Extended ENSO Predictions Using a Fully Coupled Ocean–Atmosphere Model

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ABSTRACT

Using a fully coupled global ocean–atmosphere general circulation model assimilating only sea surface temperature, the authors found for the first time that several El Niño–Southern Oscillation (ENSO) events over the past two decades can be predicted at lead times of up to 2 yr. The El Niño condition in the 1997/98 winter can be predicted to some extent up to about a 1½-yr lead but with a weak intensity and large phase delay in the prediction of the onset of this exceptionally strong event. This is attributed to the influence of active and intensive stochastic westerly wind bursts during late 1996 to mid-1997, which are generally unpredictable at seasonal time scales. The cold signals in the 1984/85 and 1999/2000 winters during the peak phases of the past two long-lasting La Niña events are predicted well up to a 2-yr lead. Amazingly, the mild El Niño–like event of 2002/03 is also predicted well up to a 2-yr lead, suggesting a link between the prolonged El Niño and the tropical Pacific decadal variability. Seasonal climate anomalies over vast parts of the globe during specific ENSO years are also realistically predicted up to a 2-yr lead for the first time.

1. Introduction

The prediction of El Niño–Southern Oscillation (ENSO) and its related climate impacts sufficiently ahead of its onset is vital for effective management of climate disasters. In theory, ENSO is believed to be predictable on the order of 1 or 2 yr in advance because of the self-sustained nature of the tropical Pacific coupled ocean–atmosphere system (e.g., Suarez and Schopf 1988; Battisti and Hirst 1989; Neelin et al. 1998). This was demonstrated partly by an idealized dynamical model (Cane et al. 1986; Chen et al. 1995, 2004). However, whether ENSO predictability estimated by this artificially trained simple model is realistic or not is unclear. In particular, stochastic atmospheric forcings, such as surface wind bursts in the western equatorial Pacific, which cannot be represented in the simple models, play an important role in the evolution of certain ENSO events and hence set a limit to the ENSO predictability (e.g., Lau and Chan 1986; Penland and Sardeshmukh 1995; McPhaden 1999, 2004; Moore and Kleeman 1999; Perigaud and Cassou 2000; Thompson and Battisti 2001; Fedorov et al. 2003; Flügel et al. 2004; Lengaigne et al. 2004; Eisenman et al. 2005; Zavala-Garay et al. 2005). Though Chen et al. (2004) did not find a big impact of the wind bursts in their simple ENSO forecast system, substantial contributions of massive westerly wind bursts to the development of the unprecedented 1997/98 El Niño episode were well observed (e.g., McPhaden 1999) and confirmed by some model and theoretical studies (e.g., Perigaud and Cassou 2000; Fedorov et al. 2003; Eisenman et al. 2005; Zavala-Garay et al. 2005).

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Multiscale ocean–atmosphere processes in other tropical oceans and the extratropics may also affect ENSO and seasonal climate variations in certain regions. This cannot be represented in the simple models. Sophisticated ocean–atmosphere coupled general circulation models (GCMs) should resolve both ENSO and its dynamically linked global climate variations in an accurate as well as comprehensive way. However, the majority of current state-of-the-art ocean–atmosphere coupled GCMs, despite their potential prospects, do not outperform the simple dynamical and/or some statistical models in predicting ENSO (e.g., Barnston et al. 1999).[1] For example, a recently developed multimodel ensemble forecast system based on seven European coupled ocean–atmosphere GCMs shows that ENSO over the past two decades is predictable at only a 3–6-month lead (e.g., Palmer et al. 2004; Stockdale et al. 1998).

It has been realized that skillful seasonal predictions require good performance of coupled models in simulating the major climate modes such as ENSO, in particular their periods, amplitudes, and phase relationships with the annual cycle. It is also important to resolve the associated teleconnection patterns and to retain the model's climatology close to observations. Besides, the initial conditions used for forecasts should be not only realistic but also compatible between the ocean and atmosphere. In addition, a good ensemble scheme should be designed to reflect the uncertainties in both initial conditions and model physics. In some of our earlier experiments, with a careful design and physical improvement of our forecast system to overcome those shortfalls, we are able to demonstrate that ENSO events in the past two decades are predictable out to 1 yr in advance (e.g., Luo et al. 2005b).

In this study, we have extended the model hindcasts up to a 2-yr lead based on a fully coupled GCM without any flux corrections [Scale Interaction Experiment-Frontier (SINTEX-F); see Luo et al. 2005a]. Compared to our earlier study (Luo et al. 2005b), the ensemble members have been slightly increased by perturbing both the model coupling physics and initial conditions. A special purpose of this study is to examine how far we can predict ENSO and its related climate anomalies based on the SINTEX-F coupled GCM. The results may also help to understand the roles of intraseasonal disturbances, large-scale ENSO dynamics, and Pacific decadal processes in the ENSO predictability. The coupled model and hindcast experiments are described in section 2. Extended predictions of ENSO and its related global climate variations are presented in sections 3 and 4. Summary and discussions are included in section 5.

