Correction of Systematic Errors in Coupled GCM Forecasts

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ABSTRACT

The prognostic tendency (PT) correction method is applied in an attempt to reduce systematic errors in coupled GCM seasonal forecasts. The PT method computes the systematic initial tendency error (SITE) of the coupled model and subtracts it from the discrete prognostic equations. In this study, the PT correction is applied only to the three-dimensional ocean temperature. The SITE is computed by calculating a climatologically averaged difference between coupled model initial conditions and resulting forecasts at very short lead times and removing the observed mean seasonal tendency.

Two sets of coupled GCM forecasts, one using an annual mean SITE correction and the other using a SITE correction that is a function of season, are compared with a control set of uncorrected forecasts. Each set consists of 17 12-month forecasts starting on 1 January from 1980 through 1996. The PT correction is found to be an effective method for maintaining a more realistic forecast climatology by reducing systematic ocean temperature errors that lead to a relaxation of the tropical Pacific thermocline slope and a weak tropical SST annual cycle in the control set. The annual mean PT correction, which allows the model to freely generate its own seasonal cycle, leads to increased prediction skill for tropical Pacific SSTs while the seasonally varying PT correction has no impact on this skill.

Physical mechanisms responsible for improvements in the coupled model's annual cycle and forecast skill are investigated. The annual mean structure of the tropical Pacific thermocline is found to be essential for producing a realistic SST annual cycle. The annul mean PT correction helps to maintain a realistic thermocline slope that allows surface winds to impact the annual cycle of SST in the eastern Pacific. Forecast skill is increased if the coupled model correctly captures dynamical modes related to ENSO. The annual mean correction leads to a model ENSO that is best characterized as a delayed oscillator mode while the control model appears to have a more stationary ENSO mode; this apparently has a positive impact on ENSO forecast skill in the PT corrected model.

1. Introduction

Coupled ocean–atmosphere general circulation model (GCM) forecasts of El Niño–Southern Oscillation (ENSO) have become a key focus of seasonal-to-interannual climate prediction in recent years. GCMs capable of simulating certain key aspects of the tropical climate have been judged to be a prerequisite for improving GCM seasonal predictions (Neelin et al. 1992; Mechoso et al. 1995). Some coupled GCMs have been able to simulate ENSO-like interannual variability or the mean seasonal cycle, especially the annual cycle, over the tropical Pacific (Philander et al. 1992; Nagai et al. 1992; Latif et al. 1993a, 1994; Stockdale et al. 1994; Robertson et al. 1995a,b; Schneider et al. 1997; Frey and Latif 1997; Ineson and Davey, 1997). These successes have led to attempts to make seasonal predictions with coupled GCMs in a number of groups (Latif et al. 1993b; Ji et al. 1994, 1996; Ji and Leetmaa 1997; Rosati et al. 1997; Stockdale 1997; Kirtman et al. 1997).

The successful simulation of both the tropical annual cycle and interannual variability has proved to be surprisingly difficult with many coupled GCMs. Long integrations of many coupled models simulate interannual variability that is much more realistic than is their mean seasonal cycle (e.g., Schneider et al. 1997; Ineson and Davey 1997). Systematic errors (climate drift) in the mean seasonal cycle, notably a lack of an annual cycle over the tropical eastern Pacific and Atlantic, are a serious problem faced by most coupled GCMs. These sys-

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tematic errors can be viewed as an equilibrium departure of the coupled model climatological state from observations. The causes of systematic errors are not well understood but can be attributed both to the internal errors of the component models arising from inaccurate parameterizations or numerics and also to the coupling (flux) error. Unfortunately, systematic errors are often as large as the observed anomalies (Mechoso et al. 1995) and can develop in a few months (Stockdale 1997), so they can have serious impacts on coupled GCM seasonal forecasts.

Previous modeling and theoretical studies have shown that the mean state and seasonal cycle of the coupled system can play a crucial role in determining the ENSO variability (Zebiak and Cane 1987; Schopf and Suarez 1988; Suarez and Schopf 1988; Battisti and Hirst 1989; Neelin 1991; Jin et al. 1994; Tziperman et al. 1994; Moore 1995). In order to maintain a realistic coupled model climatology for seasonal forecasts, it has generally been necessary to introduce heuristic corrections into coupled GCMs to reduce systematic error (Ji et al. 1994; Kirtman et al. 1997). More recently, advances in eliminating coupled model errors (e.g., by tuning component model physical parameterizations) have led to significant reductions in systematic errors in some coupled models (Ma et al. 1994; Rosati et al. 1997; Schneider et al. 1997). Nevertheless, the application of heuristic error correction methods may still improve simulation and forecast quality. One widely used method is the so-called flux correction originally proposed to reduce the climate drift in long-term climate simulations (Sausen et al. 1988; Manabe et al. 1991; Murphy 1995). Flux correction attempts to reduce model drift by inserting some information about observed climatological quantities into the interface between ocean and atmosphere. An extreme example of this idea is the method of anomaly coupling (Ji et al. 1994; Kirtman et al. 1997). This procedure controls the climatology of a coupled model by specifying both the observed annual cycle of SST for forcing the atmospheric GCM and the observed annual cycle of wind stress and heat flux for forcing the ocean GCM while allowing two-way interactive coupling for anomalies. Anomaly coupling effectively creates a new class of coupled model that is between an intermediate anomaly model and a fully coupled GCM. Note that flux corrections do not remove any internal errors of uncoupled models. A coupled model with such a correction may be able to maintain an equilibrium state close to the uncoupled model climatological state, but this uncoupled state may differ significantly from observations.

In this study, the prognostic tendency (PT) correction method is used to reduce systematic errors during the integration of coupled GCM forecasts. As a statistical–empirical approach, this correction was originally proposed to reduce systematic errors in atmospheric models for extended-range forecasts (Johansson and Baer 1987; Johansson and Saha 1989; Saha and Kanamitsu 1988; Sausen and Ponater 1990; Saha, 1992; R. Saravanan and D. Baumhefner 1995, personal communication). Unlike the conventional flux correction, which is only applied to surface fluxes of heat, the PT correction is applied not only to the surface but also to the subsurface of the ocean, effectively reducing errors that come from inaccuracies in the wind stress, surface heat flux, and internal dynamics of the ocean model. While traditional flux correction methods can help a coupled model to maintain an uncoupled model climatology, the PT correction has the potential to help a coupled model maintain an observed climatology for the corrected variable. The PT correction based on spatial patterns of systematic initial tendency error (SITE; Klinker and Sardeshmukh 1992) is introduced into the prognostic equations of the coupled model. The SITE can be defined as a function of season or as a constant annual mean. The latter case attempts to correct the annual mean climatology while allowing the model to produce its own seasonal cycle. Such a correction is expected to improve the seasonal cycle by preventing the annual mean from drifting resulting in improved ENSO variability due to improvements in the seasonal cycle.

Section 2 describes the coupled GCM forecast system and section 3 develops the prognostic tendency correction method and examines estimates of systematic initial tendency errors. Results of coupled GCM forecasts of ENSO with and without corrections are presented in section 4. The final section is devoted to concluding remarks.

2. Coupled GCM forecast system

The forecast system used in this study consists of a coupled ocean–atmosphere general circulation model and a method to initialize the model. Rosati et al. (1997) documented an early version of the forecast system.

