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How much of the NAO monthly variability is from ocean–atmospheric coupling: results from an interactive ensemble climate model

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Abstract The chaotic atmospheric circulations and the ocean–atmosphere coupling may both cause variations in the North Atlantic Oscillation (NAO). This study uses an interactive ensemble (IE) coupled model to study the contribution of the atmospheric noise and coupling to the monthly variability of the NAO. In the IE model, seven atmospheric general circulation model (AGCM) realizations with different initial states are coupled with a single realization of the land, ocean and ice component models. The chaotic noise from the atmosphere at the air-sea interface is therefore reduced. The time variances of monthly NAO index in the ensemble AGCM mean of the IE model is found to be about 20.1 % of that in the SC model. Therefore, more than 79.9 % of the simulated monthly variability of NAO is caused by atmospheric noise. The coupling between sea surface temperature (SST) and NAO is only found in regions south of about 40°N in the North Atlantic Ocean. The IE strategy highlighted the interaction between the NAO and the SST in the region (28°–38°N, 20°W–50°W) to the southeast of the Gulf Stream extension. While the ocean–atmosphere coupling explains <1/5th of the NAO variability in the IE model, it shows slightly larger persistence than the SC model, consistent with the hypothesis of a slower mode of variability from ocean–atmosphere coupling that has larger predictability than the variability driven by the atmosphere.

Keywords NAO · North Atlantic Ocean · Variability · Interactive ensemble · Predictability

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1 Introduction

The North Atlantic Oscillation (NAO) is a dominant mode of atmospheric variability in the extratropical atmosphere that influences climate over most parts of the Northern Hemisphere (Hurrell 1995). Although the NAO has been recognized as internal variability of the atmosphere (e.g. Robinson 1996), studies have reported that the North Atlantic sea surface temperature (SST) affects the NAO (Kushnir and Held 1996; Rodwell et al. 1999; Czaja and Frankignoul 2002, Kushnir et al. 2002; Omrani et al. 2013). Rodwell et al. (1999) reproduced the variations of the observed NAO index using a large ensemble of integrations of atmospheric general circulation models (AGCMs) forced by the observed historical SST. Bretherton and Battisti (2000) interpreted this finding that ensemble averaging filters out the atmospheric variability caused by the internal dynamics of the atmosphere, exposing the effect of the unique realization of the noise in nature recorded in the history of the observed SST. Peng et al. (2002, 2003) found that the AGCM model produced NAO pattern when the SST tripole anomalies over the North Atlantic Ocean were prescribed. There were also studies using Granger causality to diagnose the influence of SST on the NAO, finding a small yet statistically significant feedback of SSTs on the NAO (Wang et al. 2004a; Mosedale et al. 2006).

However, it is not clear how much of the observed NAO variability can be attributed to ocean–atmosphere coupling and how much is attributed to atmospheric variability alone. The coupling of the ocean–atmosphere system has larger predictability than the chaotically driven atmospheric variability because of the thermal inertia of the ocean. Therefore, study the percentage of the NAO variability explained by the ocean–atmosphere coupling has important implications for predictability of NAO.

Standard coupled general circulation models (CGCMs) do not have the ability to discriminate climate variability caused by ocean–atmosphere coupling and atmospheric noise. In the present study, we use the interactive ensemble (IE) modeling strategy that was pioneered by Kirtman and Shukla (2002) to identify the coupling of NAO and SST variability over the North Atlantic. In this approach, an ensemble of AGCMs with different synoptic variability is coupled with the same Ocean General Circulation Model (OGCM), in which the OGCM sees the ensemble averages of the atmospheric forcing. This technique therefore provides us a strategy to reduce the impacts of atmospheric chaotic dynamics on the air-sea fluxes felt by the ocean while retaining the signal that is forced by the ocean. This allows the separation of NAO and SST variability due to ocean–atmosphere coupling and that due to internal atmospheric chaotic dynamics, and facilitates the detection of coupled atmosphere–ocean signals. This modeling strategy was widely used to study the impact of atmospheric noise on SST variability of the Pacific Ocean (Yeh and Kirtman 2004; Kirtman et al. 2005), and the North Atlantic Ocean (Wu et al. 2004; Fan and Schneider 2012; Schneider and Fan 2012), as well as the forced climate response in the atmosphere (Kirtman et al. 2009, 2011). The interactive ensemble modeling has been proved to be an useful tool for understanding ocean–atmosphere interaction.

The purpose of the present study is to assess the relative contributions of coupled ocean–atmosphere interaction and chaotic atmospheric dynamics to the NAO with an IE coupled model. An additional objective is to understand the differences in the persistence of the NAO variability induced by the two factors. The IE coupled model used in this study is newly developed at Tsinghua University. The paper is organized as follows. Model description and experimental design are described in Sect. 2. Simulation results are presented in Sect. 3. Conclusions are summarized in Sect. 4.

