12.3 THERMODYNAMIC COUPLING AND PREDICTABILITY OF TROPICAL SEA SURFACE TEMPERATURE

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Abstract

Air-sea coupling involves the exchange of both momentum and heat between the atmosphere and the ocean. Dynamic coupling, which relates to the momentum exchange, is believed to play the dominant role in the tropics, especially in phenomena such as the El Nino-Southern Oscillation in the tropical Pacific. However, thermodynamic heat exchange between the atmosphere and the ocean also plays a significant role in tropical air-sea coupling. This is especially true in the tropical Atlantic, where dynamic coupling may be of secondary importance. In this study, we analyze the role of thermodynamic air-sea coupling using an atmospheric general circulation model coupled to a slab ocean model. Predictability experiments using observed sea surface temperature (SST) initial conditions show that thermodynamic coupling plays a significant role in enhancing the persistence of SST anomalies, both in the tropical Pacific and in the tropical Atlantic. Thermodynamic coupling is also sufficient to provide fairly accurate forecasts of tropical Atlantic SST in the boreal spring that are significantly better than persistence forecasts.

1 INTRODUCTION

Coupling between the atmosphere and the ocean is an important contributor to climate variability. A classic example of atmosphere-ocean interaction is the El Nino-Southern Oscillation (ENSO) phenomenon in the tropical Pacific (Philander 1990). ENSO primarily involves exchange of momentum between atmospheric surface winds and oceanic currents, which is sometimes referred to as "dynamic coupling", because thermodynamic processes such as surface heat flux exchange play a secondary role in this interaction. Dynamic coupling has been the subject of a number of studies, because of its crucial role in the ENSO mechanism.

Another example of atmosphere-ocean interaction, which has received somewhat less attention, is one dominated by the heat flux exchange between the atmosphere and the ocean. We may refer to this as "thermodynamic coupling" to distinguish it from the predominantly dynamic coupling associated with El Nino. Among the proposed thermodynamic coupling mechanisms in the literature are: the reduced thermal damping effect (Barsugli & Battisti, 1998) and the Wind-Evaporation SST (WES) feedback mechanism (Chang *et al.* 1997).

The reduced thermal damping effect can be explained as follows: when the atmosphere warms in response to a sea surface temperature (SST) anomaly, the resulting decrease in the air-sea temperature gradient leads to a decrease in the air-sea heat exchange and thus reduced thermal damping of the SST anomaly. Although many studies have emphasized the role of reduced thermal damping in the midlatitudes, the same mechanism can work in the tropics as well (Saravanan & Chang, 1999). The WES mechanism, which is inherently a tropical mechanism, involves a local *positive* feedback where an anomalous meridional SST gradient drives anomalous surface winds, resulting in surface latent heat flux anomalies which tend to amplify the original SST gradient (Chang *et al.,* 1997).

In this study, we explore the role of thermodynamic coupling in tropical SST variability. We focus on the predictability of SST anomalies in the tropical Pacific and in the tropical Atlantic. We know that in the tropical Pacific, thermodynamic coupling is likely to play only a secondary role, when compared to the strong dynamical coupling associated with ENSO. Nevertheless, we would like to quantify the role of thermodynamic coupling. In the tropical Atlantic, however, many studies have indicated that thermodynamic coupling may indeed play the dominant role (e.g., Chang *et al.,* 1997).

2 MODEL CONFIGURATION

Distinguishing between dynamic and thermodynamic coupling in the real atmosphere-ocean system is quite difficult because the two often occur together. Therefore, we use a modelling approach where we construct a coupled model that supports only thermodynamic coupling. Our experimental configuration consists of an atmospheric GCM (AGCM) coupled to a slab ocean model. We shall refer to this as the AGCM-ML model. The atmospheric model that we use is the Community Climate Model, Version 3 (CCM3) developed at the National Center for Atmospheric Research (NCAR). CCM3 provides a comprehensive simulation of the atmospheric mean circulation and its variability. The

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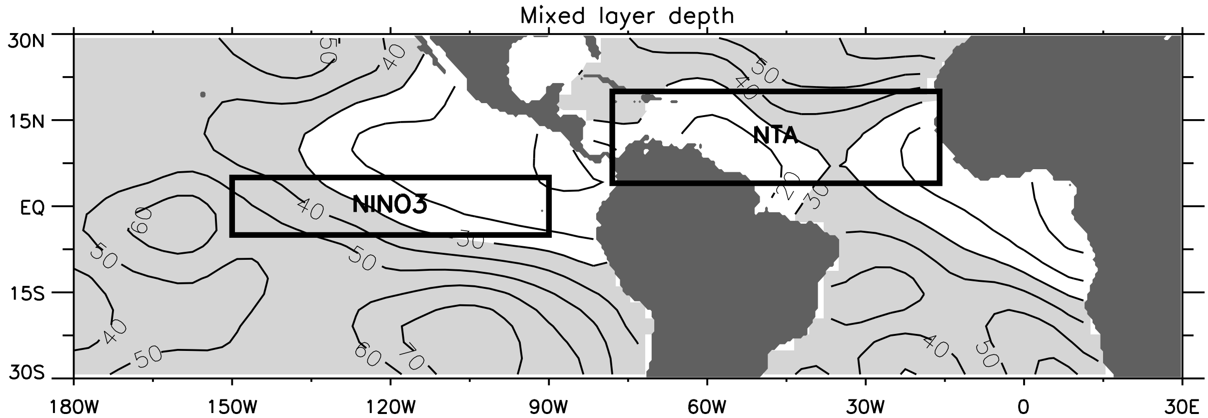

