Causes of Low Frequency North Atlantic SST Variability in a Coupled GCM

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Abstract

The low frequency sea surface temperature (SST) variability in the North Atlantic is studied using the Center for Ocean-Land-Atmosphere Studies (COLA) anomaly coupled general circulation model. The main focus is placed on the relative roles of stable and unstable coupled feedbacks in inducing the low frequency SST variability in various regions of the North Atlantic. To examine this question, a recently developed coupling technique, interactive ensembles, is applied to reduce the strength of “weather noise” in the model and isolate the atmospheric feedback to boundary forcing.

We find that the low frequency SST variability in the subtropical North Atlantic is mainly induced by stable coupled feedbacks in which the weather noise plays a central role. However, in the Gulf Stream extension area, the SST variability may be attributed to processes internal to the ocean. In this region the “weather noise” forcing the coupled system is generated by the ocean, and the coupled feedbacks are stable. Although the results are not definitive, there is no compelling evidence that unstable coupled feedbacks are important for low frequency SST variability in the North Atlantic in this model.
1. Introduction

The SST variability in midlatitudes can be thought of as induced mainly by atmospheric and oceanic internal variability and by coupled feedbacks between the atmosphere and ocean. There are two different types of coupled feedbacks: 1) stable feedback in which the coupled system passively responds to stochastic “weather noise”; and 2) unstable coupled feedback in which the atmospheric response to SST variability reinforces the SST variability leading to unstable coupled modes with preferred spatial structures and time scales independent from those of the weather noise. In the stable case, the low frequency variability will be proportional to the noise forcing, although the coupled feedbacks may lead to amplification and structural modifications. In the unstable case, the low frequency variability can exist in the absence of the noise. The response of the passive ocean to weather noise was first pointed out by Hasselmann (1976), who showed that the SST response of an ocean mixed layer to presumed white weather noise forcing has a red spectrum due to its selective amplification at lower frequencies. The Hasselmann theory was extended to the coupled system by Barsugli and Battisti (1998) through including the response of the atmosphere to the SST variability forced by weather noise. They argued that stable coupled feedbacks reduce the damping of the SST anomalies compared to the Hasselmann theory. The theory of stochastically driven stable feedbacks of Barsugli and Battisti was applied to interpret uncoupled GCM experiments in which the atmospheric response to a specified evolution of SST or the oceanic response to specified atmospheric forcing is found (Bretherton and Battisti, 2001).

Some potential mechanisms of decadal and longer timescale SST variability involving unstable coupled dynamic feedbacks are summarized by Sarachik et al. (1996)
and Latif (1998). These dynamical mechanisms of unstable feedback involve large scale circulation features of the ocean such as the thermohaline circulation and oceanic gyre circulations (western boundary currents). Potential process involved in low frequency midlatitude SST variability are described by Frankignoul et al. (1997), Jin (1997), Saravanan and McWilliams (1998), Goodman and Marshall (1999), and Cessi (2000). The paper of Ferreira et al. (2001) synthesizes some of the stable and unstable coupled feedbacks in a conceptual model. Since both the weather noise and the coupled feedback processes can be controlled in the simple model of Ferreira et al., this approach can be used as a theoretical guideline to understand low frequency SST variability.

These theoretical studies guide our understanding of the decadal climate variability in midlatitudes. However, it is necessary to transfer this understanding to the more directly applicable GCM setting. One task, which has implications for predictability, is to identify regions where various mechanisms dominate. The study of Grötzner et al. (1998) describes North Atlantic low frequency SST variability in a coupled GCM with characteristics of an unstable coupled feedback. However, Zorita and Franignoul (1997) find little evidence for unstable coupled feedbacks in the North Atlantic in a coupled GCM simulation. The view of Zorita and Franignoul is also echoed in the response of an ocean GCM to atmospheric forcing specified from observational analysis (Seager et al. 2000).

In this study, we will identify the regions in the North Atlantic where stable or unstable coupled feedbacks dominates in an anomaly coupled general circulation model (ACGCM) developed in the Center for Ocean-Land-Atmosphere Studies (COLA) (Kirtman et al. 2002). While it is very hard to separate the roles of various unstable
coupled feedbacks in a coupled GCM, it is relatively straightforward to identify the regions where stable feedbacks forced by weather noise dominate if one can control the strength of the weather noise. The interactive coupled ensemble technique (Kirtman and Shukla 2002) provides us with exactly such a control.

