Interactive coupled ensemble: A new coupling strategy for CGCMs

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[1] This paper presents a new strategy for coupling state-of-the-art oceanic and atmospheric general circulation models. The procedure is to use multiple realizations of the atmospheric GCM coupled to a single realization of the ocean GCM. The ensemble mean state of the atmospheric GCM fluxes are coupled to the ocean model thereby affecting the evolution of the coupled system. The traditional approach for generating a coupled ensemble is to apply the ensemble averaging to a collection of individual realizations a posteriori. This interactive ensemble technique is distinct from the traditional procedure because here the ensemble mean of the atmospheric models continuously interacts with the ocean model as the coupled system evolves. Simulation experiments with and without the interactive ensemble are described. The interactive ensemble coupled model produces realistic ENSO events that are irregular. This technique also dramatically improves the simulation of the global teleconnection associated with ENSO, and the ENSO-monsoon relationship. *INDEX TERMS:* 0312 Atmospheric Composition and Structure: Air/sea constituent fluxes (3339, 4504); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4522 Oceanography: Physical: El Niño

1. Introduction

[2] It is well established that interannual variations of large scale atmospheric circulation and rainfall, especially over tropical oceans, can be simulated by current state-of-the-art Atmospheric General Circulation Models (AGCM) with a high degree of realism provided that the sea surface temperature (SST) is prescribed. This is because the influence of boundary forcing is so strong that it can capture a large fraction of observed variability in spite of model deficiencies. In other words, the atmospheric tropical circulation is nearly insensitive to the initial atmospheric conditions and largely determined by the SST boundary conditions [*Shukla*, 1998]. Likewise, it is also well established that interannual variations of tropical SST can be simulated by the current state-of-the-art Ocean General Circulation Models (OGCM) with prescribed atmospheric forcing. However, once the two state-of-the-art component models of the atmosphere and the oceans are coupled, the resulting simulations have large systematic errors [*Mechoso et al.*, 1995].

[3] There is a simple and straightforward hypothesis for the deficiency of the coupled models. Because the tropical atmosphere is so strongly forced by SST, as long as the SST is prescribed, the atmospheric circulation is constrained to respond to the prescribed SST [*Shukla*, 1998]. However, in a coupled model, the tropical atmosphere is highly sensitive to changes in SST, some of which might be erroneous due to model deficiencies. The tropical ocean-atmosphere system is highly coupled; therefore, errors in one component of the coupled model quickly influence the other component which in turn affects the first component. Since the feedbacks between the atmosphere and the oceans are critical for the evolution and decay of large scale SST anomalies, the challenge for coupled modeling is to find ways to reduce the growth of undesirable and erroneous fluctuations in the coupled system without seriously affecting the growth and decay of natural phenomena like El Niño and the associated Southern Oscillation (ENSO).

[4] The most desirable, and also perhaps the most appropriate procedure to reduce the errors of coupled models is to improve the individual parameterizations in AGCMs and OGCMs. We strongly support this approach. However, in this paper we suggest a new strategy for coupled modeling. We suggest that, as the coupled model simulation evolves, the OGCM should be forced by the ensemble mean of multiple realizations of the atmospheric circulation. The procedure is to couple multiple realizations of a particular AGCM or multiple realizations of different AGCMs to a single OGCM. The AGCM ensemble mean fluxes are used to drive the ocean model, while all atmospheric ensemble members experience the same SST produced by the OGCM.

[5] This suggestion was motivated by the fact that current AGCMs are problematic in the representation of the fluxes at the air-sea interface, particularly those associated with internal dynamics. We have seen, in a large number of AGCM simulations, that the AGCM ensemble mean has less error than any single ensemble member suggesting that there are serious problems with the variability associated with internal dynamics. The recent results of *Krishnamurti et al.* [2000] for super ensemble forecasts further support this notion. However, the suggestion put forward here for compensating for this problem is quite different from the *a posteriori* super-ensemble procedure. We suggest that the ocean model continuously interact with the ensemble mean atmosphere. The end result of such a simulation could be quite different from averaging the end results of several coupled model simulations.