Figure 1: Annual-mean mixed layer depths derived from Levitus (1982). Contour interval is 10m. Shading denotes values > 30m.)

slab ocean model, as the name suggests, is a very crude representation of the ocean, defined by the following simple equation:

$$\frac{\partial T_o}{\partial t} = \frac{F}{\rho_w C_w H} + Q, \qquad (1)$$

where T_o is the slab ocean temperature, F is the heat flux into the ocean, ρ_w is the density of sea water, C_w the heat capacity, and H is the local mixed layer depth. Q is a seasonally-varying "q-flux" that represents oceanic heat transport, which is diagnosed from a control run of CCM3 with prescribed, seasonally-varying, SST values. The thickness H of the oceanic mixed layer was specified from the annually-averaged observational estimates of mixed layer depth, which is derived from Levitus (1982). Figure 1 shows the annual-mean mixed layer depth in the tropical region of interest to this study.

Since the slab ocean has no ocean dynamics, the AGCM-ML allows only thermodynamic coupling, and no dynamic coupling. Forecast experiments were carried out using the AGCM-ML for 16 years, from 1981 to 1996. The slab ocean was initialized with observed December-mean SST values for each of the years. The AGCM was initialized with the observed atmospheric state for Dec. 15th of each year. The atmospheric initial state was perturbed slightly in nine different ways to generate ten initial conditions. The ten member ensemble was integrated forward for 9 months, giving a total of 160 forecasts for the 16 years.

3 RESULTS

First, we consider how the coupled model forecasts the evolution of two strong ENSO events, the warm event of 1982-83 and the cold event of 1988-89. We focus on SST anomalies in the NINO3 region (150°W-90°W, 5°S-5°N). As we see in Figure 2a, the simulated 1982-83 warm anomaly decays faster than the observed anomaly, but it still persists for several months. The coupled model's prediction of the 1988-89 cold event is rather accurate (Figure 2b). The simulated and the observed cold anomaly decay at about the same rate for this event.

The above result suggests that even this simple coupled system, with no ocean dynamics, is capable of capturing important features of the decay of warm and cold ENSO anomalies. However, one would not necessarily expect this coupled system to be able to generate new ENSO anomalies, because one can think of the slab ocean as being described locally by a damping coefficient that is inversely proportional to the mixed layer depth. This is indeed true in the tropical Pacific, where this coupled model does not spontaneously generate strong SST anomalies of the kind associated with ENSO. In the tropical Atlantic, though, the situation is quite different. We consider the evolution of SST anomalies in the Northern Tropical Atlantic (NTA) region, averaged over the box (78°W-16°W, 4°N-16°N), during the the 1982-83 warm ENSO event. As we see in Figure 3, the observed NTA SST shows a rapid warming from January to March 1983. The coupled model is able to reproduce this rapid warming, albeit with a systematic error. The reason for the growth of the simulated NTA SST anomaly is the well-known remote influence of ENSO on the tropical Atlantic (e.g. Enfield and Mayer, 1997). Thus, we see that this simple coupled system does not only capture the local SST feedbacks, but also the remote effects associated with the tropical "atmospheric bridge" that links the Pacific and the Atlantic.

Next, we consider the statistically-averaged skill associated with the forecasts over all 16 years, as measured by the correlation between the observed and predicted SST anomalies in the NINO3 and NTA regions (Figure 4). Also shown in the figure is the skill of the persistence forecast based upon the initial value of the SST. Note that in the NINO3 region, the model skill is comparable to persistence for about three months, and then it decays rapidly. In the NTA region, the

