A Comparison of the Atmospheric Response to ENSO in Coupled and Uncoupled Model Simulations

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ABSTRACT

In the Atmospheric Model Intercomparison Project (AMIP) simulations the sea surface temperatures (SSTs) are specified and the oceanic evolution consistent with air–sea interaction is not included. This omission could lead to errors in the atmospheric response to SSTs. At the same time, the AMIP experimental setup is well suited for investigating many aspects of climate variability (e.g., the attribution of the interannual atmospheric variability) and continues to be extensively used. As coupled El Niño–Southern Oscillation (ENSO) SST variability is a dominant factor in determining the predictable component of the observed interannual atmospheric variability, the difference in the atmospheric response to ENSO SSTs between AMIP and coupled simulations is investigated. The results indicate that the seasonal atmospheric response to ENSO between coupled and uncoupled integrations is similar, and the inclusion of oceanic evolution consistent with air–sea interaction does not play a dominant role. The analysis presented in this paper is one step toward assessing differences in atmospheric response to SSTs in coupled and uncoupled simulations, and is required to correctly interpret the results of AMIP simulations.

1. Introduction

The scientific underpinning for seasonal climate prediction efforts is the global atmospheric impacts of tropical sea surface temperature (SST) variability related to the El Niño–Southern Oscillation (ENSO) phenomenon. An understanding of ENSO’s global teleconnection started with the analysis of the observed interannual climate variability (Horel and Wallace 1981), and was subsequently augmented using theoretical developments (Hoskins and Karoly 1981). Due to data limitations, however, analysis based on observations continues to be limited in its scope and reliable estimates of the influence of the ENSO SSTs can only be discerned for a composite ENSO SST state.

Faced with limitations in the observational data, efforts based on the analysis of atmospheric general circulation model (AGCM) simulations have also been pursued. In the AGCM-based approach, an analysis of multiple atmospheric realizations allows separation of the atmospheric signal related to different ENSO SSTs. Indeed, atmospheric response to ENSO SSTs has been extensively documented using an ensemble of AGCM simulations forced with observed SSTs [the so-called Atmospheric Model Intercomparison Project (AMIP) simulations; Gates 1992; Trenberth et al. 1998; Hoerling and Kumar 2002]. AGCM analyses have extended our knowledge base of atmospheric response to SSTs beyond a single ENSO composite, and this understanding is currently used in seasonal climate prediction efforts (Goddard et al. 2006).

Extensive use of AMIP simulations in the analysis of the atmospheric interannual variability notwithstanding, it is also recognized that the experimental setup of the AMIP simulations is an approximation for the observed reality because AMIP simulations do not include coupled ocean–atmospheric evolution and SSTs are treated as an external forcing. The one-way forcing of the atmosphere by the SSTs is known to alter char-
acteristics of the air–sea interactions and possibly affects atmospheric variability and atmospheric response to SSTs (Barsugli and Battisti 1998; Bretherton and Battisti 2000). It is therefore of interest to document potential errors in the atmospheric response to ENSO SSTs in the AMIP simulations, and we approach this analysis by comparing the atmospheric response between coupled and AMIP simulations.

The intent of the analysis is not to document differences in the characteristics of air–sea interaction between coupled and AMIP simulations for which a firm theoretical basis exists (Barsugli and Battisti 1998; Bretherton and Battisti 2000), but to analyze what impact differences in the two sets of simulations have on the atmospheric response to ENSO SSTs. The potential difference in the atmospheric response to ENSO between coupled and AMIP simulations, however, is relative and does not tell which one is more realistic. The realism of the atmospheric response is assessed by comparing against the observed atmospheric response to ENSO. Because the coupled simulations are closer to the observed reality, a prior expectation is that the atmospheric response in the coupled simulation would be closer to their observed counterpart.

Analysis of the differences in the ENSO response between coupled and AMIP model integrations is of interest for various practical reasons. For example, are inferences about the atmospheric response based on AMIP simulations accurate enough to be used in seasonal climate predictions (Quan et al. 2006; DelSole and Shukla 2006)? Similarly, in the attribution analysis of the observed seasonal mean atmospheric anomalies, it is often a standard procedure to use AMIP simulations that are forced with the observed SSTs in different ocean basins (Biasutti et al. 2006; Kharin et al. 2005). For such a methodology to lead to justifiable conclusions, an assessment of the accuracy of the atmospheric response to the specification of SSTs in the AMIP simulations is required.