2 Model and experimental design

2.1 The coupled climate model

The CGCM model used in this study is a variant of Community Climate System Model version 3.0 (CCSM3.0) that has a different AGCM component. The AGCM model is the grid-point atmospheric model of the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, version 2.0 (GAMIL2.0) (Li et al. 2007, 2013). Other model components, including the Community Land Model version 3.0 (CLM3.0) (Dickinson et al. 2006), the Parallel Ocean Programversion 1.4.3 (POP1.4.3) (Smith and Gent 2002), and Community Sea Ice Model, version 5 (CSIM5) (Briegleb et al. 2004) are the same as in CCSM3.0 developed at the National Center for Atmospheric Research (NCAR). These four model components are coupled by the CCSM Coupler version 6.0 (Cpl6.0) (Craig et al. 2005). This CGCM model is referred to as SC for "standard coupling".

The AGCM model GAMIL2.0 uses a hybrid horizontal grid, which has a Gaussian grid of 2.8° between 65.58°S and 65.58°N and a weighted equal-area grid poleward of 65.58°. The dynamical core of this model includes a finite difference scheme that conserves mass and effective energy in solving the primitive hydrostatic equations of baroclinic atmosphere (Wang et al. 2004b). There are 26 layers in the vertical with the model top at 2.194 hPa. The vertical resolution is coarse in the stratosphere with only eight levels above 100 hPa. A zero vertical velocity is imposed at the top interface of the model. Climatologically season mean ozone data is used as external forcing in the stratosphere without any chemistry process. The model employs an orographic gravity wave parameterization developed by McFarlane (1987). For the moisture equation, the model uses a two-step shape-preserving advection scheme (Yu 1994). The deep convective parameterization scheme is from Zhang and Mu (2005). The cloud fractions are estimated using the diagnostic Slingo-type scheme (Slingo 1987). The model uses a two-moment cloud microphysical scheme, with number concentration and mass mixing ratio of cloud particles to describe microphysical processes (Shi et al. 2010). Further detail of GAMIL2.0 can be found in Li et al. (2013).

The ocean model POP1.4.3 solves the primitive equations in general orthogonal coordinates in the horizontal direction that are subject to the hydrostatic and Boussinesq approximations. The model employs isopycnal transport parameterization from Gent and McWilliams (1990). Vertical mixing of heat and momentum utilizes a modified K-profile parameterization. The air-sea turbulent fluxes of momentum, heat, and moisture are calculated using the wind vector relative to the ocean surface current. The solar radiation absorbed in the upper ocean varies spatially and monthly according to in situ chlorophyll and satellite ocean color observations (Ohlmann 2003). In this study, the POP 1.4.3 model uses a dipole grid with 320 zonal points and 384 meridional points with the northern pole displaced into Greenland. The horizontal resolution of the model is

1.125° in longitude and from 0.27° (at the equator) to 0.64° (far north-west Pacific) in latitude. There are 40 levels in the vertical with 10 m resolution near surface. The sea ice model CSIM5 has the same horizontal resolution as the ocean model.

2.2 The interactive ensemble (IE) model

The IE model was constructed based on the SC model. Seven realizations of GAMIL2.0 with different initial conditions are coupled to a single realization of other model components in the IE system. The coupling between the multiple AGCMs and the other model components is accomplished in the Cpl6.0. Figure 1 shows the schematic of the coupling in the IE system at the air-sea interface. Each realization of the AGCM is identical except for the initial condition. The air-sea fluxes including heat flux, momentum flux and fresh water flux between each AGCM realization and the ocean are calculated. Then the ensemble mean of the fluxes are passed to the OGCM model. However, the individual AGCM realization receives different air-sea fluxes between each other, which are calculated separately according to the states of the ocean and each AGCM. The exchange frequency between the air and the ocean is 1 day. This interactive ensemble technique is different from the traditional multi-initial condition ensemble, because in the IE model the atmospheric models continuously interact with the same ocean model. As the interactive ensemble evolves, the coupling between the ocean and the atmosphere is retained, but the impact of the atmospheric noise on the ocean is reduced. So this IE simulation technique can be used to investigate the role of the ocean–atmosphere coupling. Through the comparison between the IE and SC models, the relative role of the air-sea interaction and the atmospheric noise can be identified. Note that in the IE system, the land surface and sea ice models are also coupled to the ensemble mean fluxes from the AGCM realizations.

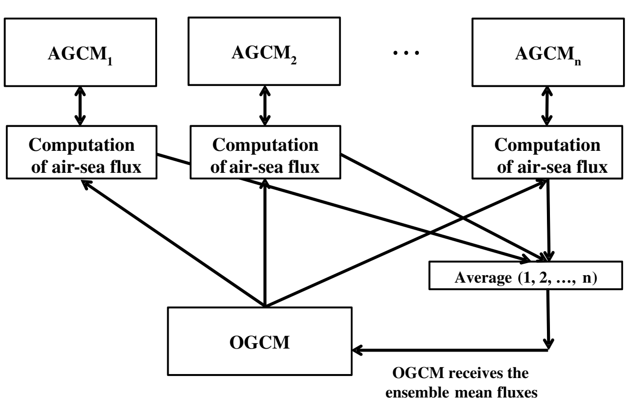

Fig. 1 Schematic diagram of coupling at the air-sea interface in the IE model

2.3 Experiments and data

A pre-industrial control run with the SC model was conducted for 450 years. Seven time slices of the simulated atmosphere from the model output after equilibrium are chosen as independent initial conditions of GAMIL2.0 in the IE model. The IE model was integrated for 250 years. Outputs of the SC experiments were evaluated against observations. The larger-scale climatic features are found to be reasonably simulated when compared to observations (Zhang et al. 2014) and results from other models used in the Coupled Model Intercomparison Project Phase 5 (CMIP5).