[6] For conceptual simplicity, variability simulated by the atmospheric model can be considered to include two components: (i) the SST forced variability (which we will refer to as signal), and (ii) the non-SST-forced variability, to be referred to as the internal dynamics noise. Currently available coupled models do not have the ability to discriminate between the signal and the noise, and both will grow because of the intrinsic strong feedbacks present in the coupled ocean-atmosphere system. If an AGCM has the property of producing unrealistically large internal dynamics noise, the strong feedbacks of the coupled system will amplify that further, and it will not be possible for the coupled model to sustain the growth of the true SST-forced signal. Our procedure is based on the assumption that the AGCM has unrealistic internal dynamics noise, and that an ensemble average of multiple atmospheric states forced by the same SST will reduce the internal atmospheric noise, thereby enhancing the relative strength of the SST forced signal. If the atmospheric model had a perfect simulation of the space-time statistics of the internal dynamics noise, and if the internal dynamics noise was important for the simulation of climate variability, then the interactive ensemble technique would degrade the simulation of the climate variability. In fact, the interactive ensemble procedure can be used to reduce or remove the internal dynamics noise and estimate just how important internal dynamics noise is in producing climate variability.

[7] Our assumption that the AGCM has too much variability due to internal dynamics is supported by the results presented in Figure 1. Here we show the COLA AGCM 850 mb zonal wind

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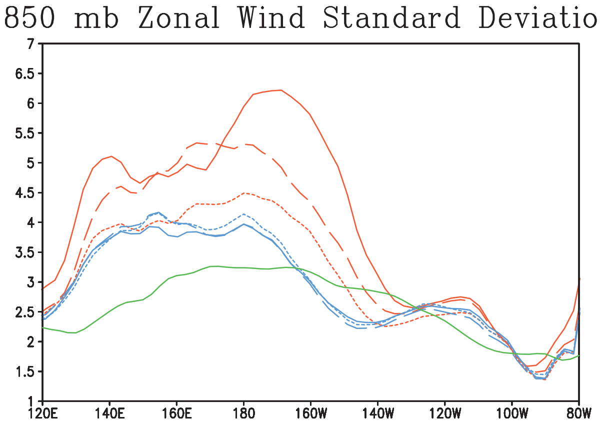

Figure 1. COLA AGCM 850 mb zonal wind standard deviation along the equator as a function of ensemble size. The solid red curve is based on one ensemble member and the long (short) dashed corresponds to an ensemble mean of two (three). The solid blue curve is for four ensemble members and the long (short) dashed curves is for en ensemble mean of five (six). The green curve is from NCEP reanalysis.

variance along the equator in the Pacific as a function of ensemble size. For comparison, the variance from NCEP reanalysis is also shown. The variances are calculated based on monthly mean data. With one ensemble member it is clear that the COLA model has considerably more variance than the reanalysis. For this particular field in this particular region, it appears that the model signal is reasonably well isolated with six ensemble members. For different fields and different regions, larger ensembles might be required for similar levels of noise reduction. It is also interesting to note that even though the variance has been significantly reduced by the ensemble averaging, the model has too much variability in the western Pacific. This is consistent with a systematic problem with the AGCM in which the wind stress anomalies are displaced too far to the west.

[8] The purpose of this paper is to describe the interactive ensemble technique and to present an example of the actual implementation of the technique. The results from this particular application suggest that there is substantial potential to improve the simulation of global coupled ocean-atmosphere variability. We focus on examining how reducing the atmospheric internal dynamics noise in the coupled model impacts global scale interannual variability. We have not investigated in detail the regional aspects, the issues regarding how to exploit the distribution defined by the AGCM ensemble, or the potential sensitivity to ensemble size. Much additional work needs to be done in this regard. Nevertheless, the results shown here are indicative of the potential utility of the technique, and we further believe that the interactive ensemble technique provides a systematic approach for isolating how internal dynamics noise impacts the variability and predictability of the coupled climate system.

2. Natural Variability

[9] In this example, six (N = 6) realizations of the AGCM are coupled to a single realization of the OGCM. The AGCM is identical for each ensemble member and the six AGCM realizations only differ in their initial conditions. Because the atmosphere is sensitively dependent on initial conditions, the six realizations evolve differently. As the interactive ensemble evolves, each AGCM realization experiences the same SST predicted by the OGCM. The OGCM, on the other hand, experiences surface fluxes that are the ensemble average of the six AGCM realizations.

