North Atlantic Oscillation influence on Atlantic Meridional Overturning Circulation and prediction of decadal SST variability

Milan Klöwer[1,2], Mojib Latif[1,2*], Hui Ding[1], Richard J. Greatbatch[1,2] and Wonsun Park[1]
[1] GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel, Kiel, Germany
[2] Christian-Albrechts-Universität zu Kiel, Kiel, Germany
* Corresponding author. Email: mlatif@geomar.de

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Introduction

The cause of Atlantic Meridional Overturning Circulation (AMOC) variability at time scales of decadal and longer is poorly understood. Direct measurements of AMOC strength have only recently become available. 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.

Here we propose an innovative method to reconstruct the AMOC variability during 1900-2010. The approach is an extension of a previously employed method (Eden and Jung, 2001) based on the variability of the North Atlantic Oscillation (NAO).

AMOC index

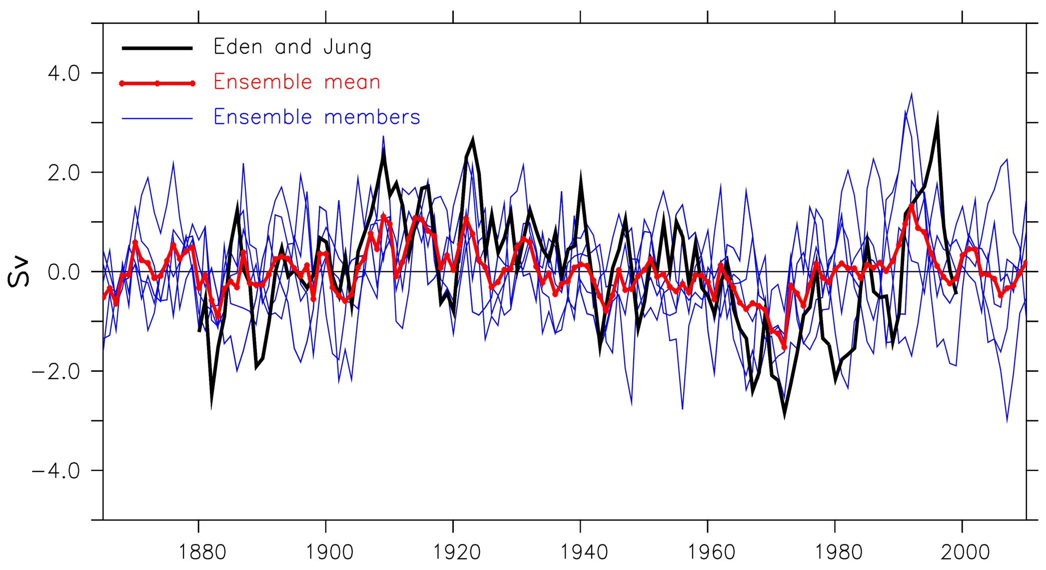

Fig. 1 Response of the AMOC to NAO-related surface heat flux forcing. The red thick line is the ensemble-mean AMOC strength at 48°N and 1,500m, and the thin blue lines depict the individual ensemble members. The black line is the AMOC at the same location simulated in a previous forced ocean model simulation (Eden and Jung, 2001).

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). The advantage of applying the heat flux anomalies to a coupled model is that ocean-atmosphere feedbacks are largely retained in a consistent manner. Model bias in coupled simulations 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. A measure of the forced response is the ensemble mean and only that will be used in the analyses.