The last 100 years of both the SC and IE experiments were selected for the analysis in this study. The external forcings for the experiments, including greenhouse gases, aerosols, ozone and solar, are fixed at the pre-industrial condition. The constant forcings facilitate the analysis of the internal variability of the atmosphere and the ocean. Xin et al. (2014) used the output of these two sets of experiments to analyze the ENSO and the SST variability in the extratropics. They found that the results are consistent with the those from earlier studies with an IE model in terms of the improvement in the relationship between ENSO and North Pacific SST, and the dominant role of the atmosphere in the North Pacific oceans (Wu et al. 2004; Yeh and Kirtman 2004).

Observational data used to verify the simulations include the sea level pressure (SLP) from the twentieth-century (20thC) dataset (Compo et al. 2006) and SST from HadISST1 dataset (Rayner et al. 2003). The time period used to compare with the simulation is from 1910 to 2009. The NAO is defined as the leading EOF of monthly anomalies of SLP in the Atlantic domain (20°–80°N, 90°W–40°E). The corresponding leading component time series is defined as the NAO index. For the NAO in the ensemble (ENS) mean of the IE model, the SLP data are ensemble averaged from the seven GAMIL2.0 realizations before the EOF calculation.

3 Results

3.1 NAO

The spatial pattern of the simulated NAO in the SC model is compared with the observation in Fig. 2. The SC model captures the north–south NAO dipole in the Atlantic sector. The dominant structure of the dipole is broadly consistent with that in the observation, except that the location of the negative center is a little to the west in the model. The NAO accounts for 32.8 % of the total variance of the SLP in the SC model, which is close to that in the observation

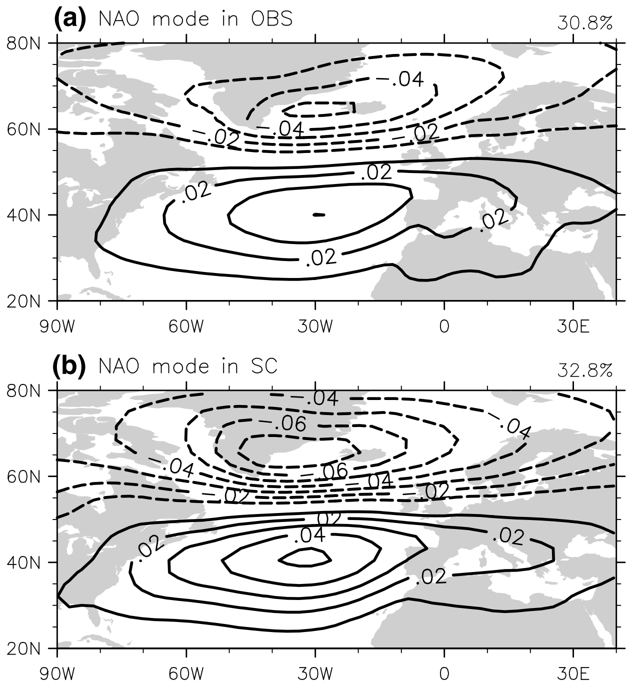

Fig. 2 The leading EOF of monthly SLP anomalies in the observation during 1910–2009 (**a**) and the 100-years simulation of the SC model (**b**). The percentage of variance accounted for by the leading mode is listed at the upper right corner of each panel

(30.8 %). The good performance of the SC model in simulating the NAO mode provides a good reference for the IE model.

Figure 3 shows the NAO mode simulated by the ensemble (ENS) mean of seven AGCM members (Fig. 3a) and the individual AGCM (Fig. 3b–h) within the IE. The location and strength of the dipole patterns over the North Atlantic in the ENS and the seven AGCMs show close resemblances with each other. The variances explained by the NAO in each AGCM are enhanced with the values all above 40 %. Thus the NAO accounts for a higher component among the total variability of SLP after the coupling strength with the ocean is reduced.

Variances of the time series of the NAO indices in the observation, SC, ENS of the IE, as well as each AGCM of the IE model are presented in Table 1. The SC model simulates comparable but smaller variance than the observations. The ENS of the IE model simulates much weaker NAO variance than that in the SC, which is 20.1 % of that in the SC model. The variance due to chaotic atmospheric variability does not average to zero in a finite ensemble. Thus, the result indicates that atmospheric noise explains at least 79.9 % of the NAO variability. That is, the NAO is primarily an internal mode of the atmosphere. Note that there are seven AGCM realizations in the IE model. If atmospheric variability was independent of the oceanic variations, we would expect a 1/7th reduction in variance through the interactive ensemble modeling. However, our simulation produces a value of about 1/5, indicating that ocean–atmosphere coupling may also contribute a small fraction to NAO variability.

The seven AGCM members in the IE model experiences the same SST condition from the ocean model. Then the analysis of the variance for NAO time series is used here to diagnose the signal from the external SST forcing. This method is used in Li (1999). Analysis on the month NAO index of the seven AGCM members shows that the forcing from the SST accounts for 7.7 % of the total variance in the IE model.

