ENSO Hindcast Experiments Using a Coupled GCM

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Abstract A group of seasonal hindcast experiments are conducted using a coupled model known as the Flexible Global Ocean-Atmosphere-Land System Model-gamil1.11 (FGOALS-g1.11) developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG). Two steps are included in our El Niño-Southern Oscillation (ENSO) hindcast experiments. The first step is to integrate the coupled GCM with the Sea Surface Temperature (SST) strongly nudged towards the observation from 1971 to 2006. The second step is to remove the SST nudging term. The authors carried out a one-year hindcast by adopting the initial values from SST nudging experiments from the first step on January 1st, April 1st, July 1st, and October 1st from 1982 to 2005. In the SST nudging experiment, the model can reproduce the observed equatorial thermocline anomalies and zonal wind stress anomalies in the Pacific, which demonstrates that the SST nudging approach can provide realistic atmospheric and oceanic initial conditions for seasonal prediction experiments. The model also demonstrates a high Anomaly Correlation Coefficient (ACC) score for SST in most of the tropical Pacific, Atlantic Ocean, and some Indian Ocean regions with a 3-month lead. Compared with the persistence ACC score, this model shows much higher ACC scores for the Niño-3.4 index for a 9-month lead.

Keywords: ENSO, coupled GCM, SST nudging, seasonal hindcast experiment


1 Introduction

Due to enormous impact of the seasonal forecast in social and economical domains, it has received wide attention by many scientists. Cane et al. (1986) developed a dynamical simplified model for the first successful prediction of El Niño-Southern Oscillation (ENSO). Since this initial study, there have been a number of models with diverse complexities (e.g., Chao and Zhang, 1990; Chen et al., 1997; Zhou et al., 1998; Stockdale et al., 1998; Luo et al., 2005; Ke et al., 2008) that have been utilized for ENSO seasonal forecasting. Furthermore, some operational climate predictions are regularly made using sophisticated coupled models of the atmosphere, ocean, and land surface.

How long the lead time should be for a seasonal forecast is still an open question; however, a lead time of around 6 months is considered realistic (Barnston et al., 1994, 1999), and a recently developed multi-model ensemble system demonstrates a lead time of only 3 to 6 months (e.g., Stockdale et al., 1998; Palmer et al., 2004). Zebiak and Cane (1987) argued that the lead time could extend to as much as one year in the equatorial Pacific Ocean, and Luo et al. (2008) conducted extended ENSO predictions with medium skill scores at lead times from 16 to 24 months in the central and eastern equatorial Pacific using a fully coupled ocean-atmosphere model. It has been asserted that, throughout the past century, prominent El Niño events could be predicted with lead times of up to two years (Chen et al., 2004).

The purpose of this paper is to evaluate the performance of a coupled model developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) on ENSO seasonal forecasts to address the question of lead time based on the results of seasonal hindcast experiments. This paper is organized as follows: Section 2 describes the coupled model, the design of hindcast experiments, and the initialization scheme. The performance of the model in ENSO prediction is described in section 3, and conclusions and discussion are given in section 4.

2 The coupled model description and the hindcast experiments design

2.1 The Flexible Global Ocean Atmosphere Land System-gamil (FGOALS-g)

The coupled model used in this study is FGOALS-g, version 1.11, which originated from the Flexible coupled general circulation model (GCM), version 1.0 (FGCM-1.0), (Yu et al., 2002, 2004, 2007) and was developed at LASG at the Institute of Atmospheric Physics (IAP). This model couples atmosphere, oceanic, land, and sea ice component models with the National Center for Atmospheric Research (NCAR) flux coupler.