[10] The atmospheric component of the interactive ensemble anomaly coupled model is the COLA AGCM with triangular truncation at wave number 42 and 18 vertical levels. The ocean model is adapted from the GFDL modular ocean model [*Rosati and Miyakoda*, 1988; *Pacanowski et al.*, 1993] version 3 (MOM3). The component models are anomaly coupled in terms of heat, momentum and fresh water [*Kirtman et al.*, 2002]. The atmospheric initial states are taken from a 30 year simulation with observed SST, and are therefore synoptically independent. Similarly, the ocean initial state is taken from a 30 year simulation with climatological surface fluxes. The coupling frequency of the models is daily with daily mean values being exchanged between the ocean and the atmosphere. Both simulations have been run for 200 years and all of the analysis shown here is based on the data for the last 150 years.

[11] Figure 2 shows the NINO3.4 auto-correlation from the standard COLA anomaly coupled model [i.e., one AGCM coupled to one OGCM; *Kirtman et al.*, 2002], the interactive ensemble coupled model and the observations. The auto-correlation shows that neither model is persistent enough at short lags (2–3 months). There is also a strong tendency to transition from one phase of ENSO to another that is not observed. Power spectral analysis (not shown) of both simulations yield a broad peak between two and four years. The interactive ensemble model has more power than the standard model near biennial time scales and both simulations have power at 48 months. While there have been periods in the observational record where the ENSO time scale is predominantly biennial [*Wang and Wang*, 1996], the dominant time scales in both simulations are shorter compared to that in observations. This is likely due to errors in the basic structure of the wind stress anomalies [*Kirtman*, 1997; see also Figure 1]. Both models produce ENSO events that peak in the boreal winter, but they are too short in duration. Observed warm SST anomalies last approximately 9 months, and in both simulations the warm SST anomalies last only about 6 months. In terms of phase locking to the annual cycle, both model simulations are too sharply peaked, the signature of which can be detected in Figure 2. In other words, the model ENSO events have a well defined maximum in December, whereas the observed maximum occurs during November through January. The ENSO events in both model simulations are irregular. Both models produce extended quiescent and active periods that are similar to the observed record.

[12] The mere fact that the interactive ensemble coupled model can produce realistic ENSO variability is of some interest. This is

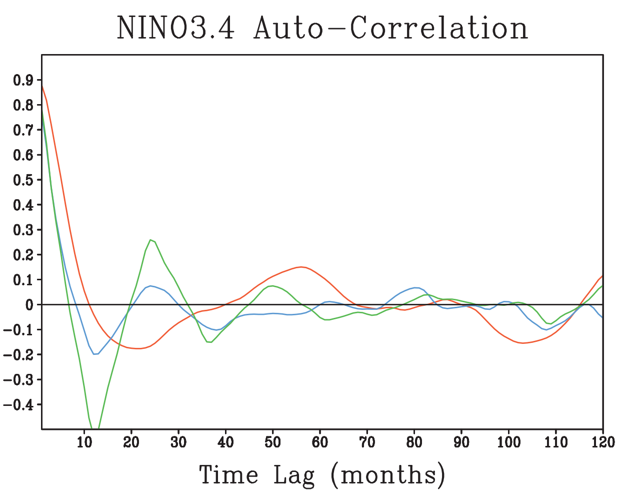

Figure 2. NINO3.4 auto-correlation for the observations (red), the standard model (blue) and the interactive ensemble model (green).

because there is an ongoing debate as to whether ENSO is self-sustained [e.g., *Zebiak and Cane*, 1987] or stochastically driven (e.g., Penland and Sardeshmukh, 1995). It is also of interest that the ENSO events in the interactive ensemble model are irregular, because there is no consensus whether the irregularity of ENSO is due to internal non-linear dynamics of the coupled system [*Chang et al.*, 1994] or external stochastic forcing [*Kleeman and Moore*, 1997; *Kirtman and Schopf*, 1998].