Briefly, the atmospheric component of the coupled model is a global spectral GCM with T42 truncation and 18 vertical sigma levels (Stern and Miyakoda 1995; Anderson and Stern 1996; Yang et al. 1998; Gordon et al. 2000). Its major physical parameterizations include a bucket hydrology over land, orographic gravity wave drag, large-scale condensation, relaxed Arakawa–Schubert convection scheme, shallow convection, cloud prediction, radiative transfer, and horizontal diffusion (Sirutis and Miyakoda 1990). The oceanic component of the coupled model is the Geophysical Fluid Dynamics Laboratory modular ocean model version 2 (Pacanowski 1995) configured as described in Rosati and Miyakoda (1988). The model has a nearly global grid with realistic bottom topography. Horizontal resolution is 1° lat $\times$ 1° long except within the equatorial band of 10°N–10°S where the meridional resolution is ⅓°. The vertical resolution is 15 unequally spaced levels with most of the levels in the upper ocean above 500 m. Physical parameterizations include penetration of solar insolation to the ocean subsurface, vertical mixing, and horizontal mixing. The ocean–atmosphere coupling procedure is as follows. The atmospheric model is run for 2 h with a 800-s time step, and 2-h averages of wind stress, heat flux, and precipitation minus evaporation are saved to force the ocean model. Then the ocean model is run for 2 h with a 1-h time step for both momentum and temperature/salinity and returns the 2-h averaged SST to be used in the subsequent 2-h integration of the atmospheric model.

The ocean initial conditions are created using the ocean data assimilation (ODA) method of Derber and Rosati (1989) and Rosati et al. (1994). The ocean model is integrated forward and observed SST and subsurface thermal data are continuously inserted into the ocean model by applying a variational principle. The ODA analysis also requires values of surface heat flux and surface wind stress. The surface heat flux is replaced by the surface restoring method in which the ocean model's surface temperature is nudged toward observed SSTs using a Newtonian damping coefficient, while the surface wind stress is obtained from independent atmospheric analyses or simulations.

Atmospheric data are not used directly in obtaining the initial conditions for the atmospheric component of the coupled model. Although direct assimilation of atmospheric data should provide additional information that could improve forecasts, most of the initial condition information resides in the more slowly varying ocean component. In this coupled model, attempting to get atmospheric initial conditions that are in some appropriate balance with the ocean assimilation appears to be more important than trying to make the atmospheric model state close to the observed atmospheric state. The atmospheric initial conditions in this study are created by an atmospheric GCM (AGCM) simulation with daily SST forcing from an ODA analysis. On the other hand, to maximize dynamical consistency of ocean and atmosphere initial conditions, the ODA analysis uses surface wind stress forcing that is itself derived from the AGCM simulation.

Initial conditions for the coupled GCM forecasts in this study are created as follows. First, an ODA preanalysis was made from January 1979 through December 1997, using daily surface windstress from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), SST data taken from the monthly mean SST analysis of Reynolds (1988) and the NCEP optimal interpolation analysis (Reynolds and Smith 1994), and subsurface temperature data [from expedable bathythermographs (XBTs) temperature profiles] taken from the National Oceanic Data Center and the Tropical Ocean Global Atmosphere Tropical Atmosphere and Ocean arrays). Second, an 18-yr atmospheric GCM simulation starting from January 1979 forced by daily SSTs from the ODA preanalysis is used to produce atmospheric initial conditions throughout the 18-yr period. Third, a final ODA analysis is made for the same period with surface wind-stress taken from the AGCM simulation of step 2 but with all other data the same as in step 1. This final ODA analysis provides ocean initial conditions throughout the 18-yr period.

3. Description of prognostic tendency correction

a. Basic idea and present application

The PT correction assesses the SITE of the coupled model and then subtracts the SITE from the discrete prognostic equations. For a prognostic variable S, the SITE is estimated as the difference between the climatologically averaged initial tendency of the model forecast and the observed tendency of the mean seasonal cycle:

$$\left(\frac{dS}{dt}\right)_{\rm err} = \overline{\frac{S_f(\Delta t) - S_{\rm obs}(0)}{\Delta t}} - \left(\frac{dS}{dt}\right)_{\rm ssn}, \qquad (3.1)$$

where $S_f(\Delta t)$ is the forecast value with a very short lead time Δt and $S_{\rm obs}(0)$ is the observed initial value. The superscript bar denotes the climatological mean (or averaging over a forecast set). The first term on the right-hand side is the forecast mean initial tendency, and the second term with the subscript ''ssn'' on the right-hand side represents the observed mean seasonal tendency. The SITE defined above is a function of space as well as a function of season.

The PT correction is made by simply subtracting the SITE from the prognostic equation, and two types of correction can be employed: the seasonal cycle (SC) correction

$$\frac{dS}{dt} = \cdots - \left(\frac{dS}{dt}\right)_{\rm err}, \qquad (3.2)$$

and the annual mean (AM) correction

$$\frac{dS}{dt} = \cdots - \left[\left(\frac{dS}{dt}\right)_{\rm err}\right]_{\rm am}, \qquad (3.3)$$

where the correction term on the right-hand side in (3.3) is a constant with respect to time and taken from the annual mean (denoted by the subscript ''am'') of the SITE defined in (3.1), while the correction term in (3.2) is a function of season. The PT correction could be applied to all prognostic variables of the coupled system or to selected prognostic variables. However, for the correction to multiple (two or more) variables, a dynamical balance (physical constraint) among variables (such as momentum and heat, zonal flow, and meridional flow) may be required (Klinker and Sardeshmukh 1992).

In the present study, the PT correction scheme is applied only to the three-dimensional ocean temperature, a single prognostic variable. This choice is based on several considerations. First, the more slowly varying ocean provides the majority of the memory of the coupled system, and the ocean temperature is of central importance for ENSO dynamics. Reducing climate drift in the ocean temperature field should have a direct impact on ENSO predictions. Second, the ocean temperature field including SST and subsurface temperature is relatively well observed compared to other oceanic variables or atmospheric boundary quantities such as surface wind stress, which makes it possible to properly estimate the SITE of the ocean temperature. Third, for a comprehensive GCM, it can be extremely challenging to impose balance requirements that are essential when correcting all variables. However, the correction to the ocean temperature does not induce any fundamental imbalances in the dynamics used in this ocean model. One might hope that applying the PT correction to the ocean temperature would help to maintain a realistic climatological thermal structure while allowing all other fields (atmosphere, oceanic current and salinity) to freely adjust to the climatological thermal structure.

b. The SITE for ocean temperature

A large set of very short coupled model forecasts is used to compute the SITE. In this study, 204 6-day coupled GCM forecasts were used, one starting at 0000 UTC of the first day of each month from 1980 through 1996, with initial conditions as described in section 2. The SITE for the ocean temperature is computed at 0000 UTC of the first day of each month of the year as follows.

First, the climatologically averaged initial tendency of the model [the first term on the right-hand side of (3.1)] is computed from the 17 forecasts for this month from 1980 to 1996. In general, the mean initial tendency can be a function of forecast lead time. However, an EOF analysis shows that the initial tendency of ocean temperature is roughly a linear function of forecast lead for several days. Therefore, values of the mean initial tendency rate are roughly invariant as a function of lead time for several days. A lead time of 4 days is chosen empirically to calculate the mean initial tendency in order to eliminate the impact of the diurnal cycle. Second, the observed mean tendency of the seasonal cycle for the ocean temperature [the second term on the right-hand side of (3.1)] is calculated from the ODA analysis. Finally, the SITE is obtained as the difference between the mean initial tendency and observed mean tendency of the seasonal cycle. In this coupled model, the mean initial tendency is more than an order of magnitude larger than the observed mean tendency of the seasonal cycle.

The SITE for the ocean temperature is mainly confined to the upper ocean. Spatial patterns of the SITE for SST at 0000 UTC of the first day for four individual months (January, April, July, and October) are shown in Fig. 1. In the Tropics the SST SITE has warming tendency errors (positive values) in the eastern Pacific, particularly along the South American coast, and cooling tendency errors in the western Pacific. The coastal warming tendency errors are very large during October (exceeding 0.1°C day^{-1}) but weak during July, indicating the impact of the annual cycle in that region. The SITE for subsurface temperature in the Tropics is also characterized by warming tendency errors in the eastern Pacific and cooling errors in the western and central Pacific (Fig. 2a). The vertically coherent pattern of SITE in the tropical Pacific is the initial drift behavior of the coupled model, which inevitably induces errors in the mean thermocline structure.