2. Data and analysis procedures

The analysis is based on a comparison of ensemble mean atmospheric response to ENSO between coupled predictions and AMIP simulations. Data for the coupled predictions is from the National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) hindcasts. The CFS hindcasts are for the 1982–2005 period. In the standard set of CFS hindcasts there are 15 forecast integrations for each month in the year. The initial conditions for the CFS integration are in groups of five initial conditions that are separated by 1 day and are centered on the 1st, 11th, and 21st of the month (Saha et al. 2006). In our analysis, forecast data from five initial conditions closest to the target season is used, and for the seasonal mean of December–February (DJF), forecasts initialized from 29–30 November and 1–3 December are included in the analysis. This choice of initial conditions, because of the shortest lead, results in the least amount of forecast errors for the CFS-predicted SSTs and ensures that the SSTs in the coupled integrations are the closest possible to the observed SSTs specified in the AMIP simulations.

For the AMIP simulations, the atmospheric component of the CFS is used for the model integrations. For both coupled and AMIP simulations an ensemble size of five is utilized. The atmospheric model for the CFS and the AMIP integrations is the same and has a triangular spectral truncation of 62 waves (T62) with 64 levels in the vertical. We should point out that in the present setup of the AMIP simulations and coupled CFS predictions, two-way ocean–atmospheric interaction is not the only difference between the model integrations. For example, while AMIP simulations are continuous integrations starting from observed initial conditions that are far removed from the analysis period (Gates 1992), coupled integrations are initialized from the observed atmosphere and land states (Saha et al. 2006). For short lead times, the specification of initial conditions in the coupled CFS predictions can also have some influence on the ENSO response. Yet another difference related to the mean SSTs between two integrations is discussed in section 3.

Our analysis of the ENSO response between AMIP and CFS integrations is for the common period of model integrations (i.e., 1982–2004). Results are mainly shown for the DJF seasonal means. This season was selected because 1) the amplitude of interannual variability of SSTs is near its maximum (Trenberth et al. 1998), and 2) tropical–extratropical interactions are strongest during this season (Kumar et al. 2003).

The analysis of the model-simulated ENSO response is also compared with the corresponding atmospheric response in the observations. Such a comparison provides an assessment of whether the ENSO response in the coupled integrations is closer to the observed reality or not. For comparison with the observed composites, the 200-mb seasonal mean heights are from the NCEP–National Center for Atmospheric Research (NCAR) reanalysis. The observed seasonal mean rainfall is from the Climate Anomaly Monitoring System-Outgoing Longwave Radiation Precipitation Index (CAMS-OPI) rainfall estimates (Janowiak and Xie 1999).

For the analysis period of 1982–2004, the warm ENSO events are chosen as 1983, 1987, 1992, and 1998, and the cold ENSO events are chosen as 1985, 1989,
1999, and 2000 (with the year defined based on the January of the DJF seasonal mean). The results of the atmospheric response to ENSO are displayed as the difference between the warm and cold ENSO composites. DJF seasonal mean anomalies for model integrations and observations are computed from respective climatologies.

3. Results

Since CFS is a coupled prediction system, the time evolution of SSTs in the CFS integrations need not be the same as the observed evolution of SSTs that are used in the AMIP simulations. Shown in Fig. 1 is the bias in the SST prediction for the CFS. This bias is also the difference in the mean of the SSTs between the AMIP simulations and the ensemble-averaged CFS predictions. The main feature to note is a large warm SST bias in the Southern Hemisphere extratropics and over the regions of persistent stratus decks off the west coast of the continental regions (e.g., Africa, South America, etc.). This warm bias is associated with the underestimation of the low-level cloudiness resulting in excessive shortwave radiative flux at the surface (not shown). SST bias in the tropical regions, with the exception near the Maritime Continent, is generally less than 0.5°C.