[13] One of the biggest challenges facing current state-of-the-art coupled general circulation models (CGCMs) is capturing the global teleconnections associated with ENSO. A clear example of this shortcoming can be seen by comparing the top and bottom panels of Figure 3. Here we show the linear regression of a typical ENSO index with global SSTA for the standard model (bottom panel) and for observations (top panel). The relatively weak regression in the Indian Ocean and in the extra-tropics is typical of current state-of-the-art CGCMs [see also *Kirtman et al.*, 2002]. The middle panel of Figure 3 shows the same calculation for a long simulation using the interactive ensemble technique. Clearly, the regression is much stronger in the Indian Ocean and in the extra-tropical Pacific, particularly along the west coasts of North and South America, and the structure of the correlation pattern is far more realistic. There are also some indications that the meridional scale of the regression in the near equatorial central and eastern Pacific is improved. This meridional scale problem has been noted in many other coupled simulations [e.g., *Kirtman et al.*, 1997]. In the Atlantic Ocean, the regression is considerably larger than observed suggesting that, perhaps, too much noise has been removed. In other words, the ENSO forced variability in the tropical Atlantic would be more coherently linked to ENSO if it were not influenced by internal dynamics noise.

[14] Estimates of climate predictability based on uncoupled AGCM simulations may underestimate the limit of predictability of the coupled system. A good example of this is the ENSO-monsoon interaction. Here we show the correlation between June-September Indian monsoon rainfall anomalies[1] and global SSTA during the winter season (December–February) following the monsoon. This relationship, in which the monsoon leads ENSO by two seasons has been notoriously difficult to simulate in both CGCMs and AGCMs. Figure 4 shows results from observations, the interactive ensemble coupled model and an ensemble of 6 uncoupled AGCM simulations with observed SST. The top panel shows the observed relationship based on 50 years of data (1949–1998). The middle panel shows the same calculation (50 years of data) using the ensemble mean rainfall from the interactive ensemble model, and the bottom panel shows the correlation based on a 50 year (1949–1998) AGCM simulation with observed SST. As with the interactive ensemble, the ensemble average (6 members) was used to calculate the correlation in the bottom panel of Figure 4. The interactive ensemble coupled model appears to capture the observed relationship well, whereas the ensemble mean from the uncoupled AGCM simulations fails to even capture the correct sign of the correlation throughout most of the tropics.

[15] There are two key aspects to the improved simulation with the interactive ensemble: (i) an ensemble is required to

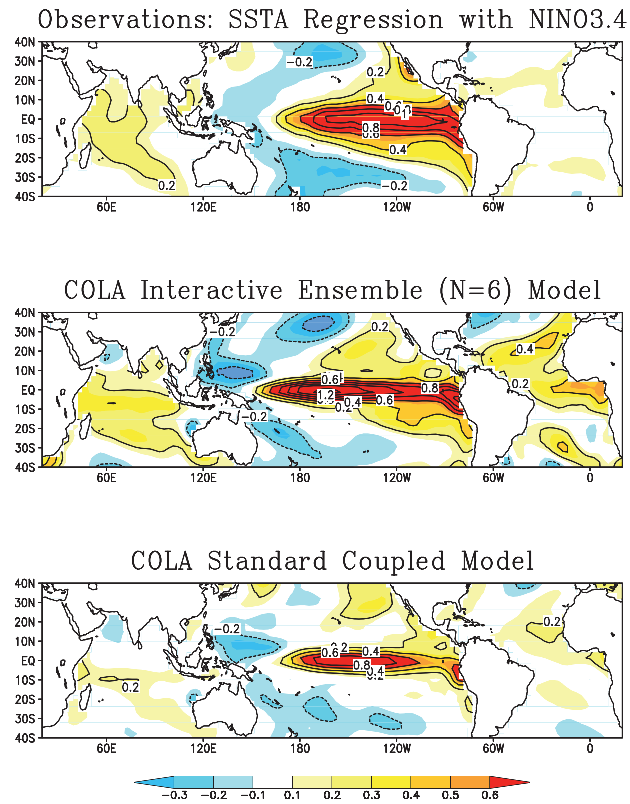

Figure 3. Linear Regression between NINO3.4 time series and global SSTA. The top panel shows the regression coefficient based on observational data, the middle panel shows the results from the interactive ensemble and the bottom panel shows the results from the control anomaly coupled model.

