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

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A B S T R A C T

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.

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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.,
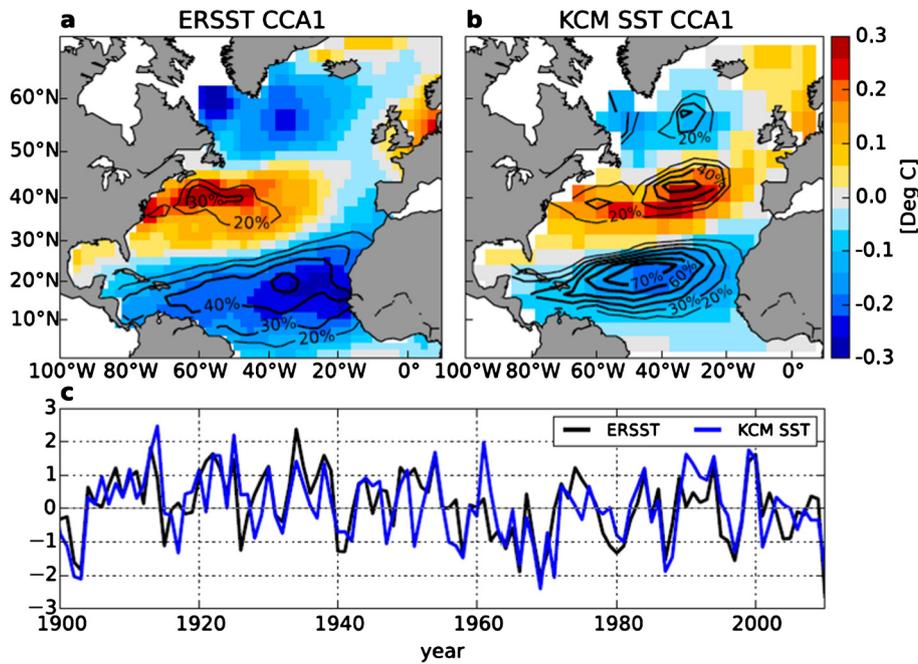
Fig. 1. The leading CCA mode between model and observed SST 1865–2010 at zero lag. (a) "Observed" pattern, (b) model pattern, and (c) time series associated with the two patterns. Color shading in (a) and (b) denote the loadings, contours the explained variances with respect to annual means. The data 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
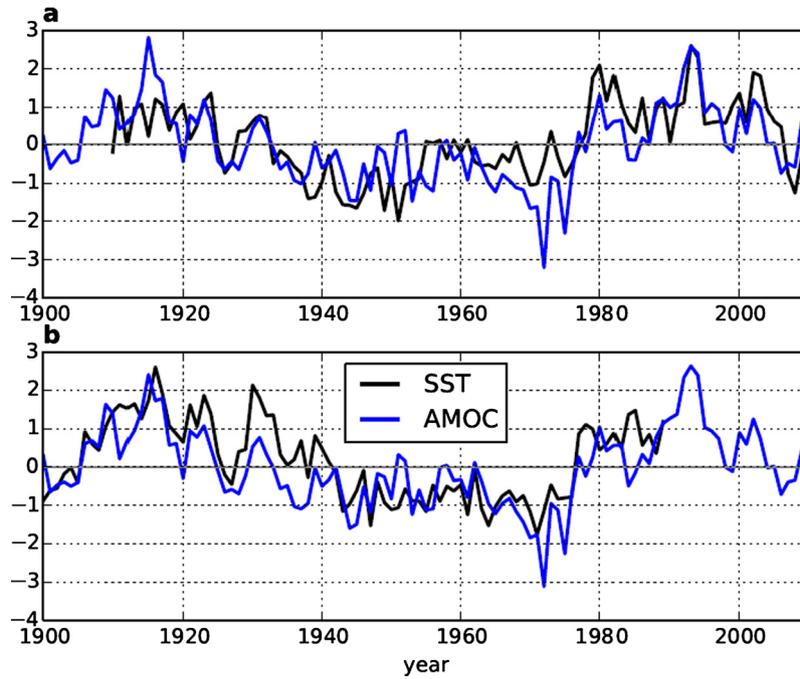
Fig. 2. Time series associated with the leading CCA modes. (a) The time series obtained from the CCA when the observed North Atlantic SSTs lead the AMOC (overturning streamfunction) by 10 years (CCA_{-10}). (b) The time series obtained from the CCA when the AMOC leads the observed North Atlantic SSTs by 21 years (CCA_{21}). The time has been adjusted in both panels to account for the time lag. The CCAs were performed on annual means and the data were linearly de-trended prior to the analysis. The time series are dimensionless.
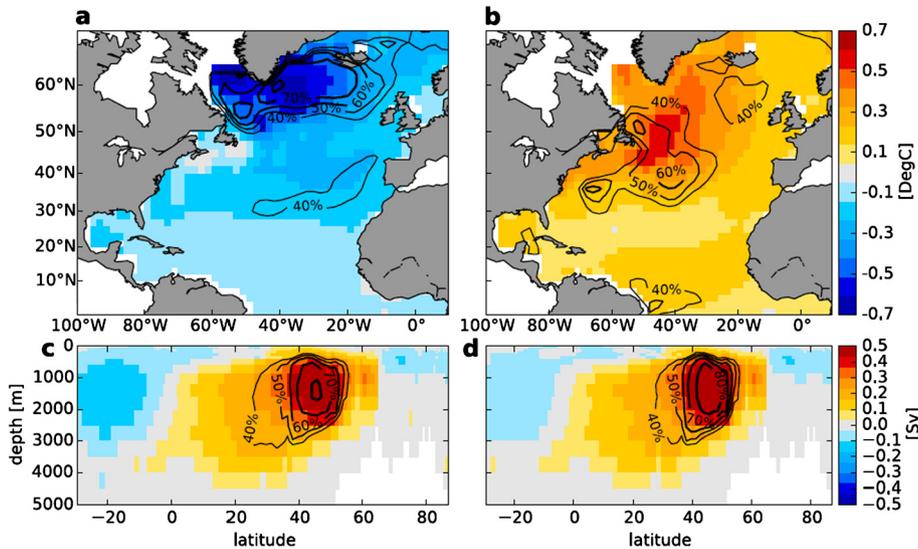