Bias in the predicted SSTs, particularly in the extratropical latitudes (together with differences in the initial atmospheric and land conditions between the CFS predictions and the AMIP simulations), is a complicating factor in the interpretation of the differences in the ENSO response. For example, we cannot determine whether the differences are due to the neglect of coupled ocean–atmosphere evolution in the AMIP integrations alone or whether other factors listed above are also contribute. However, if the atmospheric responses to the ENSO in two model simulations are similar, this would imply that the combined influence of the multitude of factors on the ENSO response is marginal (barring the possibility that the influence of various factors is in the opposing direction and sums up to a small net effect). Given that multiple factors could have easily led to appreciable differences in atmospheric response between two simulations, large-scale similarities between atmospheric responses is an important fact.
The interannual variability of SSTs is superimposed on the mean SSTs. Since the focus of our analysis is the atmospheric response to ENSO, a comparison of composite ENSO SSTs between AMIP and the CFS integrations is shown in Fig. 2. The composites are the difference between the warm and cold events. The spatial structure of the composite ENSO SSTs in the top panel (for the AMIP) and the bottom panel (for the CFS predictions) is very similar with spatial correlation being 0.92, highlighting the remarkable predictive capability of the CFS model for short lead times (Saha et al. 2006). Both composites have the characteristic warm SST anomalies in the tropical eastern Pacific surrounded by a horseshoe pattern of cold SST anomalies extending into the extratropical latitudes of both hemispheres.

We next compare the atmospheric response to the ENSO SSTs and this analysis is for the rainfall and 200-mb heights. Shown in Fig. 3 are the composite rainfall responses for the AMIP and CFS integrations, and
these responses are also compared with the observed composite. All three composites show enhanced rainfall in the equatorial Pacific near the date line, surrounded by decreased rainfall to the north and south and over the Maritime Continent. Regions of decreased rainfall are also located over South America and in the southern regions of Africa.

The spatial anomaly correlations between various combinations of modeled and observed rainfall response, and for various geographical domains, are shown in Table 1. For the global and the tropical regions, almost all the correlations exceed 0.8, indicating a high degree of spatial similarity. Furthermore, spatial correlation between the CFS and the observed rainfall composite is statistically similar to the corresponding correlations for the AMIP simulations. This fact is of importance because both the observed and the CFS ENSO responses include the possible influence of the coupled ocean–atmosphere evolution, and the a priori expectation is that the correlation between them should be higher.
Correlations for the Pacific–North America (PNA) region between the model-simulated and the observed composites are smaller than for the tropics with the CFS correlation slightly higher (0.72 versus 0.64) than for the AMIP. Furthermore, the model composites among themselves have a higher correlation of 0.92 reinforcing the conclusion that the influence of differences in the experimental setup on the model response is not strong and the low correlation with the observed composite may be an artifact of some model bias that is shared between both sets of simulations.

Various composites for the 200-mb heights are shown in Fig. 4. The spatial pattern of the 200-mb height composites is consistent with earlier modeling and observational studies (e.g., Peng et al. 2000) with above-normal heights in the tropical latitudes and a wave train response that extends into the extratropical latitudes east of the date line. For different spatial domains the anomaly correlations between the AMIP, the CFS, and the observed composites are listed in Table 1. Once again, as evidenced by the correlations that generally exceed 0.8, the spatial pattern of the 200-mb height response to ENSO SSTs are very similar, and furthermore, the magnitude of the correlation between the CFS and the observed height composite is also the same as their AMIP counterpart. Despite the high correlations over the Pacific–North American (PNA) region, there are clear differences in the amplitude between AMIP and CFS composites (see also Fig. 5b), which are discussed below.

The statistical significance of the differences between the CFS and AMIP composites is tested based on the Monte Carlo approach. A total of 1000 samples of composites for the CFS and AMIP (similar to those in Fig. 4) are generated by randomly reshuffling the respective model-simulated time series and selecting the same years in the randomized reshuffled sequence for the composite. On a gridpoint basis, instances when the amplitude of the difference between the CFS and AMIP composites in Fig. 4 exceeds the corresponding value for the composites based on the reshuffled time series are counted. Following this procedure the 95% and 99% significance levels, together with the differences between the CFS (Figs. 3 and 4, middle panel) and the AMIP (Figs. 3 and 4, bottom panel) composites, are shown in Fig. 5.