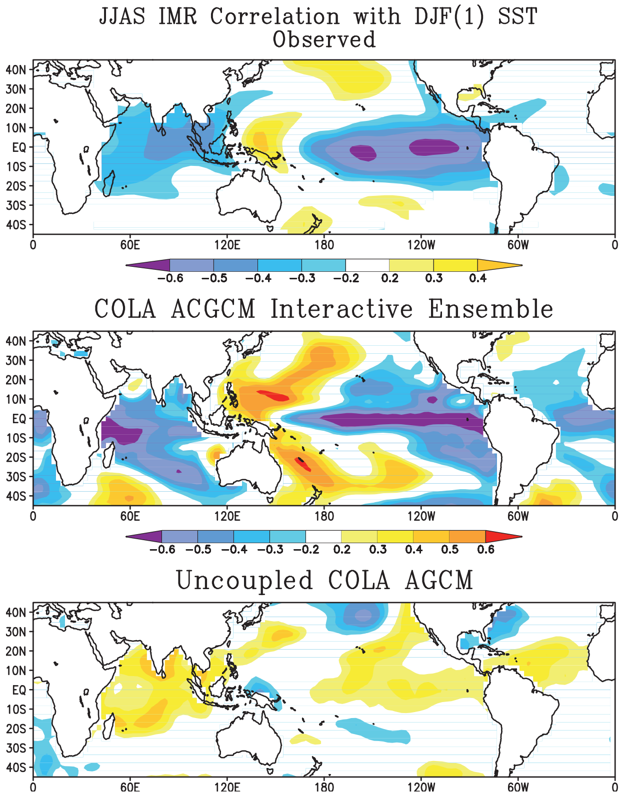

Figure 4. Correlation between Indian summer (June–September) monsoon rainfall and the subsequent winter season (December–January–February) SSTA. The top panel shows the observed correlation, the middle panel shows the results from the interactive ensemble, and the bottom panel shows the results based on a 6-member ensemble of AGCM simulations with observed SST.

[1] The observed rainfall [*Parthasarthy et al.*, 1993] includes only land based station data. For all the model simulations shown here we have included a larger area (5°N–25°N and 60°E–100°E) that extends over the neighboring oceans.

isolate the rainfall signal over the monsoon region, and (ii) the model must be coupled so that monsoon variability can affect ENSO variability [*Chung and Nigam*, 1999; *Kirtman and Shukla*, 2000]. It must be emphasized that we are not suggesting that the monsoon causes ENSO, rather we are arguing that the monsoon variability affects the timing and evolution of ENSO events. Without this explicit coupling, this impact of the monsoon on ENSO is absent, and it is difficult to capture the observed ENSO-monsoon relationship.

3. Concluding Remarks

[16] The coupling strategy presented here allows for the reduction of the chaotic part of the atmospheric circulation at the air-sea interface that is unrelated to the predicted surface boundary condition, and it has the potential to reduce the systematic error at the air-sea interface as the CGCM evolves. This new coupled modeling technique, which we refer to as an interactive ensemble, has multiple realizations of an AGCM coupled to a single ocean model.

[17] Based on multi-decadal simulations it was shown that the interactive ensemble coupled model produced realistic and irregular ENSO variability. The two coupling strategies differ substantially in terms of the global teleconnections associated with ENSO. For example, the interactive ensemble coupled model appears to produce a better simulation of the spatial correlation between ENSO and sub-tropical Pacific SSTA, and the meridional spreading of the ENSO signal along the North and South American coast. The interactive coupled model also captured the observed correlation with the Indian Ocean SSTA. This particular feature has been extremely difficult for current state-of-the-art CGCMs to simulate. Finally, we showed that the interactive ensemble coupled model correctly captured the observed ENSO-monsoon lag-correlation.

[18] We believe that the interactive ensemble approach gives a better simulation of climate variability because the AGCM's internal dynamics noise is too strong and too coherent in space and time compared to observations. Since the AGCMs have limited spatial resolution, the internal dynamics noise projects onto spatial scales that are too large compared to the observed internal dynamics noise. The stronger and more coherent the noise is in space and time, the more efficient it is in generating artificial coupled variability, and therefore in disrupting the ENSO cycle [*Kirtman and Schopf*, 1998]. This problem of internal dynamics noise that is too strong and coherent is likely to be endemic to all climate resolution AGCMs.

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