Fig. 3. (a, c) Anomalous North Atlantic SST (°C) and overturning streamfunction (Sv), when the observed North Atlantic SSTs lead the AMOC by 10 years (CCA_{-10}). (b, d) Anomalous North Atlantic SST (°C) and overturning streamfunction (Sv), when the AMOC leads the observed North Atlantic SSTs by 21 years (CCA_{21}). The locally explained variances are shown by contours and are statistically significant at the 95% level where they exceed 40%. To assess the statistical significance the number of effective degrees of freedom was used, which accounts for the autocorrelation in the time series. The strong negative SST anomaly in the subpolar North Atlantic in (a) is highly significant with explained variances up to 80%. In (b) the explained variances are particularly high along the path of the North Atlantic Current and in the Caribbean, with values of 50% and even above in selected regions. The overturning anomalies in panels (c) and (d) exhibit the highest explained variances (w.r.t. to annual means) in the midlatitudes and subtropics down to about 3000 m.

was performed with different time lags to distinguish forcing and response (Fig. S4). Two time lag-ranges stick out: one, when the observed SSTs lead the AMOC by about a decade, and the other when the AMOC leads the observed SSTs by about two decades. This 30-yr difference is consistent with the observed multidecadal timescale of the AMO (Knight et al., 2005), as will be shown below.