The paper is arranged as follows: section 2 will briefly describe the anomaly coupling strategy and interactive coupled ensemble method, the experiments we carried out, and the data that will be used; section 3 will present the results. A summary and brief discussion will be provided in section 4.

2. Model, experiments, and data

2.1. Anomaly coupled GCM

The model to be used is the anomaly coupled GCM, described by Kirtman et al. (2002). The atmospheric component is version 2 of the COLA AGCM with T42 horizontal resolution and 18 levels in the vertical. The AGCM produces a state of the art simulation of synoptic scale atmospheric weather noise. The ocean model is the GFDL MOM3 with 1.5° horizontal resolution (meridional resolution increasing to 0.5° in the tropics) and 25 levels in the vertical. Anomaly coupling is a form of flux correction applied to the SST seen by the atmosphere, and to the fluxes of heat, momentum, and fresh water seen by the ocean, which causes the climatology of the coupled model to be close to the observed climatology. Only information about anomalies is transmitted between the atmosphere and ocean components of the coupled model.

2.2. Interactive Coupled Ensemble

The interactive coupled ensemble strategy (Kirtman and Shukla 2002) uses multiple copies (in our case six) of the AGCM coupled to a single realization of the OGCM. Each
atmospheric model is forced by the same SST from the ocean model which is updated daily. However, the atmospheric models are started with slightly different initial states. Due to the chaotic nature of atmospheric dynamics the “weather” in each copy of the atmospheric model can be viewed as noise independent of that in the other models. The ensemble is interactive in that the ensemble mean fluxes over all copies of the atmosphere are then used to force the ocean model, determining the SST evolution. Therefore, the interactive coupled ensemble filters out the weather noise forcing of the ocean but preserves the coupled atmosphere-ocean feedbacks. Since transient eddies are realistically represented in each copy of the AGCM, the interactive coupled ensemble also realistically represents atmospheric transient eddy flux feedbacks to changes in SST and their interaction with the ocean.

2.3. Experiments and Data

Two experiments were carried out to isolate the role of weather noise: the control experiment (EXP_0) uses only one copy of the AGCM coupled to the OGCM; and the interactive ensemble experiment (EXP_IE) in which six copies of the AGCM are coupled to the OGCM. Both experiments were integrated multi-century. Using results from these integrations, Yeh and Kirtman (2003) studied the role of weather noise in the North Pacific decadal variability and Wu and Kirtman (2003) examined the ENSO-Monsoon interaction. In addition to these two experiments, an ocean model only integration forced by the observed climatology (EXP_OIV) is carried out to examine the contribution of noise generated internally in the ocean to the SST variability.
This study analyzes SST segments of 100 model years from EXP_0 and EXP_IE, a segment of 35 years from EXP_OIV, as well as the observed SST from 1931 to 2000 provided by the Hadley Center for Climate Prediction and Research (Rayner et al. 1996).

3. Results

The standard deviation and variance of the interannual to interdecadal SST variability are used as the basic fields of this analysis. To isolate low frequency and compare with the results of Grötzner and Latif (1998), the three-year running mean of winter (from November to March) SST is applied. Figure 1 shows the standard deviation of the low frequency SST variability of the observations (upper-left panel), the control experiment (EXP_0, upper-right panel), the interactive ensemble experiment (EXP_IE, lower-left panel), and the ocean model only integration (EXP_OIV, lower-right panel).

The SST standard deviation of the control is comparable to that of the observations in most areas. The region of strong variability to the east of Newfoundland in nature is well captured both in the location of the center and in the orientation of the axis of strong variability. The simulated variance near Cape Cod is deficient, which could be due to the use of an ocean model that is not eddy resolving and does not simulate a realistic Gulf Stream.