The SITE in higher latitudes is obviously seasonal and hemispheric, with warming errors in the summer hemisphere and cooling errors in the winter (Fig. 1). These errors, however, are confined to the surface (Fig. 2b), in contrast to those in the Tropics.

In this study, the PT correction is applied to remove these initial tendency errors at each model time step. For the SC correction, since the correction term in (3.2) is a function of season, the SITE from 0000 UTC of the first day of each month is interpolated into each model time step as required. For the AM correction, a constant-correction, the average of the SITE over all 12 months is used at all times.

4. Results of coupled GCM forecasts

Three sets of coupled GCM forecasts have been made: one with no correction of systematic errors (control), one with the annual mean PT correction, and one with the seasonal cycle PT correction, using identical models and initial conditions. Each set consists of 17 12-month forecasts starting from identical initial conditions at 0000 UTC of the first day of January from 1980 through 1996. These forecast sets are examined to evaluate if the PT correction can reduce systematic errors and maintain a realistic annual mean climate and associated seasonal cycle for the ocean temperature. The impact of the corrections on ENSO prediction skill is also examined.

a. Forecast climatology

In this study, the forecast climatology, which is a function of lead time (up to 12 months), is defined as the mean of the 17 forecasts with January initial conditions. The predicted annual mean is obtained by averaging the forecast climatology over 12 months, and the predicted mean seasonal cycle can be analyzed by removing the annual mean from the forecast climatology.

Figure 3 illustrates the spatial distribution of the observed annual mean SST based on Reynolds analysis (1980–96) at NCEP along with the model predicted SST. The observed annual mean tropical Pacific SST is characterized by the cold tongue expanding off the Peruvian coast across most of the equatorial eastern Pacific and the warm pool occupying the western Pacific and eastern Indian Ocean (Fig. 3a). The control forecasts have large systematic SST errors across all the tropical oceans (Fig.

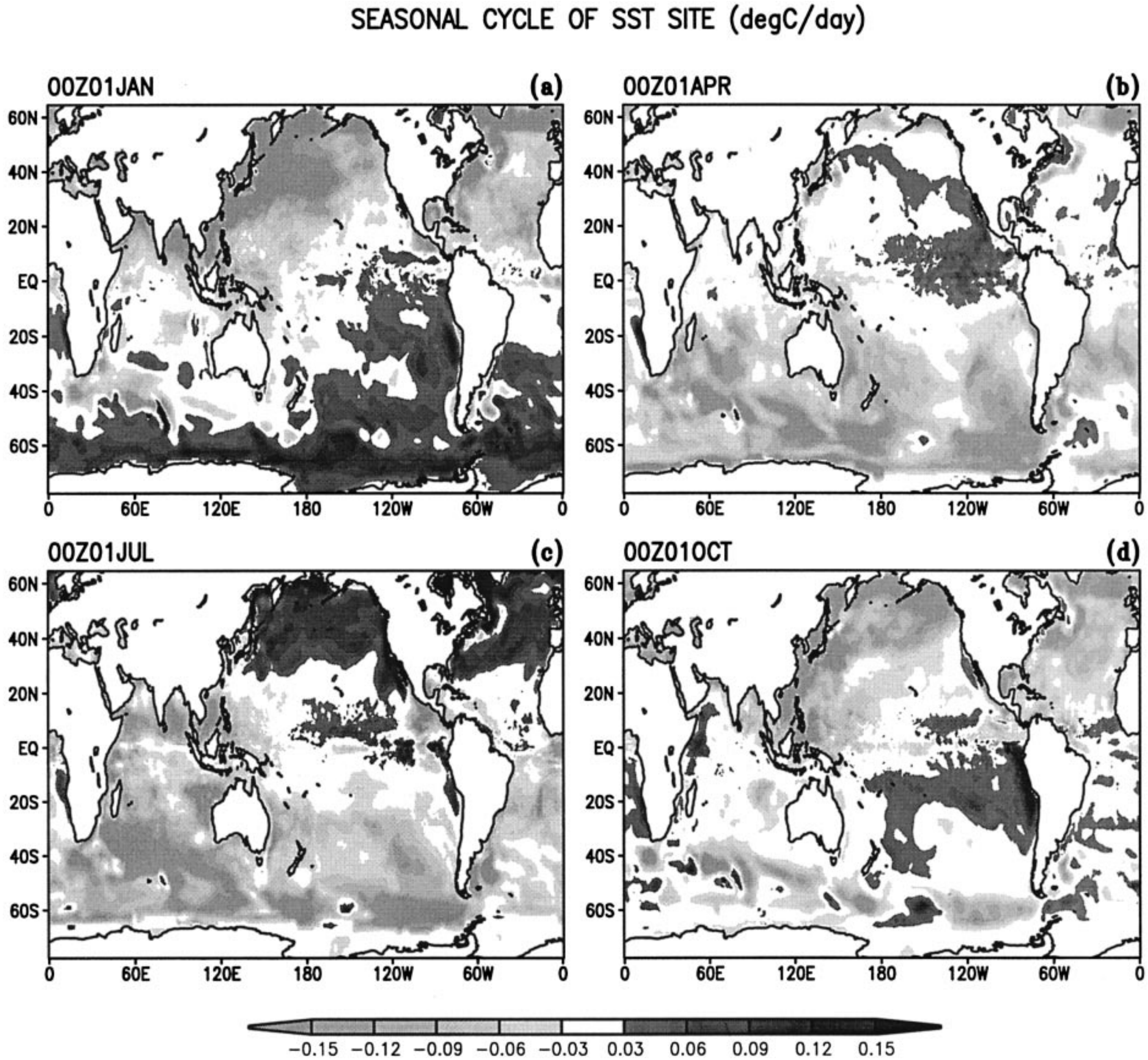

FIG. 1. The SITE (°C day^{-1}) for the SST at 0000 UTC of the first day of (a) Jan, (b) Apr, (c) Jul, and (d) Oct.

3b). In the western Pacific the warm pool splits into two parts in the central Pacific and Indian Ocean. The SSTs around Indonesia and in the South Pacific convergence zone (SPCZ) region are too cold but SSTs are too warm in the eastern Pacific, indicating that the cold tongue is weak. Similar errors can be observed in the tropical Atlantic. These errors result in a dramatic decrease of the zonal SST gradient.

Both PT correction cases greatly reduce these errors (Figs. 3c,d). The warm pool and the cold tongue are much closer to their observed locations and intensities. Centers of warm SST greater than 29°C over the SPCZ region agree with the observed for both cases, although their extents appear to be somewhat smaller. This success is encouraging, since reduction of errors in the annual mean SST may be of great importance to prediction of the seasonal cycle and interannual variability.

Figure 4 presents the climatological seasonal anomaly of the equatorial SST (5°S–5°N) from the Reynolds analysis (1980–96) and for the model predictions. Observed seasonal SST variations include strong annual harmonics (~1.5°C) in the eastern Pacific and eastern Atlantic with the warm phase around April and cold phase around September, and weak semiannual harmonics (~0.5°C) in the western Pacific (Fig. 4a). The control forecasts are largely unsuccessful in predicting these seasonal variations (Fig. 4b). In the eastern Pacific, the control predicts no discernible annual cycle since there is a large warm drift that overwhelms the seasonal cycle. In the eastern Atlantic, the annual cycle is much weaker than is observed.