NAO influence on deep convection

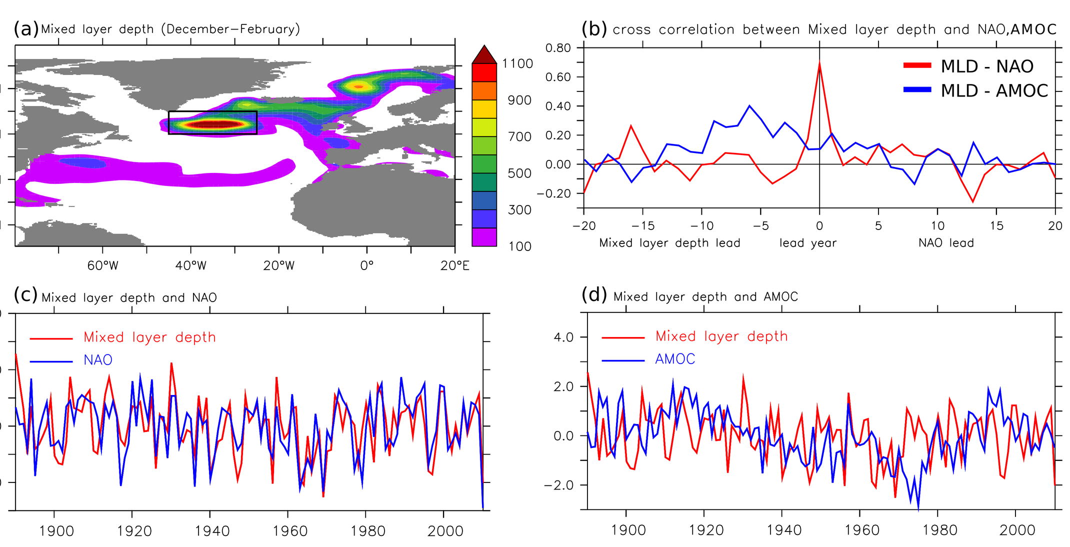

Fig. 2 Variations of the North Atlantic Oscillation (NAO) are associated in the KCM with changes in deep convection in the subpolar North Atlantic. (a) Regression of the mixed layer depth, a measure of convection, upon the NAO index. (b) Cross correlation as function of the time lag (year) between the mixed layer depth index and the NAO/AMOC. (c) Time series of the NAO index and mixed layer depth averaged over the black box in (a). (d) Time series of the mixed layer depth and the AMOC.

Link between SST and AMOC

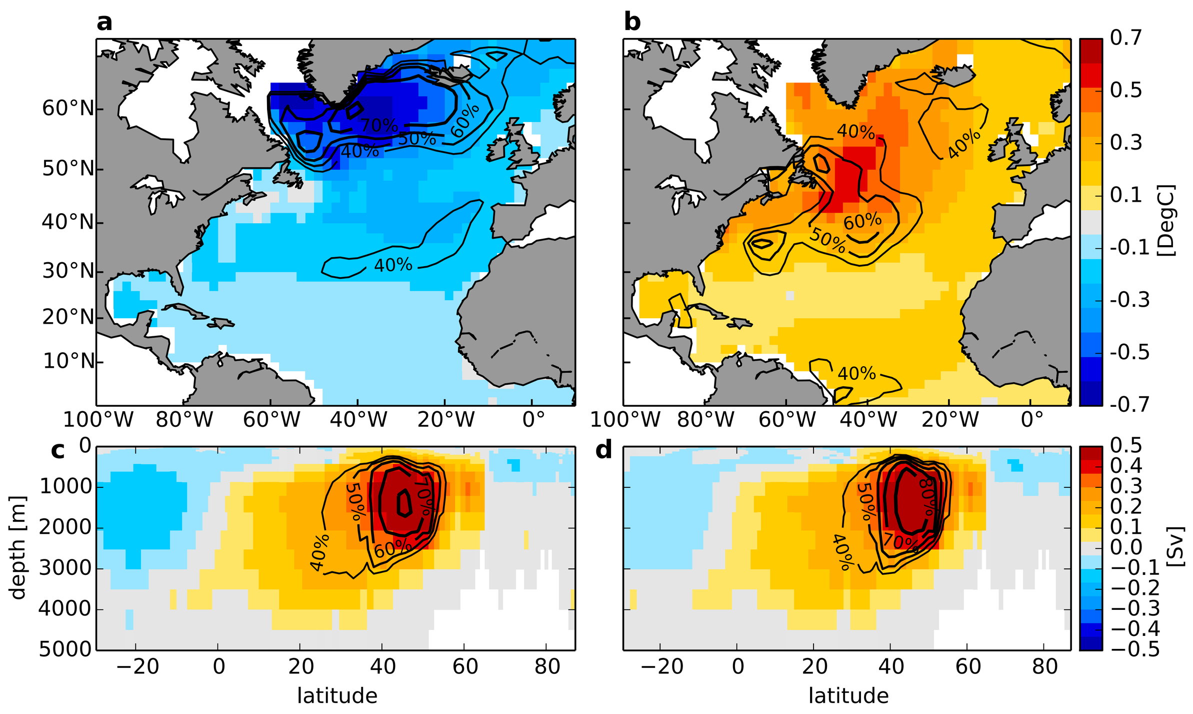

Fig. 3 (a, c) Anomalous North Atlantic SST (°C) and overturning streamfunction (Sv), when the observed North Atlantic SSTs lead the AMOC by 10 years (CCA_{-10}). (b, d) Anomalous North Atlantic SST (°C) and overturning streamfunction (Sv), when the AMOC leads the observed North Atlantic SSTs by 21 years (CCA_{21}).