The area of large SST variability to the east of Newfoundland is also found in the interactive ensemble experiment, although its amplitude is slightly reduced. In the ocean only integration, the low frequency SST variability is very small in the most of the North Atlantic. However, in the Gulf Stream extension area, the ocean-only SST variability has about the same amplitude and spatial structure as that in the interactive ensemble experiment.
According to statistical theory, if the typical variance of the noise in a single atmospheric simulation is $V$ and there are $N$ realizations, then the expected variance of the noise in the average of the $N$ realizations is $V/N$. If the low frequency SST variability in the interactive ensemble is locally and linearly forced by the weather noise and the weather noise can be viewed as internal to the atmosphere (uncoupled from the ocean), as in Barsugli and Battisti, then the expected ratio of both the noise in the single atmosphere to the ensemble mean of six atmospheres, and the SST variance in the (single atmosphere) coupled model to that in the (six atmosphere mean) interactive coupled ensemble will be six. If, on the other hand, the low frequency SST variance is due to a coupled unstable oscillation, as in Latif and Barnett (1994, 1996), or due to internal ocean variability, these ratios will be close to one.

The ratio of low frequency SST variance between the control and the interactive ensemble experiments (Fig. 2) lies between one and six, consistent with the theory. In most regions of subtropical North Atlantic, the ratio is three to six, indicating that the local stable coupled feedback driven by atmospheric weather noise is the major source of the SST variability. In the vicinity of the Gulf Stream extension and higher latitude regions, especially the northern flank, the ratio approaches unity, implying that the unstable coupled feedback and/or oceanic internal variability (Moron et al. 1998) are main sources of the SST variability in these regions.

The remaining question is then how much of the variability in the interactive ensemble can be attributed to unstable coupled feedbacks, and how much to oceanic internal variability (Moron et al. 1998) in the presence of stable coupled feedbacks. Figure 1 suggests that the center of low frequency SST variability off the coast of
Newfoundland in the interactive ensemble experiment may be mainly caused by the ocean internal variability, since the ocean only experiment has a center of variability of comparable magnitude in the same region. Although the results presented are not definitive, there is no compelling evidence that unstable coupled feedbacks are important in inducing low frequency SST variability in the COLA anomaly coupled model.

4. Summary and Discussion

The low frequency sea surface temperature (SST) variability in the North Atlantic is studied using the Center for Ocean-Land-Atmosphere Studies (COLA) anomaly coupled general circulation model. Indeed, the long control simulation with the anomaly coupled GCM gives a realistic-appearing North Atlantic low frequency SST variability.

To identify the relative roles of stable and unstable coupled feedbacks in inducing the model’s low frequency SST variability, we adopted the interactive ensemble coupling technique to control the strength of atmospheric weather noise forcing of the ocean. We found that the SST variability in the subtropical North Atlantic is mainly induced by stable coupled feedback in which the “weather noise” and local thermal coupling plays a central role. However, in the high latitude region of strongest variability, especially in the Gulf Stream extension area, the weather noise seems to play relative minor role in causing the SST variability. An ocean only experiment indicates that this variability is probably attributable to processes internal to the ocean. Therefore, in our coupled model, unstable coupled feedbacks are not detected conclusively. The results suggest that the interactive ensemble technique could be extended to provide more definitive results if ocean internal variability was reduced by using multiple copies of the ocean.
Given results from the prior GCM studies, our conclusions appear to be model-dependent, and also suggest that our model may be inadequate. If oceanic internal variability is an important driver of low frequency North Atlantic SST variability, then the ocean component of the coupled model should be eddy-resolving in order to realistically simulate this variability for the right reasons. However, the methodology developed here is not model dependent, and could be applied in any coupled model to quantitatively isolate the sources of low frequency SST variability.

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References


Figure 1: The standard deviation of low frequency SST variability in the North Atlantic for 70 year UK/GLOBAL SST from 1931-2000 (upper-left panel); 100 year SST of EXP_0 (the control experiment, upper-right panel); 100 year SST of EXP_IE (interactive ensemble experiment, lower-left panel); and 20 year SST of EXP_OIV (only model only integration, lower-right). In all the analysis, the winter (NDJFM) average is used and a three-year running mean is applied. The contour intervals are specified by the color bars below each panel with a unit of °C.
Figure 2: The ratio of low frequency SST variances between the control experiment and the interactive ensemble experiment (variance of EXP_0 divided by that of EXP_IE).