When the observed North Atlantic SST anomalies lead the model overturning anomalies by a decade (CCA_{-10}), the canonical correlation amounts to 0.66 (Fig. S4). The two CCA_{-10} time series (Fig. 2a) are dominated by multidecadal variability with

higher-frequency interannual variability superimposed, where the multidecadal variability is similar to that seen in the AMOC index at 48°N (Fig. S3). This mode captures to some extent the time-lagged effect of the NAO-induced changes in the oceanic heat loss on the AMOC. A high phase of the NAO, for example, is known to be associated with enhanced oceanic heat loss and negative SST anomalies in the subpolar North Atlantic. Consistent with this, the SST anomaly pattern associated with CCA_{-10} (Fig. 3a) features the strongest (negative) SST anomalies in the subpolar North Atlantic where explained variances reach up to 80%. A secondary maxi-

mum in the explained variance is seen in the eastern Atlantic in the region 30°N–40°N. The overturning streamfunction anomalies associated with CCA_{-10} (Fig. 3c) are positive from about 60°N to the equator extending down to about 3000 m and 4000 m depth in the midlatitudes and subtropics, respectively, indicating an anomalously strong AMOC with large vertical extent. A relatively large fraction of the AMOC variability is explained by CCA_{-10}, with values exceeding 70% in the region 40°N–50°N and 1000–2000 m.

The SST anomaly pattern of CCA_{-10} (Fig. 3a) shares the enhanced cold anomalies in the subpolar North Atlantic with the tripole pattern (Fig. 1) that is directly linked to the positive NAO. In the ensemble-experiment with the KCM shown here, enhanced heat loss (Fig. S1) associated with the positive NAO-phase stimulates oceanic deep convection in the subpolar North Atlantic and the Atlantic portion of the Arctic (Fig. S5), as expressed by a larger mixed layer depth (MLD) in these regions. The enhanced deep convection subsequently accelerates the AMOC in the model (Fig. S6). The NAO and MLD are in phase, while the MLD leads AMOC at 48°N by 5 years. The SST anomaly pattern of CCA_{-10} (Fig. 3a) also includes a basin-wide cooling reminiscent of the AMO. Thus, the 10-yr lead time obtained from the maximum canonical correlation, when the North Atlantic SSTs lead the model AMOC, only partly represents the NAO forcing of the AMOC in the KCM. We hypothesize that the 10-yr lag is also an expression of the long time scale of the AMO, at which the monopolar SST anomaly pattern prevails. This can explain why i) the CCA_{-10} SST anomaly pattern is AMO-like, and ii) at the same time, has the strongest loadings in the subpolar North Atlantic where the AMOC is driven.

When the model AMOC leads the North Atlantic SST, the largest canonical correlation coefficient amounting to 0.76 is found at a lag of 21 years (CCA_{21}, Fig. S4). The peak, however, is very broad with statistically significant correlations at lags between about 10 and 25 years, suggesting a slowly developing SST response. The two CCA_{21} time series (Fig. 2b) are similar to those of CCA_{-10} (Fig. 2a), again dominated by multidecadal variability and consistent with that of the AMOC index at 48°N (Fig. S3). The SST anomaly pattern of CCA_{21} (Fig. 3b) is also reminiscent of the AMO pattern, being associated with basin-wide warming, but the regional details are quite different to those associated with CCA_{-10} (Fig. 3a). The largest loadings are now seen in the mid-latitudes in the region of the North Atlantic Current off Newfoundland, which suggests a strong AMOC influence in this region. Large loadings are also seen in the tropical Atlantic. CCA_{21} accounts for a large fraction of the observed SST variability in the mid-latitudes and Caribbean, with explained variances exceeding 60% in the central North Atlantic, suggesting a large decadal SST predictability potential solely arising from the history of the AMOC. The overturning streamfunction anomaly pattern and explained variances of CCA_{21} (Fig. 3d) are virtually identical to those associated with CCA_{-10}. This is reassuring, because it confirms a robust link between the NAO, the model AMOC and the observed North Atlantic SSTs. In summary, as expressed by the corresponding spectra (Fig. S7) the results suggest that the AMOC acts as an efficient dynamical filter on the NAO-related heat flux forcing, enhancing low-frequency variability and possibly enabling skillful prediction of decadal North Atlantic SST variability.