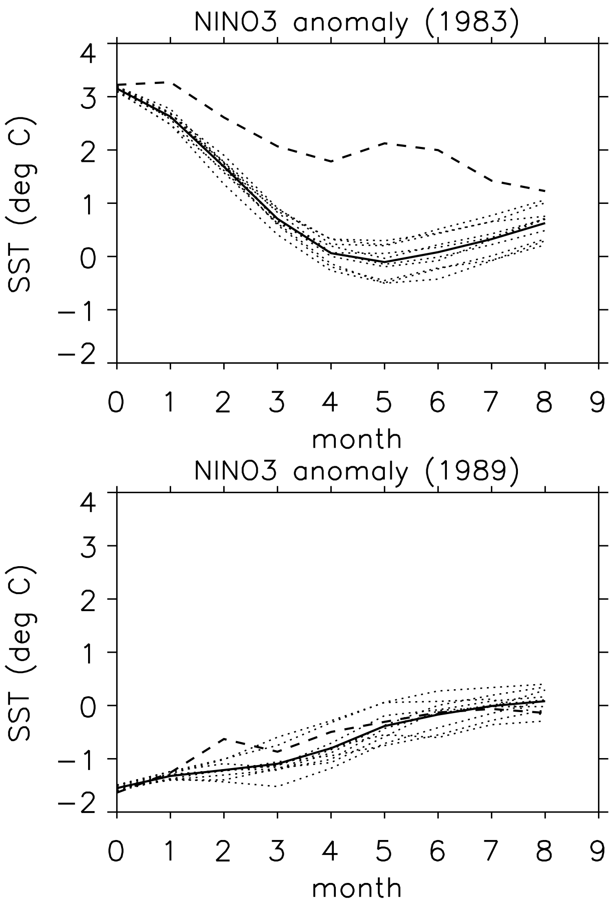

Figure 2: Evolution of NINO3 SST anomaly during the 1982-83 warm event (a) and the 1988-89 cold event (b), as function of forecast lead time: ensemble-average (solid), observed (dashed), and ensemble members (dotted). Month 0 represents December.

model skill actually beats persistence after about two months. Much of this skill presumably comes from the remote influence of ENSO (e.g. Enfield and Mayer, 1997), as seen for the 1982-83 warm event in Figure 3. However, there could also be local feedbacks contributing to this skill, as discussed in the next section.

Finally, we consider whether the predictability of tropical SSTs in this simple coupled system translates into useful predictive skill over land. In particular, we consider the predictive skill over the Pacific-North American (PNA) region during the boreal winter (January-February-March). Figure 5 shows the anomaly correlation of 500 hPa geopotential height in the PNA region, ordered by the strength of the NINO3 anomaly for the warm or the cold event. Note that for strong warm or cold event, the anomaly correlation exceeds 0.5, with a high value of 0.75 for the strongest event (1982-83). The skill of this forecast model is therefore comparable to the skill of hindcast

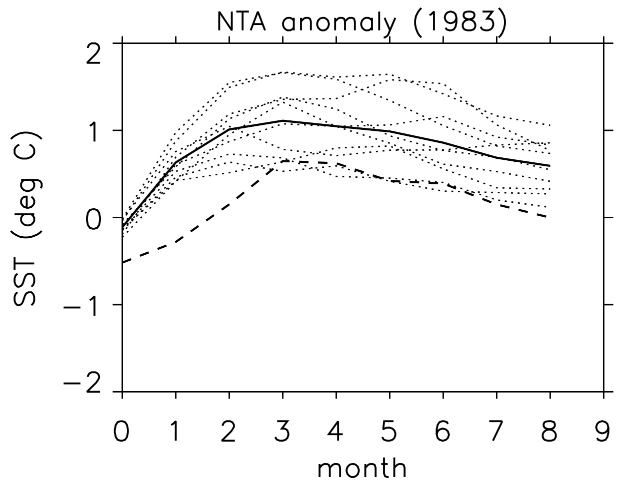

Figure 3: Evolution of NTA SST anomaly during the 1982-83 warm event, as function of forecast lead time. Line styles as in Figure 2.

models used in dynamical seasonal prediction studies (Shukla *et al.,* 2000), where an AGCM is forced by observed SST anomalies. This suggests forecasts using the AGCM-ML configuration could be quite competitive with those from fully coupled models on seasonal timescales.

4 SUMMARY AND DISCUSSION

We have carried out forecast experiments using an atmospheric model coupled to a slab ocean model. This coupled model only supports thermodynamic coupling, or surface heat exchange, between the atmosphere and the ocean. It does not support dynamic coupling, i.e., surface momentum exchange. We find that this coupled model is able to capture the persistence characteristics of SST anomalies in the tropical Pacific. The model is also able to simulate the growth of SST anomalies in the North Tropical Atlantic, leading to fairly high forecast skill on seasonal timescales, beating out persistence. This suggests that thermodynamic coupling can play a significant role in determining the evolution of tropical SST anomalies on seasonal timescales.