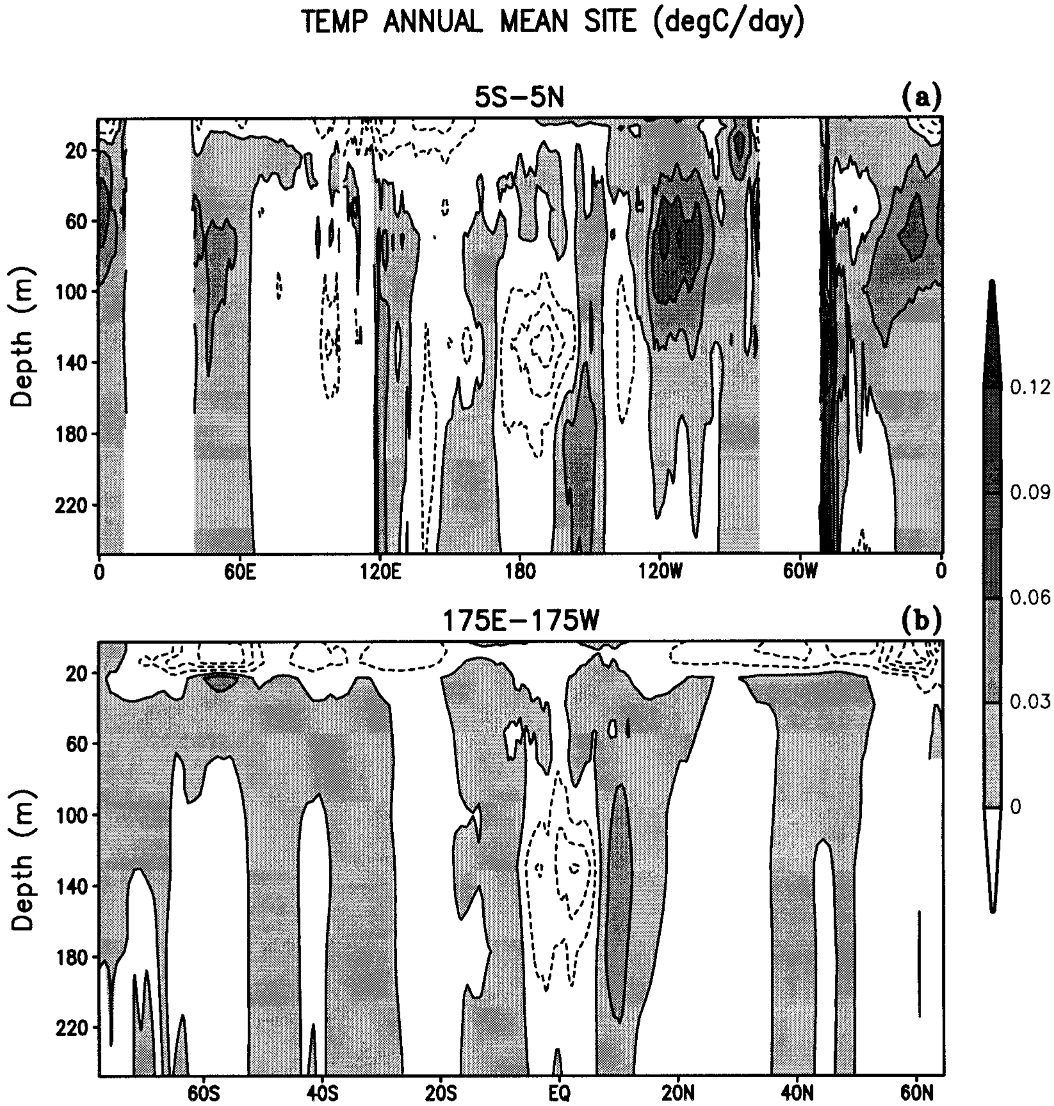

FIG. 2. The annual mean SITE (°C day^{-1}) for the ocean temperature as shown in (a) a depth–longitude diagram along the equator (5°N–5°S) and (b) a depth–latitude diagram along 180° (175°E–175°W).

The seasonal cycle PT correction case greatly reduces errors in the eastern Pacific and eastern Atlantic (Fig. 4d). Regions with annual harmonic amplitude exceeding 1.5°C are confined to the eastern basins in agreement with observations. It is intuitive that the seasonal cycle correction maintains a good annual cycle, since the correction term explicitly includes annual cycle information.

The correction term in the annual mean PT correction case is a constant with respect to time, so any impact on the seasonal cycle can be viewed as an indirect impact of improvements in the annual mean state. This correction does predict relatively realistic seasonal variation, which is dominated by the annual cycle in the eastern parts of the basins (Fig. 4c). The phase of the predicted annual harmonics are approximately correct with a warm peak in spring and a cold one in fall and the amplitudes are close to the observed. However, the extent of the region with large annual cycle that extends westward from the coasts is too large, especially in the Atlantic. The seasonal cycle in the eastern Pacific is also relatively realistic but tends to be slightly stronger than observed. Despite these shortcomings, it is intriguing that the coupled model is able to produce its own annual cycle if systematic errors of the annual mean are reduced. This may give insight into physical mechanisms responsible for the annual cycle and its interaction with the annual mean state.

The PT corrections also reduce systematic errors in the ocean subsurface thermal structure and the atmospheric surface wind. In the equatorial Pacific the thermocline (approximated by the depth of the 20°C isotherm here) is generally deep in the west (~150 m) and

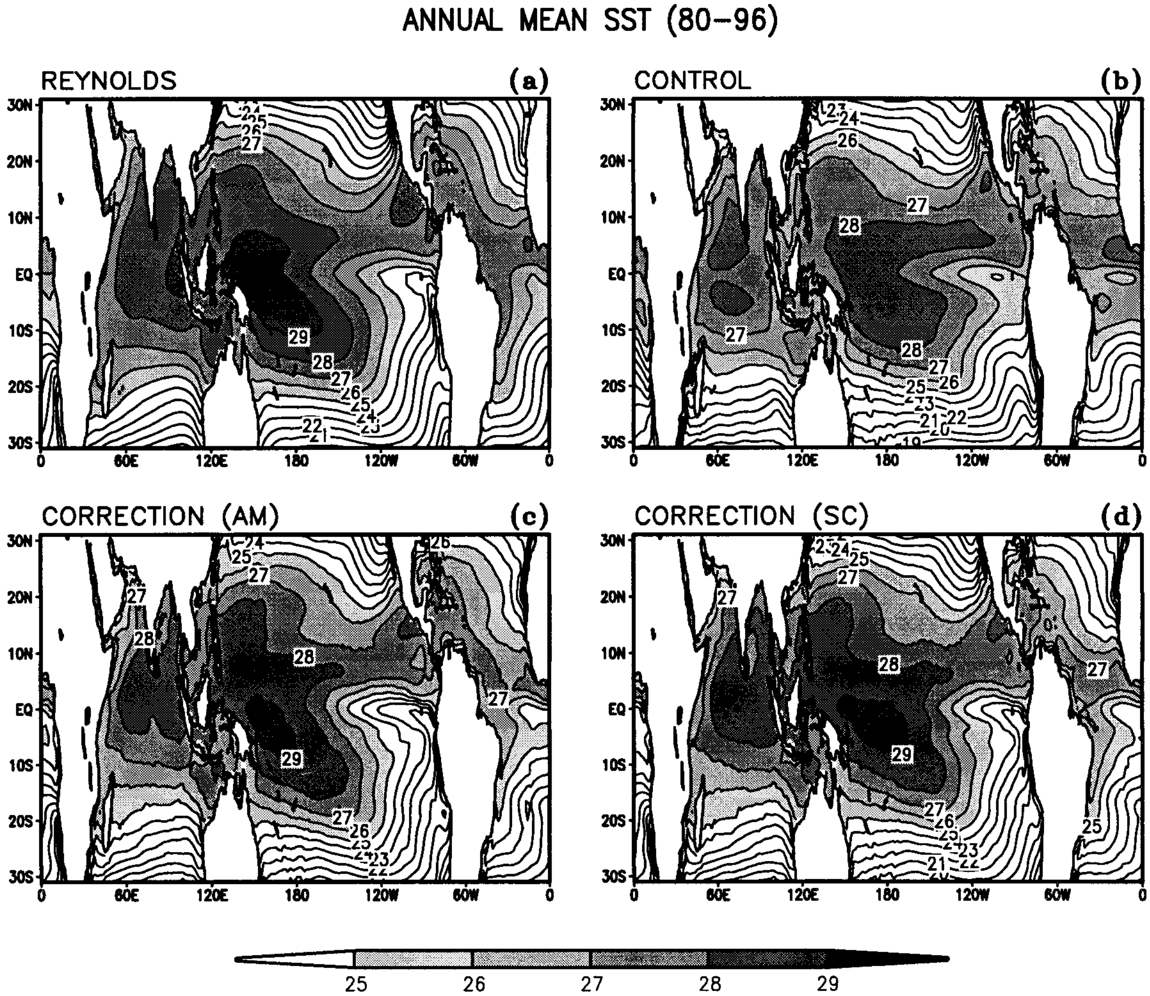

FIG. 3. Climatological annual mean distributions of the SST from (a) the Reynolds analysis (1980–96), and (b) from the forecast climatology of the 17-case coupled GCM forecasts for the control case, (c) AM correction case, and (d) the SC correction case.