AMOC reconstruction and its link to observed SST

To relate the model-based reconstructed AMOC during 1900-2010 to the observed SSTs (from ERSST) in the North Atlantic, Canonical Correlation Analysis (CCA) was performed to find the leading modes of co-variability between the AMOC (overturning streamfunction) and the observed North Atlantic SST anomalies. As the NAO and North Atlantic SSTs are closely linked, CCA was performed with different time lags to distinguish forcing and response. Two time lag-ranges stick out (Fig. 4): One, when the observed SSTs lead the AMOC by about a decade (CCA_{-10}), and the other when the AMOC leads the observed SSTs by about two decades (CCA_{21}).

This 30-yr difference is consistent with the observed 60-yr periodicity of the AMO. The overturning streamfunction anomaly pattern and explained variances of CCA_{-10} (Fig. 3c) and CCA_{21} (Fig. 3d) are virtually identical. This is reassuring, because it confirms a robust link between the NAO, the model AMOC and the observed North Atlantic SSTs.

Lead-lagged Canonical Correlation

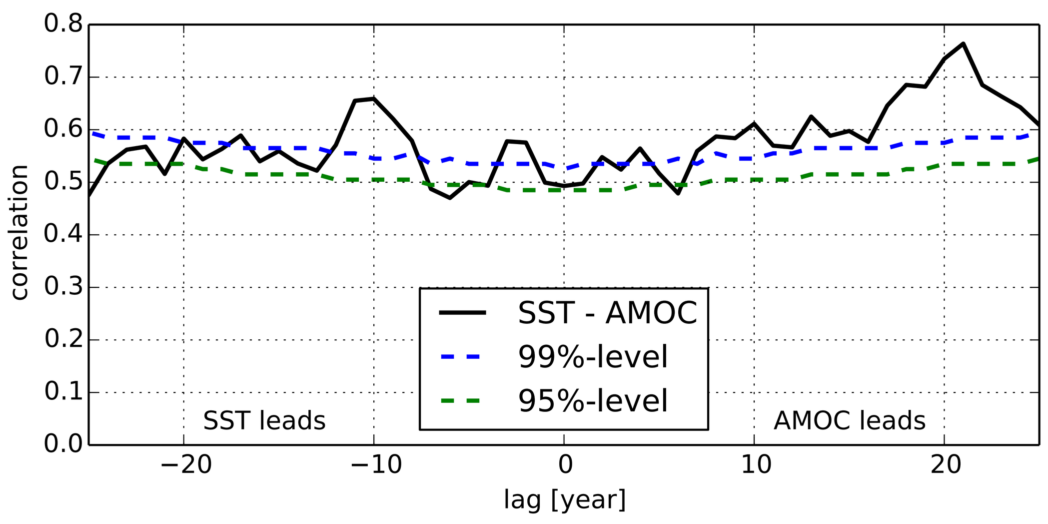

Fig. 4 Canonical correlation coefficient of the leading CCA mode as a function of the time lag (yr) between the climate model's AMOC (expressed by the overturning streamfunction) and observed North Atlantic SSTs.

Canonical timeseries

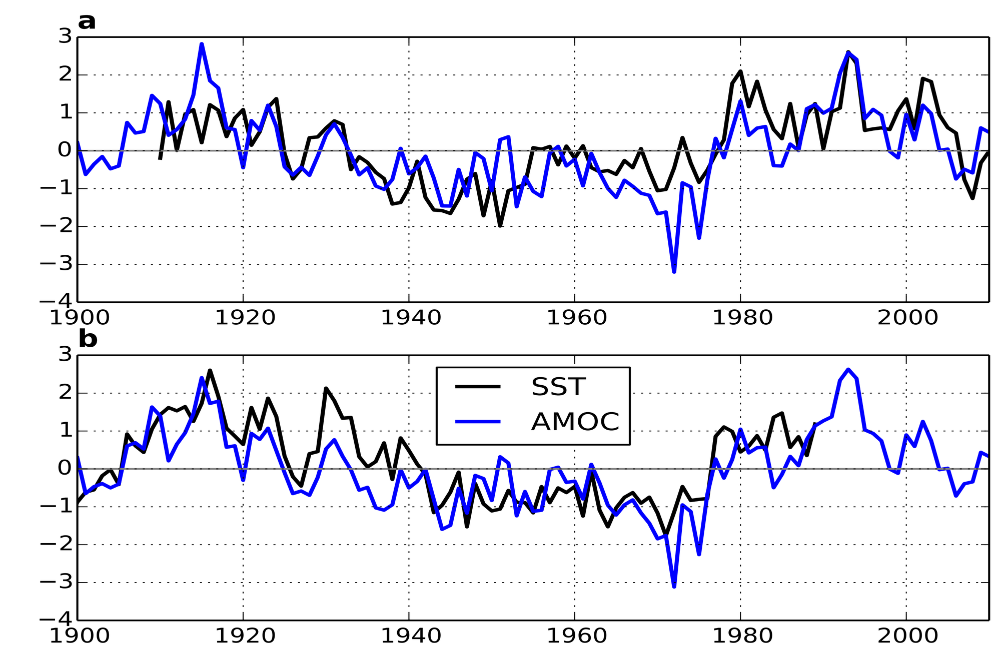

Fig. 5 Time series associated with the leading CCA modes. (a) The time series obtained from the CCA when the observed North Atlantic SSTs lead the AMOC (overturning streamfunction) by 10 years (CCA_{-10}). (b) The time series obtained from the CCA when the AMOC leads the observed North Atlantic SSTs by 21 years (CCA_{21}). The time has been adjusted in both panels to account for the time lag.