The oceanic component model is a LASG/IAP Climate system Ocean Model (LICOM), version 1.0, (Zhang et al., 2003; Liu et al., 2004). There are thirty vertical layers in this model, with twelve equal levels in the upper 300 meters. The horizontal resolution of LICOM is 1°×1° in this study. The domain of the oceanic model covers from 75°S to 88°N, and the North Pole is treated as an isolated island. More description of the ocean model can be found in Zhang et al. (2003).
The atmospheric component is a Grid-point Atmospheric Model of IAP/LASG (GAMIL), version 1.1.0. This model is based on a new dynamic core (Wang et al., 2004) and the physical parameterizations of the Community Atmospheric Model Version 2 (CAM2) of NCAR (Kiehl et al., 1996), except for a modified Tiedtke convective scheme (Li et al., 2007). The model employs a hybrid horizontal grid with a Gaussian grid of 2.8° between 65.58°N and 65.58°S and a weighted even-area grid elsewhere (Wang et al., 2004). Vertically, there are 26 o-layers from the surface to 2.194 hPa.

LICOM1.0 and GAMIL1.1.0 are coupled through NCAR coupler version 5 (Kauffman and Large, 2002). A dynamical sea ice model known as the Community Sea Ice Model, version 4 (CSIM4) (Weatherly et al., 1998) and a land model known as the Community Land Model, version 2 (CLM2) (Bonan et al., 2002) are also coupled together. The frequency of coupling is one day for the oceanic model and one hour for the atmospheric, land, and sea ice models.

2.2 The hindcast experiments design

Two steps are involved in our ENSO hindcast experiments. The first step is to integrate the coupled GCM with Sea Surface Temperature (SST) nudged to the observed one from 1971 to 2006 in order to get continuous compatible initial conditions for the ocean and atmosphere. The SST nudging approach used to generate initial conditions has been utilized in previous studies (e.g., Chen et al., 1997; Oberhuber et al., 1998; Luo et al., 2005) and proved to be effective to produce realistic thermocline and wind stress in the equatorial Pacific (Luo et al., 2005). The time scale for the SST nudging (also called SST-relaxed or SST-restored) term is two days. For the period from January 1971 to October 1981, SSTs are strongly nudged toward the monthly Global Sea-Ice and Sea Surface Temperature (GISST) observations (Rayner et al., 2006). For the period from October 1981 to December 2005, the SSTs are strongly nudged toward the weekly National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) observations (Reynolds et al., 2002). Both GISST and OISST have been linearly interpolated into a daily mean before the SST nudging experiment. The results generated in the first step are a set of compatible oceanic, atmospheric, land, ice, and coupler initial conditions.

The second step is to utilize the initial values from the SST nudging experiment on 1 January, 1 April, 1 July, and 1 October from 1982 to 2005, respectively. Furthermore, the coupled GCM is integrated one year without SST nudging. In total, there were 96 hindcast experiments carried out in the second step, and each hindcast experiment was integrated for 12 months.

3 Results

3.1 Initial conditions

To examine the validation of oceanic initial conditions, 20°C isotherm depth anomalies along the equatorial Pacific (2°S–2°N) from both the Global Ocean Data Assimilation System (GODAS: Xue et al., 2008) and model results are given in Fig. 1. The model can realistically reproduce the eastward propagation of warm sub-surface ocean signals during positive ENSO events, though with smaller amplitudes of the thermocline variations. In comparison to the GODAS assimilation, the thermocline fluctuations associated with the interannual ENSO events over the past 20 years are well simulated. It is important to note that, in this SST-nudging experiment, the SSTs influence the wind stress through surface heat flux, and then the wind stress influences thermocline depth through upwelling. Realistic subsurface signal simulation comes from good simulation of wind stress (Fig. 2). Both strong anomalous westerly signals (1982/83, 1997/98) and weak ones (1986/87, 1991/92, 2002/03) are captured in simulation without magnitude decay. Additionally, negative signals related to La Niña events as well as positive signal propagation are well simulated.