shallow in the east (∼50 m), corresponding to the warm pool versus cold tongue structure in the SST field. As a component of the coupled tropical ocean–atmosphere system, this large-scale ocean thermal structure is closely associated with the atmospheric surface wind. To a large extent, the trade winds that prevail over the central and eastern equatorial Pacific support the thermocline structure and the associated SST pattern, which, in turn, determines the surface wind pattern.

Figure 5 shows time–longitude sections of the predicted climatological mean depth of the 20°C isotherm and zonal wind stress in the equatorial Pacific. The control model (Fig 5 top) does not sustain the observed thermocline structure. The surface trade winds become progressively weaker while the thermocline deepens in the east and shallows in the west. By the end of the forecast year, the thermocline is quite flat and the surface trade winds are dramatically weakened. However, both PT correction cases (Fig 5 middle and bottom) maintain a steady thermocline structure and associated surface winds throughout the year. The corrections improve predictions of seasonal variations in the depth of the thermocline and the surface winds such as the stronger trade winds in the late summer and fall.

Why is the annual mean correction able to produce a well-defined SST annual cycle, especially the cold phase in the fall? After a careful investigation, the well-defined SST seasonal cold phase in the annual mean correction can be attributed to air–sea interaction through the wind–SST feedback in which the proper annual mean structure of the thermocline plays a key role. The annual mean correction maintains a more realistic shallow thermocline in the east that allows seasonally intensified trades to cool the SSTs easily through upwelling. This cooling results in an effective positive feedback between wind and SST, which allows the annual mean correction case to develop a mature seasonal cold phase in fall.

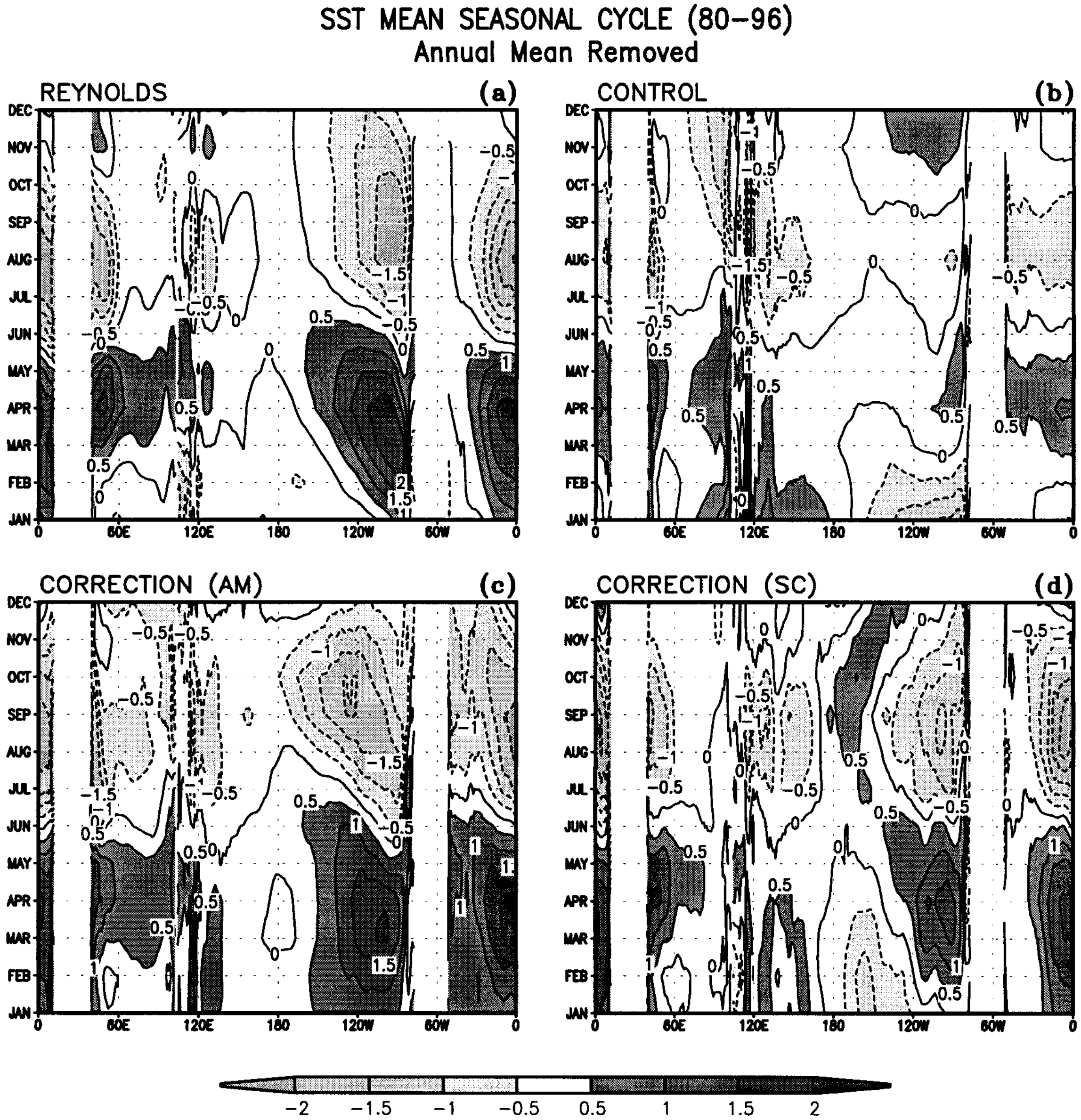

FIG. 4. Time–longitude plots of the seasonal anomalies of SST along the equator (the annual means were removed). The panels are as in Fig. 3.

b. ENSO forecast skill

Traditionally, forecasts of SST anomalies in the tropical Pacific, especially those over the Niño-3 region (5°N–5°S, 150°–90°W), have been used to evaluate ENSO predictions. Here, the forecast skill for SST anomalies is evaluated using an anomaly correlation together with an rms (root-mean-square) error. Model SST anomalies were calculated by subtracting the forecast climatology from the individual forecasts.