2. Model and hindcast experiments

The global ocean–atmosphere coupled general circulation model used in this study, SINTEX-F (Luo et al. 2003, 2005a), was developed at the Frontier Research Center for Global Change under the European Union–Japan collaboration. The atmospheric component has the resolution of 1.1° × 1.1° (T106) with 19 vertical levels (Roeckner et al. 1996). The oceanic component has the resolution of a 2° Mercator mesh (increased to 0.5° in the latitudinal direction near the equator) with 31 vertical levels (Madec et al. 1998). Those two components are directly coupled every 2 h without any flux corrections using a standardized model coupler (Valcke et al. 2000). No sea ice model is incorporated into the current system. The SINTEX-F model realistically simulates the ENSO variability including its magnitude, period (3–5 yr), and spatial distribution of sea surface temperature (SST) anomalies (Luo et al. 2005a, and references therein). We note that such good performance of an ENSO simulation is found to be related to the high resolution (T106) of the atmosphere GCM (Guilyardi et al. 2004).

Uncertainties for seasonal predictions are originated not only from the initial conditions but also from the model physics. Classical ensembles for seasonal predictions are made by merely perturbing initial conditions of the atmosphere and/or ocean. Ensembles with perturbed model physics have recently been found to be important to improve the climate prediction (e.g., Krishnamurti et al. 1999; Palmer et al. 2004, 2005). Concerning the large uncertainties in surface wind stress estimations, we perturb the model coupling physics in three different ways with regard to the importance of strong ocean surface currents in the tropics (Luo et al. 2005a). In the first model, effects of surface ocean currents on the wind stress calculation are neglected as was done in most previous coupled GCMs. In the second one the ocean surface is still kept stationary for the atmosphere, but the surface wind stress is calculated by the relative velocity between the surface winds and ocean currents, that is, $\boldsymbol{\tau} = \rho_a C_D |\mathbf{V}_a - \mathbf{V}_o| (\mathbf{V}_a - \mathbf{V}_o)$. Here, $\boldsymbol{\tau}$ is the surface wind stress, ρ_a is the density of air, C_D is the drag coefficient, $\mathbf{V}_a$ is the wind velocity at the lowest level of the AGCM, and $\mathbf{V}_o$ is the ocean surface velocity at 5-m depth (the uppermost layer of the OGCM). In the third model, which has the best coupling physics, ocean surface current momentum is di-

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[1] We note that some advanced forecast systems based on coupled GCMs have encouragingly produced better skills than statistical models (e.g., van Oldenborgh et al. 2005).

rectly passed to the atmosphere. The horizontal velocity is continuous across the air–sea interface. This affects both wind stress and heat flux calculations. The external momentum source further influences the global angular momentum budget of the atmosphere (Luo et al. 2005a).

Three different initial conditions for each model are generated by a coupled SST-nudging scheme (e.g., Chen et al. 1995, 2004; Luo et al. 2005b). Model SSTs are strongly nudged toward the National Centers for Environmental Prediction (NCEP) SST observations (Reynolds et al. 2002) during the hindcast period 1982–2004. Weekly NCEP mean SSTs are interpolated into daily means using a cubic spline method. Three different large negative feedback values (-2400, -1200, and -800 W m^{-2} K^{-1}) to the surface heat flux are used. They correspond to 1-, 2-, and 3-day restoring times for temperature in a 50-m mixed layer. Such an initialization approach (without subsurface information assimilated) requires good model performance in simulating the tropical climate. It could provide compatible initial conditions between the atmosphere and ocean and, hence, reduce the initial shock during forecasts (e.g., Chen et al. 1995; Luo et al. 2005b).

Nine-member ensemble retrospective forecasts with lead times up to 24 months are made from the first day of each month from 1982 to 2004. Over the 2-yr forecast period, model SST drifts in the equatorial Indo-Pacific Ocean are less than 1°–1.5°C (Fig. 1). Model SSTs in the eastern equatorial Pacific quickly become colder than the NCEP observations when the forecasts start (Fig. 1a); this is due to a too shallow thermocline there in the initial conditions (Luo et al. 2005b). The cold SST biases extend gradually westward to the western Pacific during the following months up to about a 1-yr lead (Fig. 1b). The basinwide SSTs then warm up gradually, approaching the model's own climatology (Fig. 1c; see Luo et al. 2005a). The cold SST biases in the equatorial Pacific are reduced by improving the coupling physics (see the green and blue lines in Figs. 1b,c). This is because better coupling physics tends to produce better warm pool–cold tongue structure along the equator (Luo et al. 2005a, and references therein). We note that the climate drifts of individual ensemble members have been removed a posteriori from the retrospective forecasts (see also Kirtman et al. 1997; Stockdale 1997).