As mentioned by Luo et al. (2005), when the Atmospheric General Circulation Model (AGCM) component forced by such generated SSTs, which are very close to the observed values, the model tends to produce realistic wind stress, heat and water fluxes. Furthermore, the Oceanic General Circulation Model (OGCM) driven by the wind stress tends to produce realistic thermocline variations in the equatorial Pacific. Therefore, the success of the simple coupled SST nudging scheme for initialization crucially depends on the performance of the coupled GCM. The results of initial conditions show that the coupled model, FGOALS-g1.11, is able to reproduce realistic oceanic memory for the ENSO prediction using the simple SST nudging scheme.

3.2 ENSO predictability

ENSO is one of the most important modes of interannual variability in the tropics and imposes significant influence on the natural climate system (Philander, 1990). SSTs in the tropical Pacific are a major source of predictability in the atmosphere on seasonal time scales, and model performance in the tropical Pacific is of particular interest (Palmer et al., 2004). In order to assess our model’s performance, we take into account the ability to predict ENSO events.

Figure 3 exhibits the spatial distribution of the Anomaly Correlation Coefficient (ACC) score for 3-month and 6-month lead times. The ACC score is the correlation between the SST anomalies from predictions and observations. Considering the 3-month lead case, for example, prior to calculating the ACC, all 3-month lead hindcast results of the four seasonal groups are combined together by temporal order. There are 24 time points for the hindcast results of a single season, so combining the hindcast results of four seasons will lead to a series of 96 time points from March 1982 to March 2006. Similar treatments are implemented for the 6-month lead case, and the series covers from June 1982 to June 2006. The interval is 3 months because hindcast integration is started in January, April, July, and October. Subtracting the climatologically seasonal mean, we obtain an anomalous series
of predictions and corresponding observations (monthly NOAA/Climate Diagnostic Center (CDC) SST (Reynolds et al., 2002). Then, both the anomalous model outputs and the anomalous observations are smoothed by the 6-month running mean to eliminate intraseasonal time scale variations. After these pretreatments, we compute the correlation between predictions and observations (ACC score) using the following formula:

\[
A_{CC} = \frac{\sum_{i=1}^{n} P_i' O_i'}{\sqrt{\sum_{i=1}^{n} P_i'^2} \sqrt{\sum_{i=1}^{n} O_i'^2}},
\]

where \( i \) represents the time index and \( P_i' (O_i') \) represents the smoothed anomalous prediction (observation) when the time index is \( i \). This indicator (ACC score) has been widely used to assess the ability of a model to predict ENSO (e.g., Zhou et al., 1998; Palmer et al., 2004; Luo et al., 2005). Figure 3 indicates that the model results best predict observation in the cold tongue area, i.e., the central and eastern equatorial Pacific, for both the 3-month and 6-month lead times. The model produces useful predictions (ACC score \( \geq 0.6 \)) of the SST in most of the tropical Pacific and Atlantic Oceans for a 3-month lead time (Fig. 3a). While for a 6-month lead time, the region with useful predictions (ACC score \( \geq 0.6 \)) shrinks to the equatorial and near equatorial area over the central and eastern Pacific. Simulations in the Indian Ocean are not as good as those in the tropical Pa-
specific. When the lead time extends to 6 months, the ACC score dips below 0.4 over most of the Indian Ocean (Fig. 3b).

Niño-3.4 SST anomalies of observation and model predictions are given in Fig. 4a. Three important characteristics of the model are demonstrated in this figure: (1) El Niño event forecasting is better than La Niña event prediction. The El Niño events in 1986/87, 1991/92, and 1997/98 are successfully predicted for up to a 1-year lead time. The El Niño event in 1982/83 is successfully predicted for up to a 9-month lead time. Only a single warm event, which occurred in 2002/03, is not well simulated. For this work, success in ENSO hindcast is defined by the simulation of a positive phase that is consistent with the observed positive phase and a approximately consistent large simulated amplitude compared with the corresponding observed amplitude. In particular, the strong warm event in 1997/98 is the best simulated as the predicted phase and amplitude are nearly identical to observation for up to a 9-month lead time. (2) A strong La Niña event in 1988/89 is successfully simulated, while weak ones in 1984/85 and 1999/2000 are not reproduced well and have much larger simulated amplitudes. (3) When the lead time exceeds 6 months, an unrealistic warm event occurs in the simulation. Beyond a 6-month lead time, cold event prediction tends to be amplified and an unrealistic warm event emerges. These results support the argument by Barnston (1994, 1999) that a 6-month lead time is considered more realistic.