Correlations between the predicted and observed values of SST anomalies over the entire tropical Pacific were computed as a function of forecast lead time. Figure 6 shows the spatial distribution of the correlations for seasonal mean SST anomalies during September, October, and November (SON). The high positive correlation regions for both the control and the seasonal cycle PT correction forecasts are confined to the eastern tropical Pacific. For SON, the area with correlation coefficient larger than 0.5 for the control case is very small (Fig 6 top). The seasonal cycle correction has a higher correlation over the region from 130° to 110°W, but this limited change over a small region does not significantly increase the Niño-3 area-averaged skill (Fig. 7). It is the annual mean PT correction that produces the highest forecast skill over most of tropical Pacific (Fig. 6). Of particular interest is the significant skill during the 1980s

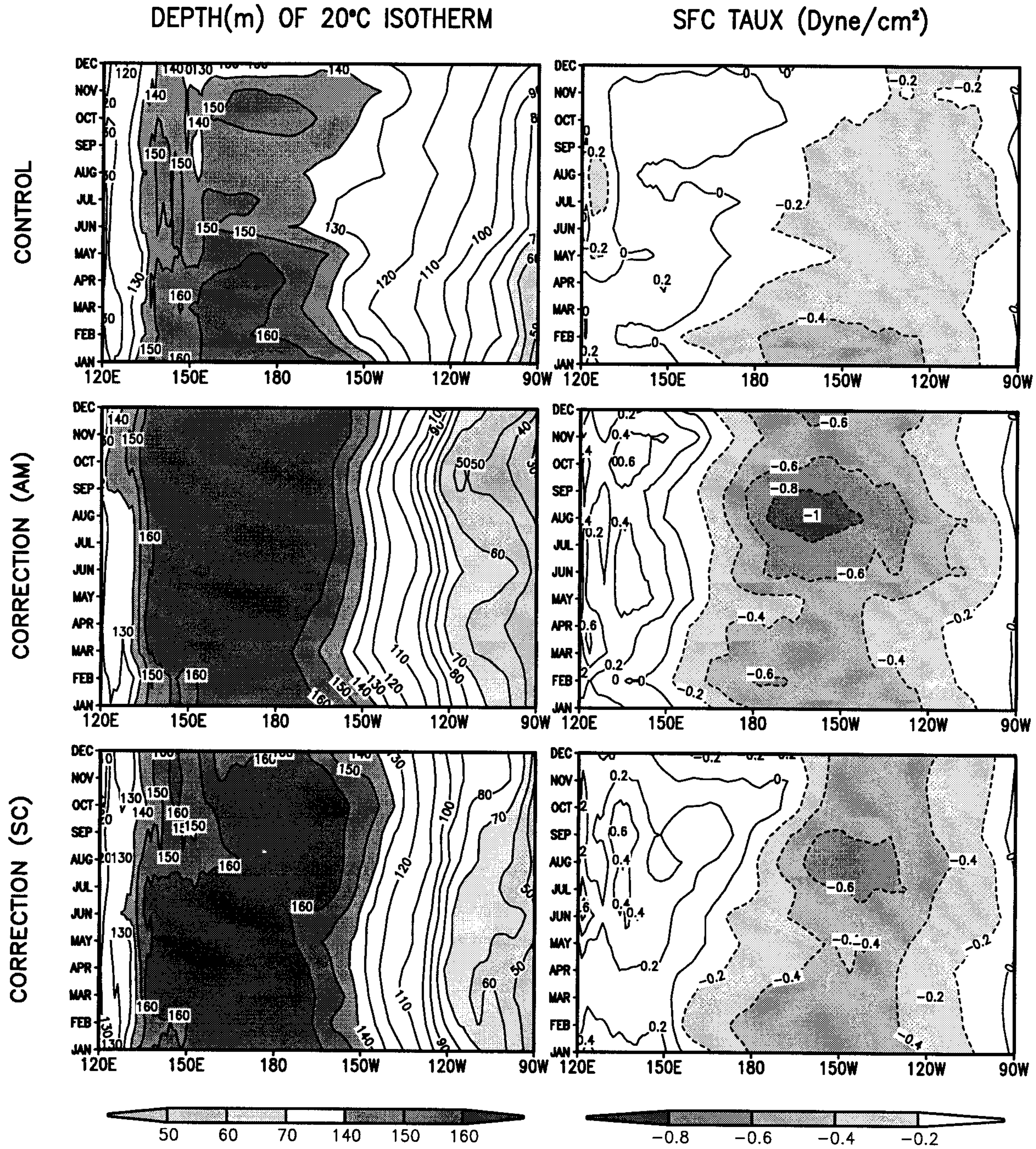

FIG. 5. Time–longitude diagrams of the forecast climatology along the equator for (left) the depth of the 20°C isotherm and (right) zonal wind stress for (top) the control case, (middle) the AM correction case, and (bottom) the SC case.

in the central equatorial Pacific (the Niño-4 region), just north (10°N) of the equator in the western Pacific, north (20°N) of the equator in the central Pacific, and in the SPCZ region.

Anomaly correlations and rms errors for Niño-3 area-averaged SST are displayed as a function of lead time in Fig. 7. The forecast skill in the 1980s is shown separately to facilitate comparison with previous studies such as Rosati et al. (1997). It has been theorized that the ENSO variability in the 1980s is dominated by the so-called delayed oscillator mode that is easily predicted with coupled models, while the 1990s seem to be controlled by different mechanisms that are more difficult to predict with current coupled models (Ji et al. 1996). The control forecasts exhibit decreasing forecast skill with increasing lead time with anomaly correlation de-

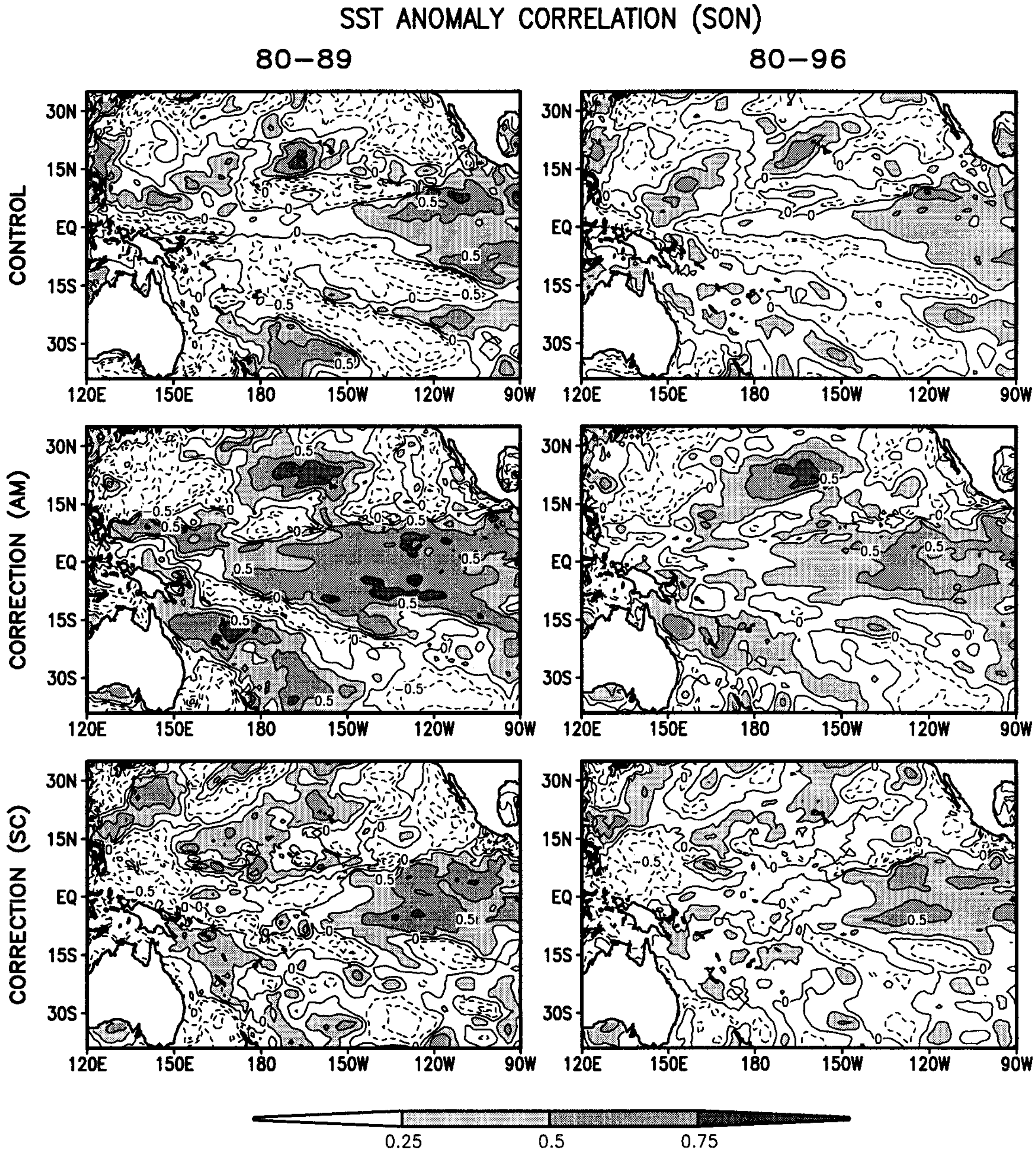

FIG. 6. Anomaly correlations of seasonal mean SST anomalies in the tropical Pacific in SON for (top) the control, (middle) the AM correction, and (bottom) SC the correction cases. (right) For 17 forecasts (1980–96), while (left) are for 10 forecasts in the 1980s (1980–89).