Prediction of North Atlantic SST

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, the CCA mode can be used to hindcast/forecast AMO-related SST anomalies.

The forecast calls for a continuation of the current positive AMO phase during the next years (Fig. 6b). The predicted AMO index declines thereafter, consistent with previous work (Knight et al. 2005). The negative tendency in the AMO index is due to the decline of the NAO index observed during the last two decades (Fig. 6a).

AMO prediction based on AMOC

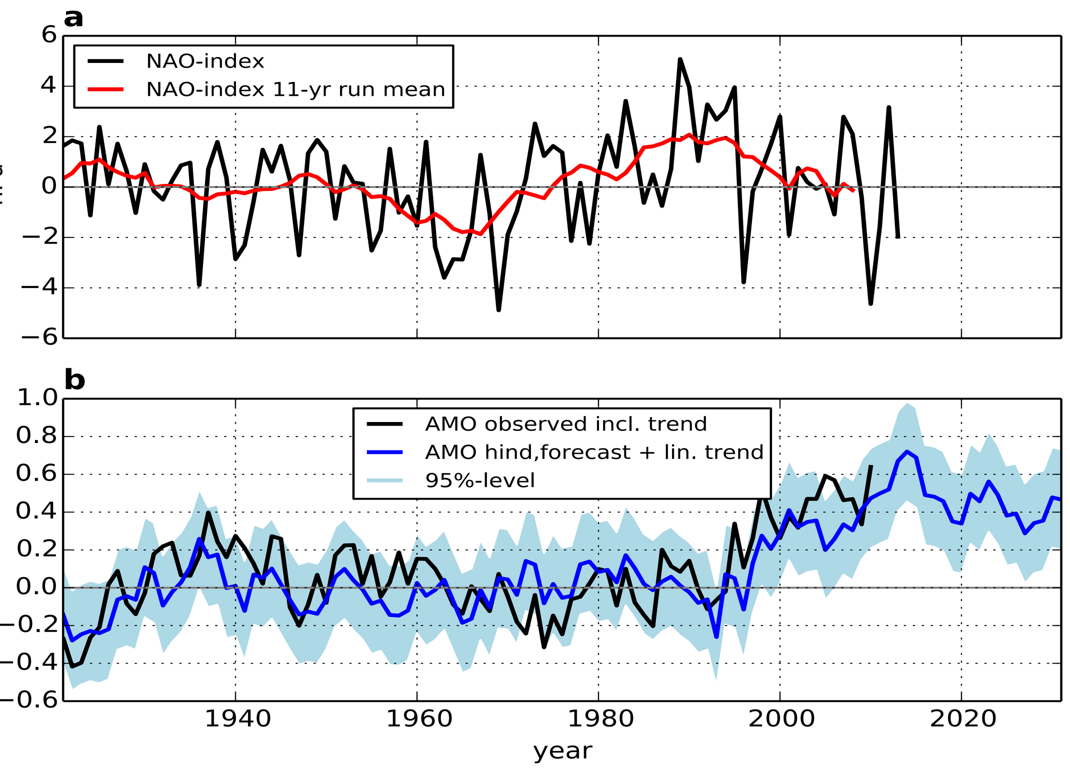

Fig. 6 Forecast of North Atlantic SST (°C) with the leading CCA mode obtained when the AMOC leads the observed North Atlantic SSTs by 21 years. This basically constitutes a prediction of the AMO: (a) The North Atlantic Oscillation (NAO) index for winter (December-March, DJFM; black) and the 11-yr running 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.

Predictive scheme

NAO
↓
Heat flux anomalies
↓
Deep convection
↓
Meridional Overturning Circulation
↓
Oceanic heat transport
↓
SST anomalies

Fig. 7 Predictive skill in the North Atlantic

Discussion

Decadal climate forecasts may become more skillful when the NAO impact on the AMOC is realistically captured in climate models, but this is generally not the case. The vast majority of the climate models including the KCM suffer from large biases in the North Atlantic. In particular, the models simulate a too zonal path of the North Atlantic Current leading to a cold bias that 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.

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.

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