To further understand the characteristics of thermodynamic coupling, we compute the decay time of SST anomalies in the tropics, assuming that there is no thermodynamic coupling, i.e., no reduced thermal damping or WES feedbacks. We approximate the surface heat flux F from (1) as follows:

$$F = \kappa(T_a - T_o) \qquad (2)$$

where T_a is the surface atmospheric temperature, and κ is an exchange coefficient relating the heat flux to the local air-sea temperature difference. Estimates of κ are quite uncertain and scale-dependent. We choose a reference value of $40Wm^{-2}K^{-1}$, based on linearizations of bulk formulae for air-sea flux exchange (e.g.,

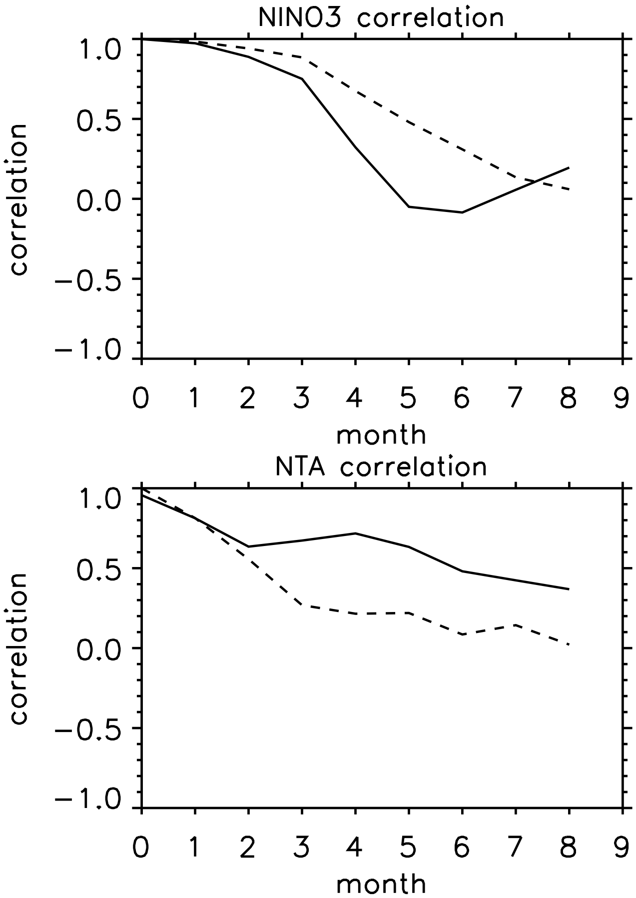

Figure 4: Correlation between observed SST anomalies and ensemble-average predicted SST anomalies (solid line) and persisted SST anomalies (dashed line), as a function of forecast lead time. a) NINO3 region. b) NTA region

Haney 1971). Note that the mixed layer depths in the NINO3 and NTA regions (Figure 1) are quite shallow in this region, of the order of a few tens of metres. For a reference mixed layer depth of 30m (say), and the reference value of κ, the e-folding decay time of SST anomalies is about 40 days.

We see from our coupled forecasts that the SST anomalies persist for periods substantially longer than 40 days. We do not expect the WES feedback to be very important in the equatorial eastern Pacific because the mean surface wind structure does not favor it. Therefore, it seems likely that some form of the reduced thermal damping feedback operates to maintain the SST anomalies in the NINO3 region. In the NTA region, the most important effect is perhaps the remote influence of ENSO. However, the mean surface flow is conducive to the WES feedback in this region. It seems likely that both the reduced thermal damping effect and the WES feedback contribute to the model forecast skill in the tropical Atlantic, which clearly beats the persistence skill.

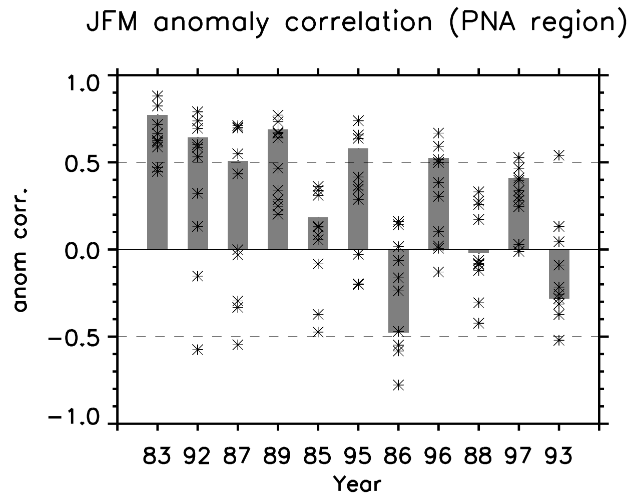

Figure 5: Anomaly correlation between predicted and observed 500 hPa geopotential height in the Pacific-North American region (180°W-60°W, 15°N-70°N). The abscissa denotes the year of the ENSO event, in descending order of the absolute magnitude of the SST anomaly, starting with the strong ENSO of 1982-83. The vertical bar denotes the ensemble-average anomaly correlation, and the asterisks denote the correlation for each ensemble member.

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