creases and rms error increases. The rapid decrease of skill during the first 3–4 months may be due to the fast error growth as noted by Blumenthal (1991), Latif and Graham (1992), and Rosati et al. (1997). Beyond roughly 4 months, the control forecasts tend to be better than persistence, but very little useful predictive information is available in the control cases since the skill decreases quickly to insignificant levels.

Forecast skill with the seasonal cycle PT correction is roughly equivalent to that of the control (Fig. 7), even though the correction does lead to a much more realistic forecast climatology for the tropical mean and annual cycles. The annual mean PT correction, however, has much better forecast skill for Niño-3 SST anomalies at lead times past 5 months. This is especially evident for the 10 forecasts during the 1980s (left panels of Fig. 7). Anomaly correlation coefficients at the longer lead times appear to be significantly larger than those for both the control and seasonal cycle correction cases, but the rms errors are much smaller. The forecast skill stays at a relatively steady level after an initial decrease. The skill for all 17 January forecasts (1980–96) (right panels

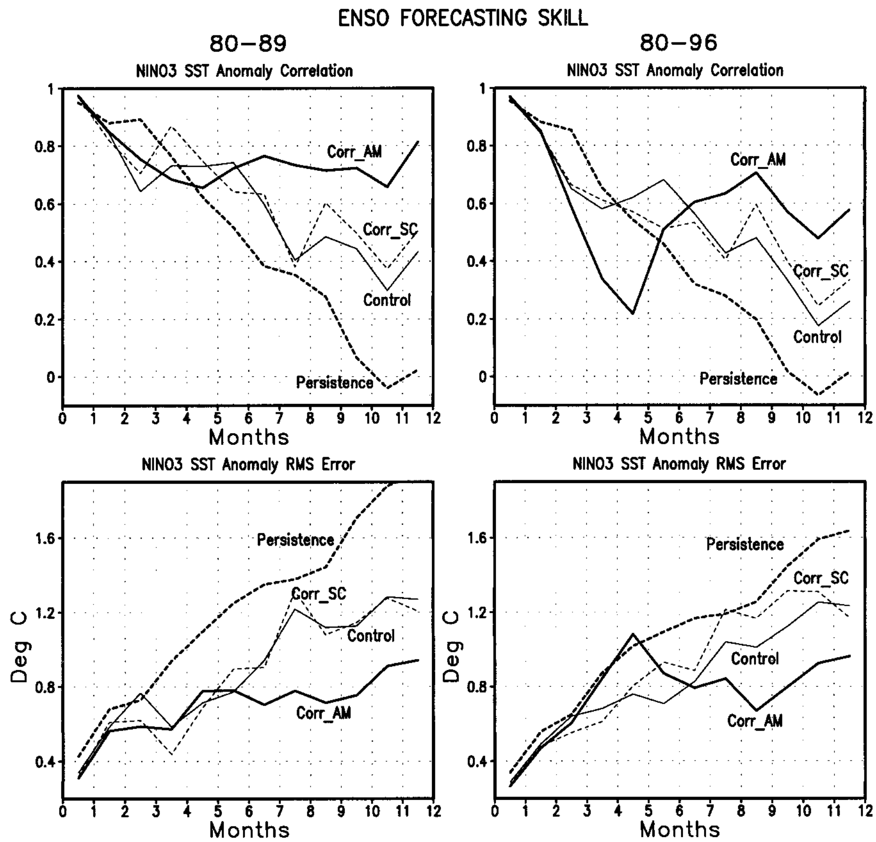

FIG. 7. (top) Niño-3 SST anomaly correlations and (bottom) rms errors, plotted as a function of lead time, for the control (light solid curve), AM correction (heavy solid curve), and SC correction (light dashed curve) forecasts. Persistence (heavy dashed curve) is also shown for comparison. (right) For 17 forecasts (1980–96), while (left) are for 10 forecasts in the 1980s (1980–89).

of Fig. 7) exhibits similar features except for a transient drop of the skill during the spring.

These results suggest that the annual mean state and seasonal cycle components of the forecast model climatology have fundamentally different impacts on ENSO prediction skill. The annual mean correction leads to higher forecast skill by imposing a temporally constant correction to reduce the drift in the annual mean state, whereas the seasonal cycle correction approach with corrections not only to the time mean but also to the seasonal cycle does not improve the skill. Since both correction methods create similar forecast climatologies of the annual mean and the seasonal cycle, why do they have such different impacts on prediction skill? One possibility is that a freely generated model annual cycle is somehow important to the prediction of ENSO. In other words, the ENSO forecast skill is dependent on the annual cycle while the annual cycle is determined by the annual mean state. Physical mechanisms responsible for the annual cycle created by an annual mean correction may also be important for the evolution of interannual anomalies; a direct correction to the seasonal cycle may distort these mechanisms.

A variety of previous theoretical and modeling studies have revealed possible physical mechanisms that govern the ENSO cycle. A conceptual ‘‘delayed oscillator’’ model proposed by Schopf and Suarez (1988) has been widely accepted as a basic ENSO mode. According to this mode, ENSO phase variation can be attributed to propagation of ocean dynamical waves in the equatorial waveguide region and their reflection at the western (eastern) boundaries. These waves are associated with variations of upper-ocean heat content and upwelling (downwelling) through thermocline displacement, and these effects can be amplified by atmospheric feedback. The delayed oceanic effect due to the slow propagation of waves becomes the relatively long ‘‘memory’’ of the tropical Pacific that provides one of the physical bases for ENSO prediction (Rosati et al. 1997). It is therefore of interest to investigate the dominant modes of ENSO evolution in the coupled GCM forecasts. This investigation was made by calculating a lag correlation between the Niño-3 SST and the upper-ocean heat content as defined by Rosati et al. (1997).