The NAO index in each AGCM of the IE model is uncorrelated with others, the correlation coefficients range from −0.11 to −0.03. This reinforces the conclusion that NAO variability is mainly determined by the atmospheric noise. The NAO variance of the individual members of the IE is much larger than the SC and ENS of the IE. Therefore, reducing the coupling strength between the atmosphere and the oceans by the interactive ensemble modeling amplifies the NAO variance in the atmospheric model. The ocean can play two possible types of roles in NAO. In the first type, it interacts with the atmosphere to produce a coupled variability or it creates an ocean internal variability and then impact the atmosphere, which has been shown in the IE as very weak; in the second type, it acts passively to damp atmospheric variability to provide a negative feedback to NAO, as in the SC model relative to the individual AGCM in the IE model. It should be noted that IE has changes in the climatology compared to the SC model (Zhang et al. 2014). These changes could also lead to differences in the NAO variability between the IE model and the SC model.

The damping role of the interactive ocean is in contrary to the result from comparisons between the AMIP-type simulation by AGCM model and the coupled simulation in previous study in terms of surface air temperature. Barsugli and Battisti (1998) pointed out that the variance of atmospheric surface temperature in coupled models is larger than that in AGCMs driven with prescribed surface boundary conditions. This was attributed to the smaller heat flux with a coupled ocean in a coupled model relative to an uncoupled model that favors the maintenance of atmospheric anomalies. We are not yet able to fully understand the physical causes of the amplified magnitude of the individual AGCMs in the IE model and leave this for future study.

3.2 SST

Figure 4a shows the correlation between SST and the NAO index in observations. There is an obvious "negative-positive–negative" tripole pattern from the high latitude to the subtropics over the North Atlantic Ocean. The SC model captured the tripole mode (Fig. 4b), but the IE model

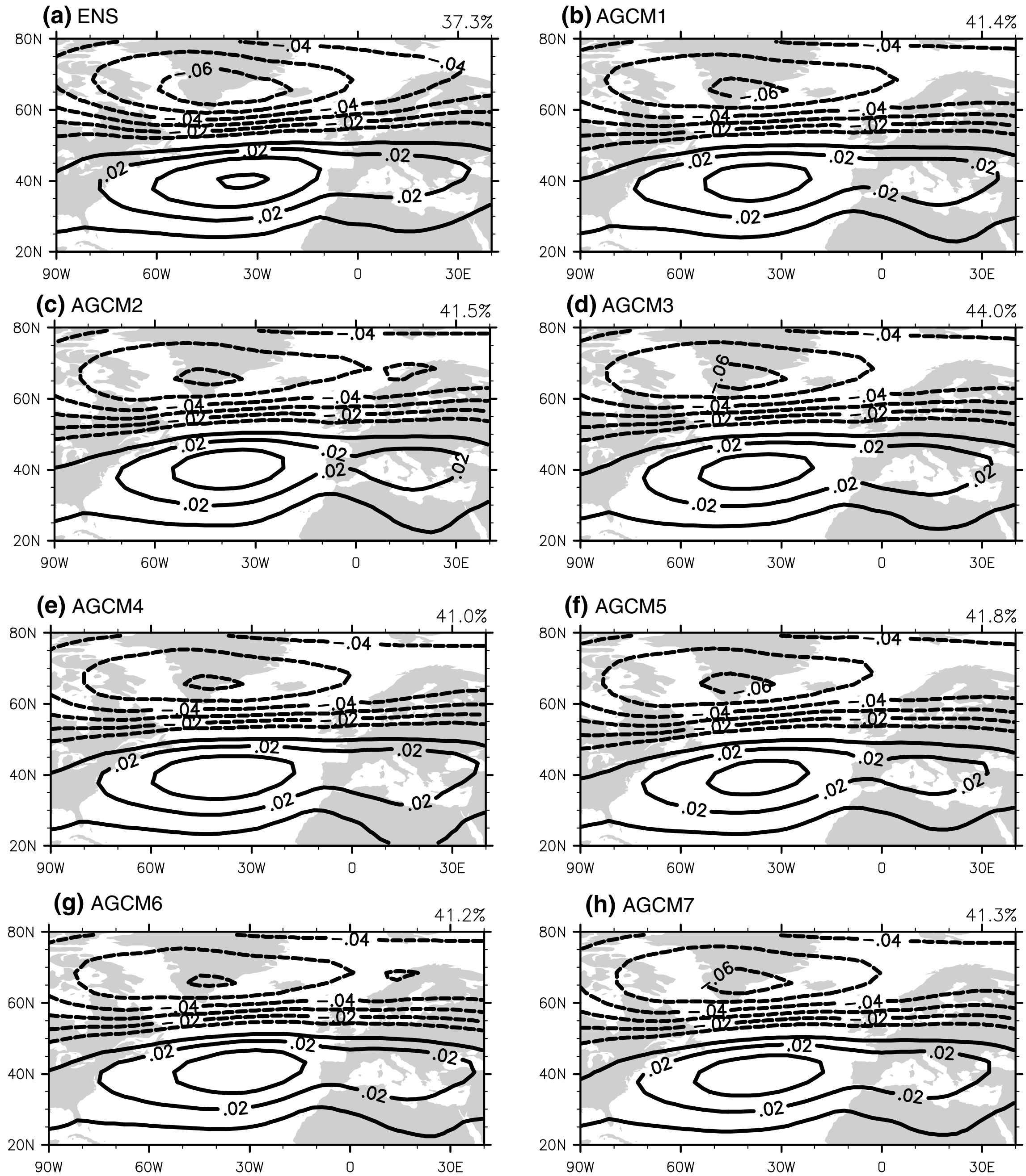

Fig. 3 The same as Fig. 2, but for the 100-years simulation of the ensemble mean (ENS) (**a**) and each AGCM realization of the IE model (**b**–**h**)