Figure 4b shows the persistence forecast and ACC scores of the Niño-3.4 SST index. The persistence of the Niño-3.4 SST index is the correlation of the observed
Niño-3.4 SST with itself when shifted in time by a certain lag. It represents the SSTs’ autocorrelation over the Niño-3.4 region and, hence, the persistence in the real ENSO system. In this work, variable ACC is defined as the correlation between prediction and observation over the Niño-3.4 index and not a particular spatial spot’s anomalous index. When the ACC scores are higher than the persistence for a certain lead time, it suggests that the ENSO prediction ability of the model is better than the forecast ability via computing autocorrelation for that time scale. Zhou et al. (1998) and Luo et al. (2005) have compared these two variables in their study. Without a good initialization procedure, the ACC scores are not very large within a 5-month lead time (Zhou et al., 1998). In this study, the ACC scores of the Niño-3.4 SST index are much higher than the persistence forecast not only for long (9-month beyond) but also for short lead times. This is a verification of the ENSO prediction abilities of the model. As the ACC of the Niño-3.4 SST index is the only consideration in this work, the model shows a high prediction ability (ACC $\geq 0.6$) when the lead time is extended to 8 months, and, therefore, a realistic lead time might vary from 6 to 9 months for the coupled model.

5 Conclusion and discussion

In this study, we present ENSO seasonal hindcast experiments from 1982 to 2005 using a coupled climate model developed at LASG. The following conclusions could be drawn from this model: 1) Initial conditions are realistic for both the wind stress anomaly and the thermocline anomaly, and they are reproduced well not only during strong warm (cold) events but also weak events; however, the simulated thermocline anomaly is slightly smaller than observation. This model demonstrates that SST nudging is an effective assimilation methodology for the coupled GCM. 2) After filtering out intraseasonal variation of both observations and simulations, ENSO events are well simulated for warm events or strong events with a slightly amplified magnitude. From a comprehensive perspective, taking both the Niño-3.4 SST anomalies (Fig. 4a) and the ACC of the Niño-3.4 SST index (Fig. 4b) into account, the coupled model tends to demonstrate a realistic lead time of 6 to 9 months.

It should be noted that the coupled model reproduces realistic anomalous westerly and easterly wind stress with an amplitude comparable to observation (Fig. 2), but the amplitude of the related thermocline depth anomaly is not as large as the observation (Fig. 1). This might be attributed to the weak feedback provided by the ocean to wind stress in the coupled model. Additionally, it was found that, although sub-surface simulation is smaller than observation (Fig. 1), related ENSO predictions show an amplitude approximately equal to that of observations (Fig. 4a). To understand this phenomena, we calculate the

![Figure 3](image-url)

Figure 3 Model ACC scores of global SST predictions for (a) 3-month and (b) 6-month lead times. The contour interval is 0.1 and regions with values above 0.2 are shaded. Thick solid lines denote 0.6 contours. Results have been smoothed by a 6-month running mean.
climatic zonal average value of the observed thermocline depth and the simulated one in the equatorial Pacific (2°S–2°N, 130°E–80°W). FGOALS-g1.11 produced a shallower climatic thermocline at a depth of 103 m in contrast to the observed thermocline at a depth of 119 m. As a result of this discrepancy, the sea surface temperature in the tropical Pacific is more sensitive to a sub-surface anomaly. The source of the weak feedback of the ocean to the atmosphere as well as the prediction of shallower thermocline depths remains unknown and is a subject for future investigation.

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