4. Prediction of North Atlantic SST anomalies

Virtually all climate models suffer from large SST biases in the North Atlantic. This also applies to the KCM. We therefore cannot expect skillful predictions of North Atlantic SST anomalies when running the model in forecast mode. The AMOC, on the other hand, is thought to be simulated reasonably well, although thorough model verification is hindered by the limited observational database. Here we adopt a hybrid, dynamical/statistical approach to forecast North Atlantic SST anomalies: we use the model-based

AMOC as a predictor to statistically predict by means of CCA the observed North Atlantic SST anomalies. Since the SST anomaly pattern associated with CCA_{21} is basically the AMO pattern and was obtained when the AMOC leads by about two decades (Fig. 3b), the CCA mode can be used to hindcast/forecast AMO-related SST anomalies. External forcing was accounted for by adding back the linear trend which was removed prior to the CCA. Our simple hybrid approach has a number of limitations. First, it does not capture SST variability which is not driven by NAO-related heat fluxes or unrelated to the AMOC. Second, it does not account for an AMOC-related SST signal that is not described by CCA_{21}. Third, adding back the linear trend may not correctly capture the effects of external forcing. A cross-validation strategy was adopted to reduce artificial skill during the hindcast period and to estimate prediction uncertainty (Supplement): CCA_{21} was repeated 18 times with consecutive 5-yr intervals omitted, and these were predicted with the newly calculated mode. The AMO index, defined as the area-averaged North Atlantic SST anomalies over the region 0°–60°N, is well predicted by CCA_{21} during the hindcast period 1921–2010 (Fig. 4b) with a correlation of 0.73 with respect to annual means. When the linear trend is removed, the correlation amounts to 0.67. When the time series are low-pass filtered by applying an 11-yr running mean, the correlations are 0.84 (0.74) with (without) the inclusion of the linear trend.

A forecast of the AMO index until 2031 can be obtained with CCA_{21}, as AMOC variability was reconstructed until 2010. The linear trend during the hindcast period was simply extrapolated into the future to account for the external forcing which is not explicitly calculated during the prediction. The forecast calls for a continuation of the current positive AMO phase during the next years (Fig. 4b). The predicted AMO index declines thereafter, consistent with previous work (Knight et al., 2005) but stays positive during the remainder of the forecast. The negative tendency in the AMO index is due to the slow decline of the NAO index observed during the last two decades (Fig. 4a), which is associated with reduced oceanic heat loss over the subpolar North Atlantic in response to which the AMOC slows (Figs. S1, S5 and S6).

5. Discussion

The only driver of the AMOC in the coupled model experiments presented here is the monthly surface heat flux anomalies associated with the variability of the NAO. It is the memory of the AMOC in response to this heat flux forcing that enables skillful decadal predictions of North Atlantic SST. Wind-induced redistributions of heat and freshwater in the upper ocean which alter the west–east density gradient across the basin may also impact the AMOC (Lozier et al., 2010), and their inclusion may even further enhance the forecast skill of North Atlantic SST. However, ocean and climate models suggest that the decadal to multidecadal AMOC variability is largely heat flux-driven (e.g., Eden and Jung, 2001; Delworth and Greatbatch, 2000), and it is this long-term AMOC variability and its impact on SST which is the focus of this study. Recently, aerosol forcing has been suggested to explain a large part of decadal SST variability in the North Atlantic (Booth et al., 2012). This study presents an alternative view and assigns a key role to the variability of the AMOC. An inspection of the individual components of the driving heat flux reveals that the turbulent latent and sensible heat fluxes provide by far the largest contributions to the total heat flux (Fig. S1), supporting our conjecture. However, the issue remains controversial, as the NAO itself, and the driving heat fluxes through SST, may contain contributions from aerosol forcing.