There are very few regions where the rainfall differences are statistically significant. The largest difference occurs in the tropical equatorial Pacific east of the date line where a north–south couplet of increased–decreased rainfall exists. For 200-mb heights, the largest differences, which are also significant, exist in the Northern Hemisphere polar latitudes. A possible explanation for this is the differences in the lower boundary conditions for the sea ice, which for the CFS simulations are initialized, but for the AMIP simulations, have long adjusted to the model climatology. Such differences in the ice conditions (and surface temperatures) could lead to (barotropic) changes in the upper-level heights. Statistically significant differences also exist over the PNA region, however, as indicated by the correlations in Table 1, the CFS composite response does not correlate better with its observed counterpart. On the other hand, for the AMIP composite the wave pattern has stronger amplitude. The cause is not clear but a possible explanation is that the differences in the mean state between the simulations may affect the characteristic tropical–extratropical teleconnection, and for a similar tropical rainfall signal, may lead to a stronger response for the AMIP integrations.

To summarize, a comparison of the rainfall and 200-mb height composites for the coupled and uncoupled simulations indicates that for the boreal winter season the global atmospheric response to ENSO SSTs between coupled and AMIP simulations is quite similar despite a multitude of factors that could have led to dissimilarities in the atmospheric response to ENSO SSTs (e.g., coupled air–sea evolution, initial conditions, mean state leading to the altered characteristics of tropical–extratropical interactions, etc.). The comparison further indicates that the AMIP simulations are a suitable tool for the analysis of the atmospheric interannual variability.

4. Summary and discussion

Global atmospheric response to the ENSO-related SST anomaly is a key factor for seasonal prediction efforts. An extensive knowledge about the global response to ENSO has evolved based on AMIP simula-
tions, and it is not clear what the associated errors are because of the experimental setting of the AMIP simulations (e.g., neglect of ocean evolution consistent with the air–sea interaction, etc.). An approach for estimating such errors is the analysis of the SST responses between AMIP and coupled integrations, and was the objective of this paper.

The analysis in this paper focused on the composite rainfall and 200-mb height response to ENSO SSTs and a comparison of this response between coupled predictions and AMIP simulations was made. The results indicate that the atmospheric response between the two sets of integrations was similar, despite the additional factors (e.g., SST climatology between coupled and AMIP simulations, particularly in the extratropical latitude of Southern Hemisphere, which had large differences) that could have had further influence on the atmospheric response to ENSO.

The comparison presented in this paper is for the dominant mode of ocean–atmospheric interannual variability (i.e., the ENSO). Similar analysis of other modes of variability (e.g., the summer monsoon over the Asian...
continent, Indian Ocean dipole, interannual variability in the equatorial Atlantic Ocean, etc.) needs to be documented between AMIP and coupled integrations (Wang et al. 2005; Krishna Kumar et al. 2005). Such a documentation of differences and similarities in atmospheric response to SSTs in AMIP and coupled simulations will provide a better perspective on the utilization of the AMIP simulations as a tool for the analysis of atmospheric interannual variability.

The experimental setup used in this paper was not the best possible in that SSTs predicted by the coupled system were not identical to the specification of observed SSTs in the AMIP simulations, and differences in the initial conditions also existed. A potentially improved experimental setup is where SSTs simulated in a long coupled integration are also specified in the AMIP simulation. On the other hand, for such an experimental setup, SSTs in the AMIP simulations no longer match the observed evolution of SSTs, and the realism of atmospheric responses may be harder to infer. Although an experimental setup where SSTs in coupled and uncoupled integrations are the same, and are also

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**Fig. 5.** Difference between warm–cold composites for the CFS and the AMIP for (top) rainfall (mm day$^{-1}$, negative contours are dashed) and (bottom) 200-mb height (m, negative contours are dashed). Differences that are significant at 95% (99%) level based on the Monte Carlo approach are shaded in light gray (dark gray).
the same as that for the observations is not feasible, the various experimental setups discussed above could be utilized to further quantify potential differences between the coupled and uncoupled atmospheric variability.

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**REFERENCES**