Table 1 Time variance of the NAO index in observation, SC, ENS of the IE model, and each AGCM member of the IE model

NAO time series	OBS	SC	IE (ENS)	AGCM1	AGCM2	AGCM3	AGCM4	AGCM5	AGCM6	AGCM7
Time variance	4,847.7	2,288.8	460.0	5,304.0	5,305.2	5,989.4	5,420.5	5,642.4	5,317.1	5,505.2

simulated very weak correlation north of 40°N (Fig. 4c). This indicates that the NAO-SST tripole pattern is not an internal coupled mode of variability of NAO and SST. Instead, it is likely a reflection of the atmospheric NAO in the coupled system. The IE simulation shows statistical significant SST correlations with NAO south of 40°N (Fig. 4c). The correlation is positive from 25°N to 40°N and negative to the south of 25°N. This indicates possible

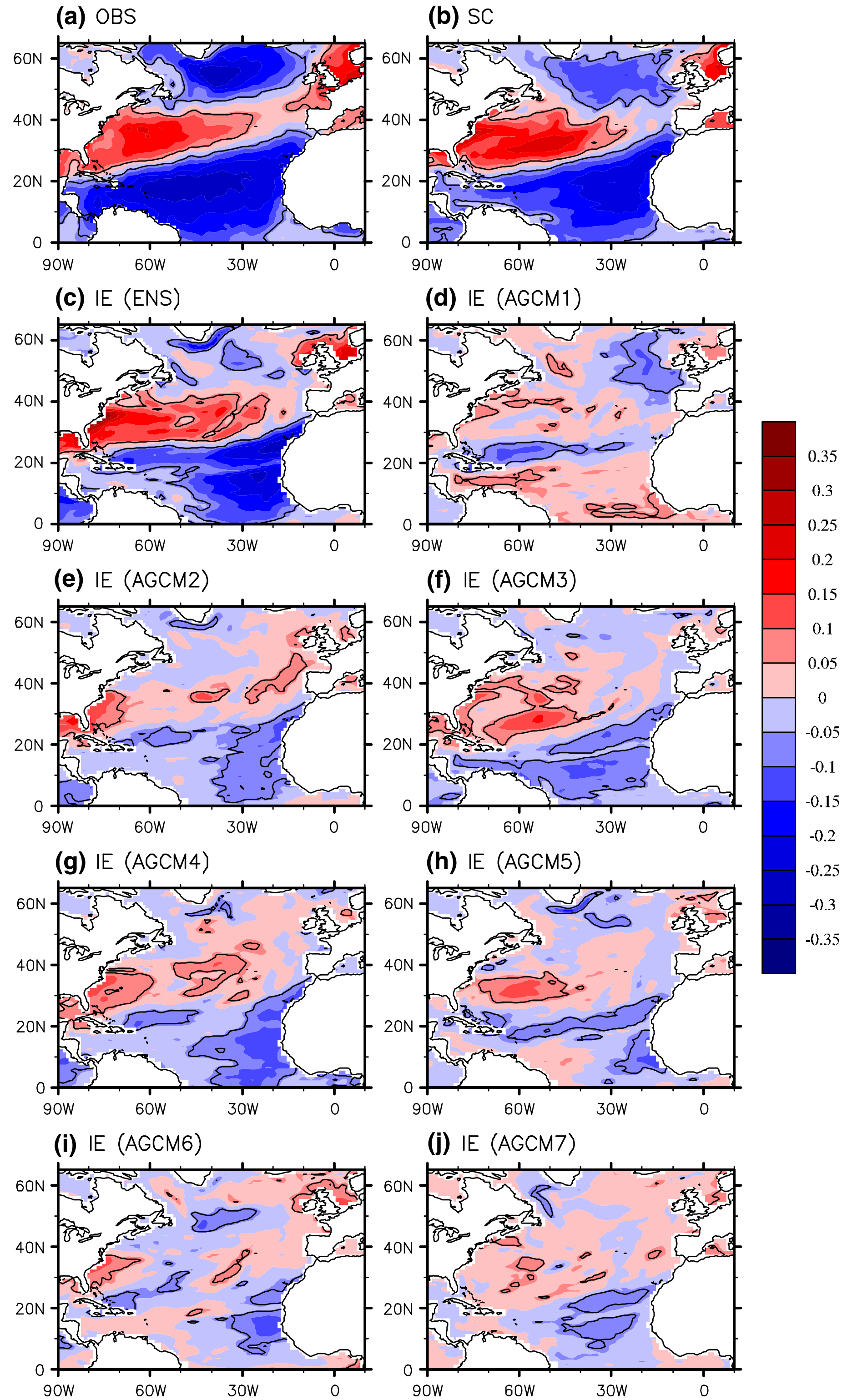

Fig. 4 Contemporaneous correlation between monthly NAO index and SST anomalies in the observation during 1910–2009 (**a**), and the 100-years simulation of the SC model (**b**), ENS (**c**) and each AGCM realization of the IE model (**d**–**j**). Linear trend of the observation data is removed before the calculation. The *black* contours show regions where values exceed the 5 % significant level

coupled variability between NAO and SST in these regions. If the signal related to the Nino3.4 index is removed from the SST fields, the result (Figure not shown) is similar to that shown in Fig. 4. This indicates the coupled variability to the south of 40°N is not influenced by ENSO.