Decadal climate forecasts (Meehl et al., 2014) may become more skillful when the NAO impact on the AMOC is realistically captured in climate models, but this is generally not the case (Ba et al., 2014). The vast majority of the climate models including
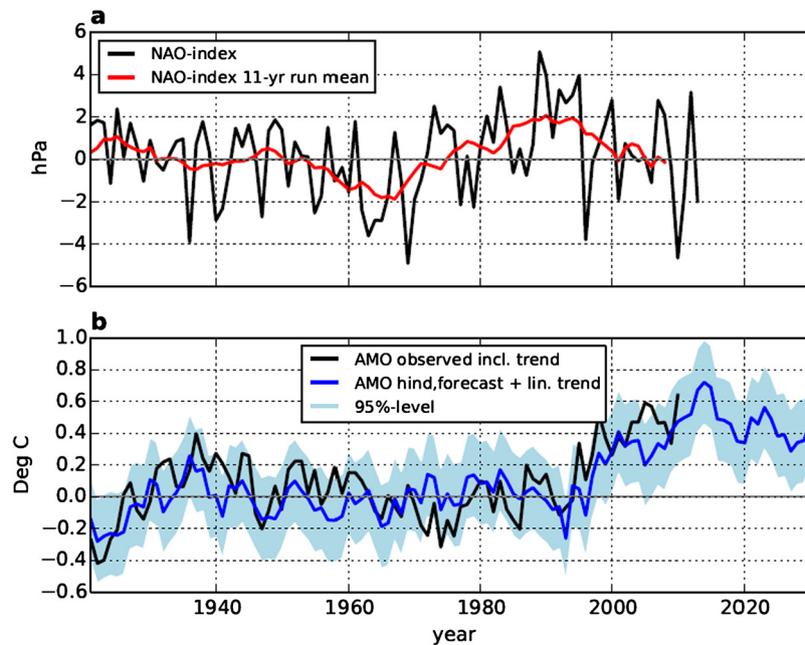
Fig. 4. Forecast of North Atlantic SST (°C) with the leading CCA mode obtained when the AMOC leads the observed North Atlantic SSTs by 21 years. This basically constitutes a prediction of the AMO: (a) The North Atlantic Oscillation (NAO) index for winter (December–March, DJFM; black) and the 11-yr running mean (red). Please note that all months were used to drive the model. (b) Time series of the observed AMO index from ERSST (black line) and that hindcasted/forecasted by using the KCM's AMOC as a predictor (Supplement). SST anomalies are relative to the 1900–2010 average. Please note that the small linear trend 1900–2010 amounting to 0.005 K/yr was put back to the AMO time series and extrapolated into the future. The uncertainty range was estimated by applying cross validation (Supplement). The correlation amounts to 0.73 for annual means, 0.67 after de-trending the annual means, 0.84 for 11-yr running means and 0.74 after de-trending the 11-yr running means.

the KCM suffer from large biases in the North Atlantic. In particular, the models lack the so called northwest corner, leading to a too zonal path of the North Atlantic Current rendering most parts of the subpolar North Atlantic much too cold, with SST errors on the order of several degrees Celsius or more. The cold bias causes an unrealistic link between the AMOC and AMO in the models. Our dynamical/statistical forecast method presented here overcomes some of the bias problem and may serve as an intermediate solution to decadal climate forecasting. We note, however, that the statistical method applied to establish the link between the reconstructed AMOC and observed North Atlantic SST may somewhat overestimate the SST forecast potential, as cross-validation does not remove all artificial skill.

A close relationship between the NAO and Northern Hemisphere surface climate has been previously suggested by means of statistical analysis (Li et al., 2013). Here, we suggest that the AMOC is the missing dynamical link. In conclusion, the results are encouraging with respect to long-range climate forecasting, as they suggest that reduction of model bias and proper forecast initialization can enhance the skill of decadal climate predictions in the North Atlantic sector. The relation between the AMOC and atmospheric forcing may change between the historical period and future, in particular regarding any future AMOC-trend. It is largely unknown how this will affect the decadal forecast skill.

Acknowledgements

Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.09.001.

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