3. Extended ENSO predictions

At the lead times of up to 12 months, model prediction skills of the tropical Pacific SST anomalies based on the nine members are similar to those produced by the previous five members (not shown; see Fig. 4 of Luo et al. 2005b). Here we show that the retrospective forecasts during 1982–2004 can be extended up to a 2-yr lead based on the nine ensemble members. The results show that SST anomalies in the central and eastern equatorial Pacific are predictable with medium skill scores at lead times of 16–24 months (Fig. 2).[2] The

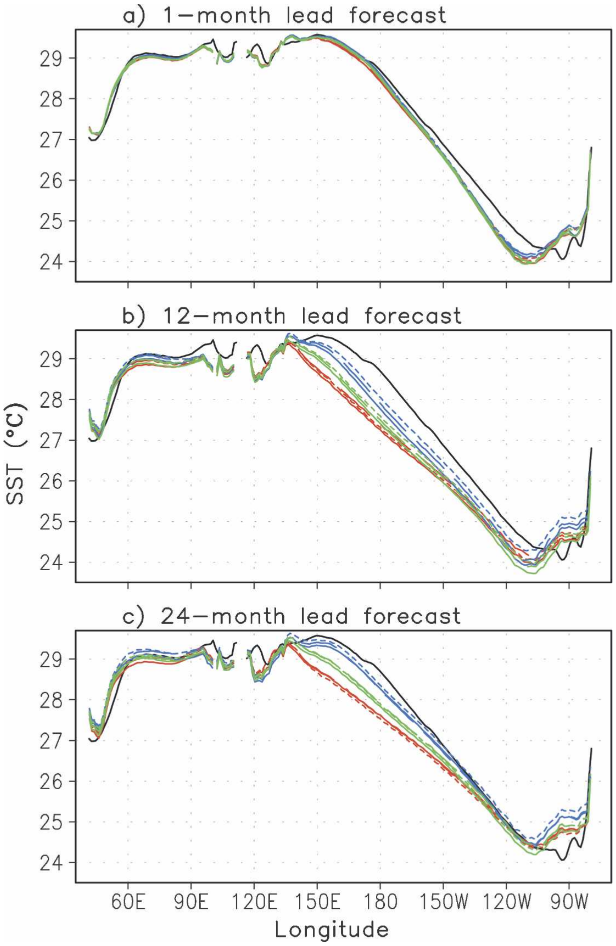

FIG. 1. SST climatology averaged along the equator (2°S–2°N) during the period 1983–2004 based on the NCEP SST observations (black lines) and model predictions (colored lines) at 1-, 12-, and 24-month leads. Climate drifts during the retrospective forecasts in the equatorial Pacific are largely reduced by passing ocean current momentum to the atmosphere (blue curves), compared to the model in which the ocean surface is stationary (red curves). Green lines are produced by the model in which ocean current is taken into account for wind stress calculations but ocean surface is still assumed stationary for the atmosphere. Details for the three models with different coupling physics can be found in Luo et al. (2005a).

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[2] High, medium, and lower predictability could be generally defined in regions where skill scores are above 0.6, between 0.3 and 0.5, and below 0.3, respectively (e.g., Marengo et al. 2005).