If the ocean only passively responds to atmospheric NAO, then we would expect little correlation of SST with NAO in the individual AGCM in the IE model, since the atmospheric noises are not correlated. Figure 4d–j show the correlation between the NAO index and SST in the

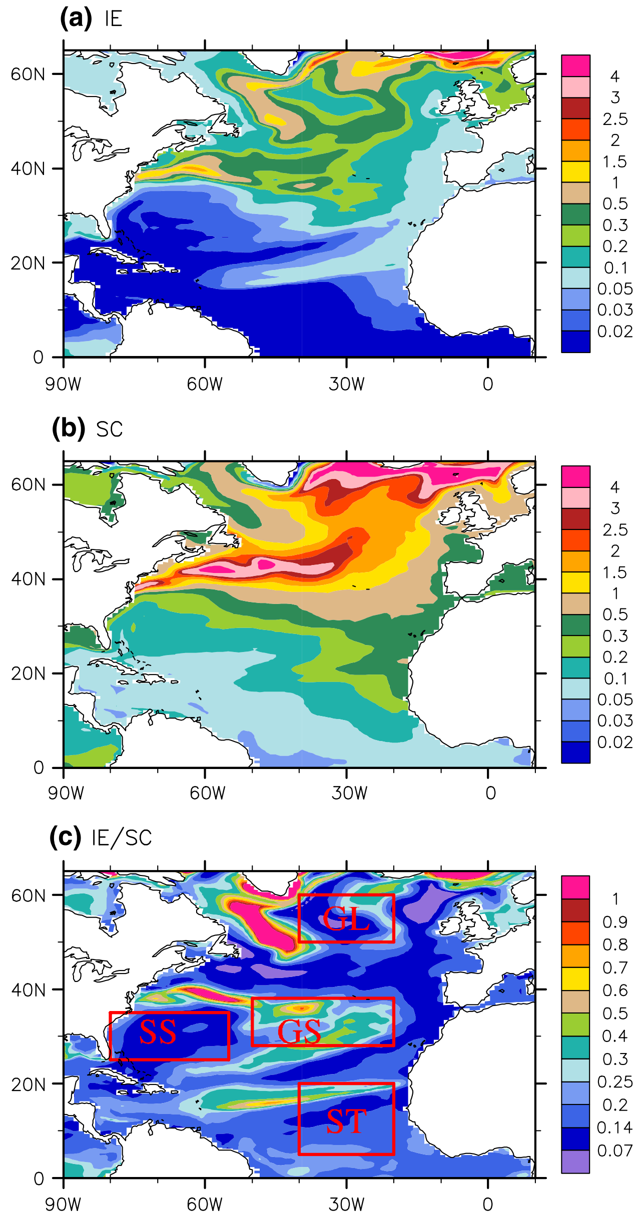

Fig. 5 Variance (Unit: °C2) of monthly SST anomalies in the 100-years simulation of the IE (**a**) and SC (**b**) model. The ratio of variance in the IE model and SC model is shown in **c**

individual AGCM realizations. The correlations in most of the AGCM realizations are much weaker than that in SC, consistent with the conclusion that air-sea coupling is not the cause of the NAO-SST triople mode. The correlations however are statistically non-zero in regions south of 40°N, most of which are consistent with the signal in the IE ENS correlation, indicating contribution of the coupled variability in these regions.

Figure 5a, b show the SST variance in the IE model and in the SC model respectively. Over most regions of the North Atlantic Ocean, the variance is considerably weaker in the IE than in SC. The ratio of SST variance (Fig. 5c) in the IE and SC shows regional different features. Wu et al. (2004) and Kirtman et al. (2005) used a heuristic model to interpret the relative forcing from the atmospheric noise and the ocean by using three type ranges of variance ratios between IE and SC. Since the IE strategy of our study is the same as in these works except for the number of the AGCMs, we use their results to explain the variance ratio shown in Fig. 6c. In the mid-latitude ocean between 40° and 50°N and in the ocean to the southeast of the Greenland, the ratio is close to 0.14 (1/M, M: AGCM member), indicating that the SST variability is primarily forced by the atmospheric noise. This is broadly consistent with the inference from the correlation map in the high latitude with little statistically significant region. In the region to the southeast of the GS extension region, the ratio is from 0.3 to 0.5 (between 1/M and 1.0), indicating impact of ocean noise or unstable coupled feedbacks. This is similar to result from Wu et al. (2004) in studying the low frequency North Atlantic SST variability with an IE model. They further pointed out that the low frequency SST variability in the Gulf Stream extension area may be attributed to processes internal to the ocean rather than unstable coupled feedbacks, through comparisons between simulations by the IE model and ocean-only model. It is noted that in the Labrador sea, the ratio is larger than 1.0, indicating unstable coupled feedbacks and/or important non-linearity there. This might be an indication of the role of ocean–sea ice interaction.