Figure 8 shows the lag correlation of the Niño-3 SST with ocean heat content anomalies in a lag–longitude

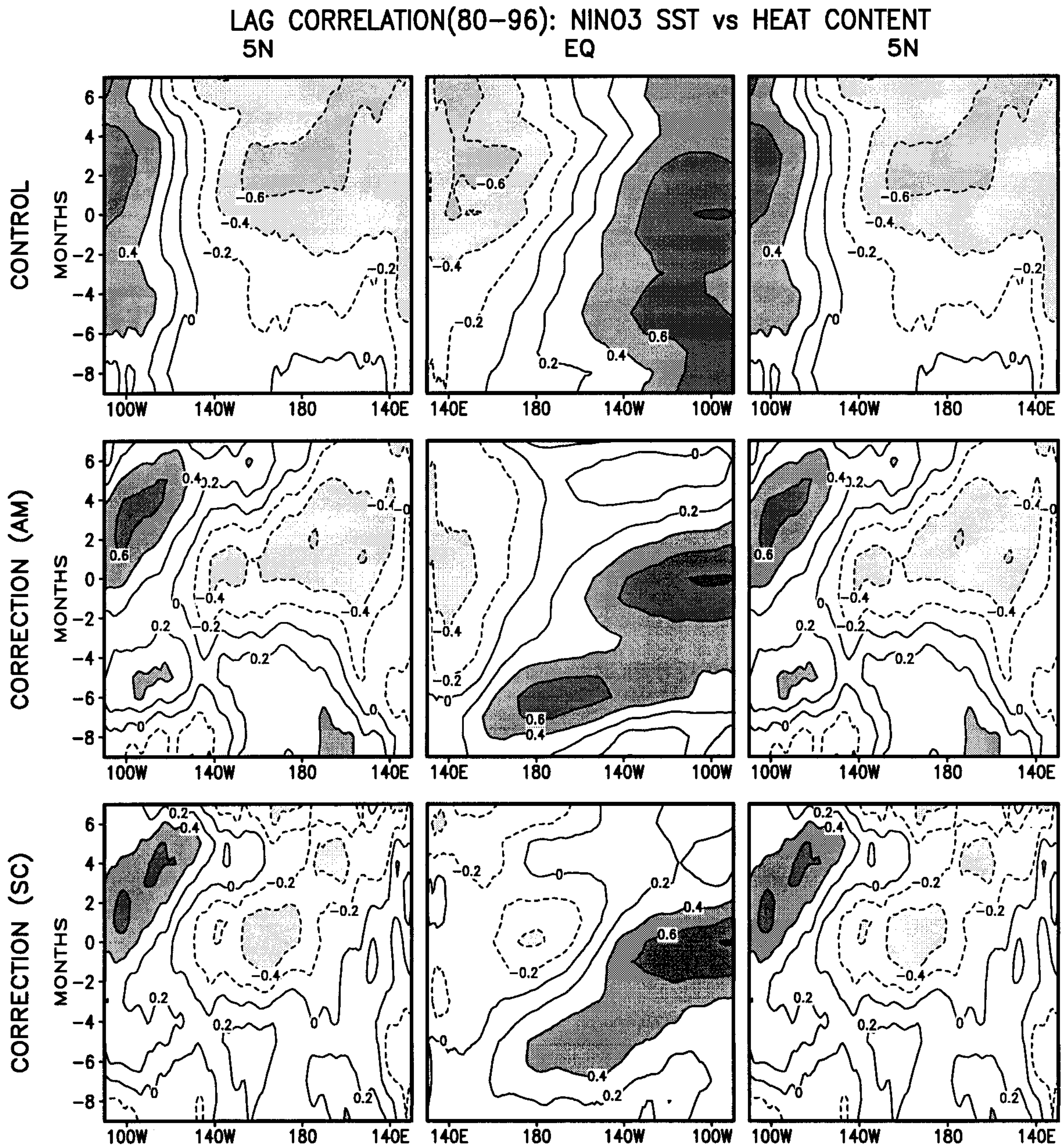

FIG. 8. Lag correlations of Niño-3 SST and upper-ocean heat content anomalies (middle column) along the equator and (right and left columns) along 5°N. The right and left panels are the same and have the horizontal axis reversed (the west to left). Negative (positive) lags indicate that SST lags (leads) heat content anomalies.

display along the equator and along 5°N in which negative (positive) lags indicate that SST lags (leads) heat content anomalies. Note that the left and right panels of Fig. 8 showing correlations along 5°N are identical and have the horizontal axis reversed (i.e., west to the left). This display is designed to exhibit propagation of oceanic waves and their reflection at boundaries. The ENSO evolution in the control forecasts and correction forecasts is apparently controlled by two physically distinct mechanisms. For the control forecasts (Fig. 8 top), the Niño-3 SST anomalies along either the equator or 5°N are positively correlated only with local heat content anomalies at any lag or lead, indicating a stationary mode. However, the Niño-3 SST anomalies for forecasts with the annual mean correction exhibit a positive lag correlation relation with equatorial heat content anomalies originating from the western and central Pacific (Fig. 8 middle row). The correlation pattern along the equator with a tilt of phase toward the upper right suggests an eastward propagation of equatorial Kelvin waves. Interestingly, the tilting phase has a clear continuity around the eastern boundary when correlation between the Niño-3 SST anomalies and heat content anomalies off the equator is shown. This suggests that westward propagating Rossby waves are reflecting from the equatorial Kelvin wave at the eastern boundary. The Niño-3 SST anomalies also have simultaneous and negative lead correlations with heat content anomalies off the equator in the central-western Pacific. These correlations along 5°N can be explained as the ENSO-induced Rossby modes that tend to migrate westward and reflect at the western boundary so that the same negative correlations can be observed at the equator around the western boundary. Although the seasonal cycle correction (Fig. 8 bottom) shows correlation patterns similar to those found in the annual mean correction case, the correlations are somewhat weaker. The lag correlation analysis suggests that the delayed oscillator mode has greater control over ENSO evolution in the coupled GCM forecasts with the annual mean PT correction than in those with the seasonal cycle correction, while the control forecasts totally fail to capture this mode. This may explain why the annual mean correction can achieve a higher ENSO forecasting skill.

5. Concluding remarks

The prognostic tendency (PT) correction method has been used to reduce systematic errors in coupled GCM forecasts. The PT correction method removes the systematic initial tendency error (SITE) of the coupled model from the discrete prognostic equations. The SITE was estimated by calculating a climatologically averaged tendency between forecast values at a very short lead time and initial values and discarding the observed mean seasonal tendency. The SITE has been defined as a function of season and as an annually averaged constant.

The PT correction in this study was applied only to the ocean temperature, for which the SITE was computed using a very large set of very short forecasts with a coupled GCM and with initial conditions based on an ocean analysis using observed SST and subsurface thermal data. Large values of the SITE were found in the subsurface as well as at the surface, in the high latitudes, and in the tropical regions.

The PT correction was incorporated into the coupled GCM forecast system and three parallel sets of coupled GCM forecasts were made: one without any correction of systematic errors (control forecasts), one with the annual mean correction that subtracts the SITE defined as a constant, and the third with the seasonal cycle correction that subtracts the SITE defined as function of season. Both correction approaches can effectively reduce systematic biases of the ocean temperature, prevent the thermocline in tropical oceans from drifting, and help generate more realistic SST annual cycles in the eastern equatorial Pacific and in the eastern equatorial Atlantic. Therefore, the PT correction helps maintain a forecast climatology of the ocean temperature that is close to the observed and maintain a forecast climatology for the atmosphere that is close to the uncoupled climatology. The annual mean correction produces a higher skill for ENSO predictions. The seasonal cycle correction that imposes constraints not only on the annual mean but also on the seasonal cycle does not show any significant improvement of ENSO forecast skill, despite its success in maintaining a realistic model climatology including the seasonal cycle.

Possible mechanisms responsible for the correction-induced improvements of the ENSO forecast skill were investigated. It was found that ENSO evolution tends to be controlled by the delayed oscillator mode in both corrected cases rather than the stationary SST mode as in the control forecasts. The ability to capture this delayed oscillator type of mode may be related to the skill of ENSO predictions. The delayed oscillator mode is most clearly observed in the annual mean correction case, which may explain why this correction achieves a higher ENSO forecasting skill.

The prognostic tendency correction proposed here is a preliminary attempt to reduce systematic errors in the ocean temperature field that could result from deficiencies in the surface wind, surface heat flux, and the internals of the ocean model. It has been demonstrated to be successful in reducing systematic bias of the forecast climatology and improving ENSO forecast skill. This success may lead to an attempt to apply the method to the entire coupled system, although this will be technically more difficult. Also, this study suggests additional interesting issues that need to be further explored, such as the role of the annual mean state and the associated seasonal cycle in ENSO variability. Finally, it should be pointed out that despite the success of the PT correction, further development of coupled GCMs, especially physical parameterizations, should eventually eliminate major sources of systematic errors and make any correction approach unnecessary.

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