been supported by forcing an OGCM with an NAO-related surface heat flux anomaly pattern exhibiting a "white noise" time evolution (Mecking et al., 2014).

2. Methodology of AMOC reconstruction

We apply over the North Atlantic the monthly surface heat flux anomalies reconstructed from the observed NAO index 1865–2010 to the Kiel Climate Model (KCM, Park et al., 2009; Supplement) and note that the KCM simulates internal variability consistent with the aforementioned stochastic scenario (Park and Latif, 2010). The advantage of applying the heat flux anomalies to a coupled model is that ocean–atmosphere feedbacks are largely retained in a consistent manner, which is not the case in uncoupled (forced) OGCM simulations. Further, the use of anomalies avoids introducing drift to the coupled model. The drift problem, which is due to model bias and is particularly strong in the North Atlantic, is a major issue in climate forecasting and hinders us from exploiting the full predictability potential that may exist in the climate system. The experiment with the coupled model was repeated five times with different initial conditions (Supplement). A measure of the forced response is the ensemble mean and only that will be used in the subsequent analyses. Finally, only annual means were used and all data linearly de-trended.

The model has some skill at simulating observed SSTs in the North Atlantic. Canonical Correlation Analysis (CCA, Barnett and Preisendorfer, 1987; Supplement) was applied to compare the simulated with the observed North Atlantic SSTs (Fig. 1). CCA finds those patterns from two datasets whose time evolutions are most strongly correlated. The canonical correlation of the leading CCA mode (CCA1) amounts to 0.71. Both CCA1 patterns (Fig. 1a, b) are characterized by a tripolar SST anomaly structure typical of that observed during a positive NAO phase, reminiscent of the spatial structure of the turbulent latent and sensible heat flux anomalies contributing by far the largest contributions to the total heat flux forcing (Fig. S1). The two CCA1 time series (Fig. 1c) are dominated by interannual variability but also depict significant decadal variability. The variances explained locally by CCA1 are relatively high in the subtropics and midlatitudes, but much smaller in the subpolar North Atlantic, especially in the observations.

A similar forcing strategy, but using observed wind stress anomalies globally, was successfully applied to the KCM (Ding et al., 2013) to simulate and predict variability associated with the Pacific Decadal Oscillation (Mantua et al., 1997) which is the leading mode of SST variability in the North Pacific. In that ensemble experiment, neither significant decadal AMOC variability nor skill in hindcasting North Atlantic SST anomalies was attained, with the exception of the Labrador and Irminger Seas (Fig. S2) suggesting that wind stress forcing cannot be neglected in these regions. Nevertheless, the above results demonstrate that the methodology of forcing the coupled model only by the NAO-related heat fluxes has some potential to hindcast observed SST anomalies in large regions of the North Atlantic. Our strategy can be regarded as a null hypothesis for the generation of North Atlantic SST variability.

3. AMOC reconstruction and its link to observed SST

An AMOC index, defined as the ensemble-mean overturning streamfunction anomaly at 48°N and 1500 m, depicts pronounced decadal variability (Fig. S3). The most prominent signal in the AMOC index is the slow decline from the 1920s to the 1970s and the increase thereafter, which is consistent with measurements of the thickness of the Labrador Sea density layer (Curry et al., 1998); a proxy for variations in deep convection which, in turn, drives variability in the AMOC in many climate models. To relate the model-based reconstructed AMOC during 1900–2010 to the observed SSTs in the North Atlantic (Smith et al., 2008), CCA was performed to find the leading modes of co-variability between the AMOC, as expressed by the overturning streamfunction, and the observed North Atlantic SST anomalies. As the NAO and North Atlantic SSTs are closely linked (e.g., Alvarez-Garcia et al., 2008), CCA