3.3 Lagged correlations

We select four regions (outlined in Fig. 5c) to show the lagged correlation between NAO and SST. One is the negative correlation region near the southeast of Greenland (GL: 50°–60°N, 20°–40°W) in Fig. 4a, b, where the IE model showed little correlation. The second in the negative correlation region in the subtropics (ST: 5°–20°N, 20°–40°W), where both models show significant correlation (Fig. 4b, c). The other two regions are in positive correlation region: SS (25°– 35°N, 55°–80°W) and GS (28°–38°N, 20°W–50°W). These two adjoining regions show different variance ratio of SST between the IE and SC, implying different role of the ocean on the SST variation.

The monthly anomalies of the time series of area averaged SSTs are used to calculate the cross correlations with the NAO index, which are shown in Fig. 6. Positive lag means that the NAO leads the regional mean SST, and vice versa. In SC simulation, the GL SST is closely related to NAO by leading 1–5 months (Fig. 6a). However, in the IE model there is little significant correlation at any lag or lead time, which supports the conclusion that there is little coupling between the NAO and SST in this region. In the ST region, the negative correlations between SST and NAO in

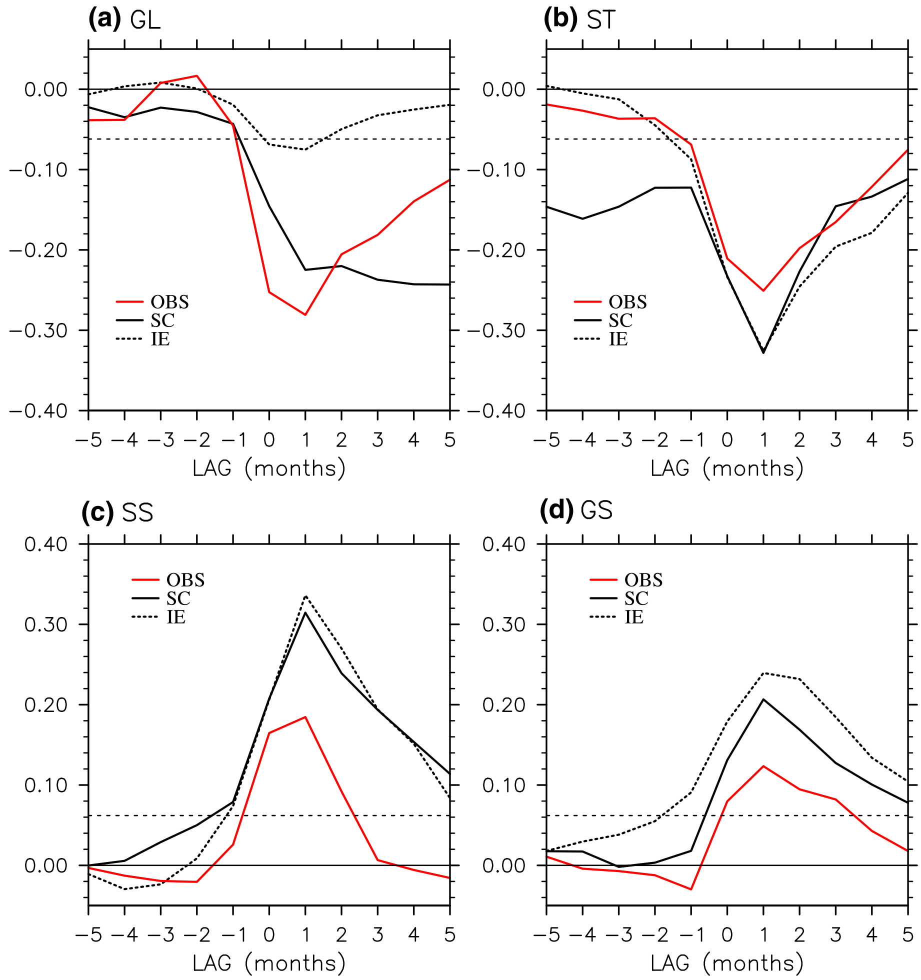

Fig. 6 Cross correlation of monthly NAO index with the GL (**a**), ST (**b**), SS (**c**), and GS (**d**) regional averaged SST time series in the observation and the 100-years simulation of SC and IE models. For positive lags, the NAO leads the SST, and for negative lags the SST leads the NAO. The *horizontal dashed lines* indicate the 5 % significant levels

both models are significant from the lag time of 2 months to leading time of 5 months (Fig. 6b). The IE strategy lowers the preceding influence of the SST in the subtropics longer than 1 month.

In the SS region, the lagged cross correlation between NAO and SST in the SC and IE show similar feature with a peak when the NAO leading by 1 month (Fig. 6c). Reducing the atmospheric noise through the IE model has little influence on the leading or lagged relationship between the NAO and SST. In the GS region where the ocean dominating the SST variability, the cross correlation at lags from "−1" to 5 months in the IE model are all much larger than the SC model (Fig. 7d). Therefore, the interaction between the NAO and the SST in the GS region is more prominent after the atmospheric noise is reduced. This region is precisely to the southeast of the Gulf Stream extension where the ocean shows important influence on the SST variability. The influence of the ocean on the NAO appeared in the Gulf Stream extension region is consistent with the result diagnosed from the observation data using Granger Causality technique (Wang et al. 2004a).

Note that in the SC simulation, the correlation of GS SST with the NAO lagged by 1 month is not significant, indicating that the atmospheric noise in the SC model may mask out the leading influence of the ocean on the atmosphere. In ST, SS and GS regions of the IE simulation, the correlation coefficients between NAO and SST lagged by 1 month are all significant at the 5 % level. So the coupling between SST and NAO mainly appears in regions south of about 40°N in the North Atlantic Ocean. The shapes of the observed cross correlation in ST, SS and GS regions are similar to those in the simulations, but the cross correlation around the peak lag time is lower than the SC and IE models. The simulations represent the pre-industry condition with fixed boundary forcing. Therefore, the observation can only provide a reference for the simulations here.

Due to the short-term atmospheric noise, the NAO has a short memory. As shown in Fig. 7, the autocorrelation of the NAO index is only significant at the lag of 1 month with a value of 0.19. However, in the IE model with the coupling highlighted by reducing the atmosphere noise, the 1-month lagged autocorrelation increases to 0.3. The

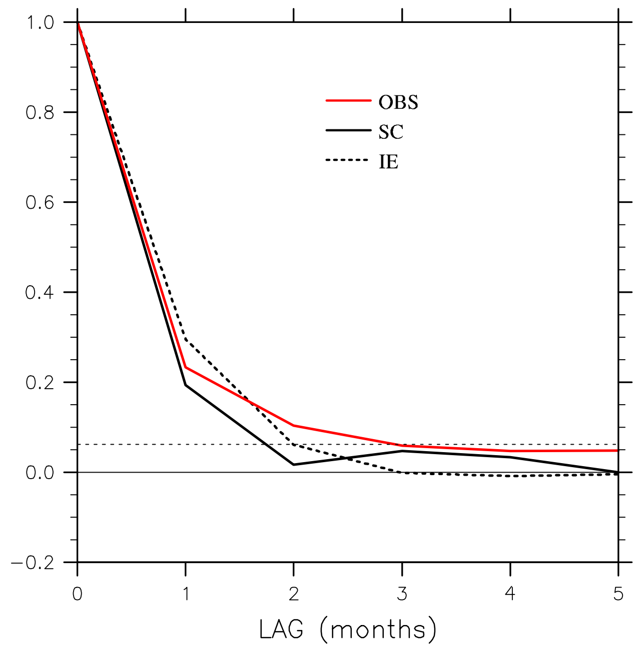

Fig. 7 Autocorrelation of monthly NAO index in the observation and 100-years simulation of the SC and IE models. The *horizontal dashed lines* indicate the 5 % significant level

2-month lagged autocorrelation (0.061) is also significant at the 5 % level. So there is longer persistence of the NAO anomalies in the interactive ensemble modeling. This is consistent with the longer memory of climate anomalies from the ocean–atmosphere coupling.

4 Conclusions

An interactive ensemble strategy was used to study the variability of the NAO and SST in the North Atlantic. The IE interactive ensemble model was constructed based on GAMIL2.0 as the AGCM and POP1.4.3 as the ocean model with seven GAMIL2.0 realizations with different initial states. Outputs of the IE and SC models were used to distinguish the roles of the atmospheric variability and the coupled ocean–atmospheric variability in the NAO and the SST. It was shown that the two models simulated very similar spatial patterns of the leading monthly NAO and SST modes. However, the two models differ substantially on the time variance of the NAO index. The variance ratio of the NAO between the IE model and the SC model is 20.1 %. The simulated coupled variability of the ocean–atmosphere system in NAO is therefore only a small fraction of that driven by the atmospheric variability. More than 79.9 % of the simulated monthly variability of NAO is caused by atmospheric noise.

The correlation map between the NAO and SST in the IE does not show the tripole pattern as in the observation and the SC model, with little negative correlation in the high-latitudes, implying the primarily role of the atmospheric forcing there. The leading influence of the SST mainly appears to the south of 40°N over the North Atlantic Ocean. The IE model showed enhanced SST-NAO interaction to the southeast of the Gulf Stream extension over (28°–38°N, 20°W–50°W) through the interactive ensemble strategy. This region is precisely the area where the ocean process play an important role in the SST variability, diagnosed from the variance ratio of SST between the SC and IE model. While the ocean–atmosphere only explains a small fraction of the NAO variability in the IE model, the NAO shows longer persistence indicating potential larger predictability of the NAO with reduced atmospheric noise.

Because the observed climate system has only one realization of the atmosphere, the interactive ensemble model is only a tool to understand the coupled ocean–atmosphere signal within the large synoptic noise. Recent studies suggested resolving the stratosphere could be important for extra-tropical ocean–atmosphere interaction (Omrani et al. 2013; Schimanke et al. 2011). However, the AGCM model used in our study has coarse representation of the stratosphere. Further improvement of the model is needed for the interactive ensemble coupling. Whether results from the present study hold true need further verification with other models, especially the percentage of the ocean–atmosphere coupling in explaining the NAO variability.

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