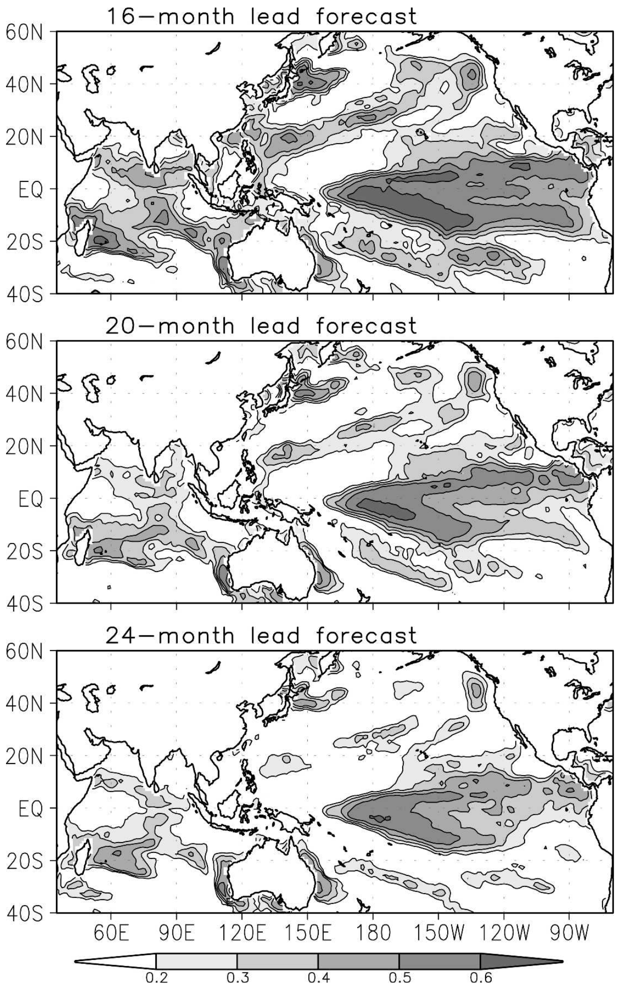

FIG. 2. SST anomaly correlations between the NCEP observations and model nine-member ensemble mean predictions at different lead times for the period 1982–2004. Contour interval is 0.1 and values below 0.2 are not shown. Skills are calculated based on the time series of a 5-month running mean of both the observations and model predictions at each lead time (see Luo et al. 2005b).

ENSO teleconnections in the central North and South Pacific and SST anomalies in the Kuroshio Extension region, east and west coasts of Australia, and tropical Indian Ocean (especially the southwestern part) are also reasonably predictable with medium skill. It is interesting to note that the highest predictability is found in the central equatorial Pacific rather than in the eastern part, despite that ENSO amplitudes are larger in the east compared to the central region. The central part is much affected by prolonged El Niño (Trenberth and Hoar 1996) and/or Pacific decadal ENSO-like variability (e.g., Ji et al. 1996; Luo and Yamagata 2001).

Interannual ENSO events over the past two decades are predicted with high skill scores up to 12 months in advance (see Luo et al. 2005b). Some strong ENSO events are even predictable about 1½ yr ahead (Fig. 3, black lines). The El Niño condition in the 1997/98 winter can be predicted to some extent at about a 1½-yr lead with the forecasted amplitude reaching the 0.5°C criterion for El Niño definition (see the yellow lines in Fig. 4d; Trenberth 1997). The predicted magnitudes at long-lead times (≥ 12 months), however, are much weaker than the observations and with a large phase delay in the prediction of the onset of this strongest warm event (Figs. 3 and 4c,d). This is attributed to the impacts of frequent and intensive westerly wind bursts in the western/central equatorial Pacific during late 1996 to mid-1997 (e.g., McPhaden 1999; Yu et al. 2003); the intraseasonal wind bursts are basically unpredictable at seasonal time scales. Moreover, the rapid decay of the warm signal in early to mid-1998 is not well predicted by the model, even when initiated from 1 July 1997 (see the green lines in Fig. 4d). We note that predicting the onset and decay as well as the intensity of the 1997/98 El Niño event seems to be rather difficult, as found in many other forecast systems (e.g., Landsea and Knaff 2000). This tends to support the idea that stochastic atmospheric forcings may set an intrinsic limit to the ENSO predictability in certain circumstances.

Interestingly, the cold signals in the 1984/85 and 1999/2000 winters during the peak phases of the past two long-lasting La Niña events are well predicted even at a 24-month lead (Figs. 3 and 4a,b,e,f). According to the classical recharge/discharge concept (e.g., Wyrtki 1985; Cane and Zebiak 1985; Jin 1997), large heat is moved out of the upper equatorial Pacific during the strong El Niño episodes of 1982/83 and 1997/98. This leads to a strong cold mean state in the equatorial band and hence requires a longtime recharge process to store enough heat in the equatorial upper ocean to precondition an El Niño event in following years. The results here suggest that ENSO, in particular La Niña events,[3] can be predictable on the order of 2 yr in advance when the recharge/discharge process in both the real ocean and model prediction operates in a dominant way (Cane et al. 1986; Chen et al. 1995, 2004).

It seems surprising that the mild El Niño–like event of 2002/03 (with the strongest warm SST anomalies appearing in the central equatorial Pacific) is also predicted well up to 2 yr ahead (Figs. 3 and 4g,h). The

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[3] Empirical studies suggest that surface wind bursts in the western equatorial Pacific could be more influential to El Niño evolutions than to La Niña ones (e.g., McPhaden 1999, 2004; Perigaud and Cassou 2000; Fedorov et al. 2003; Yu et al. 2003; Eisenman et al. 2005).

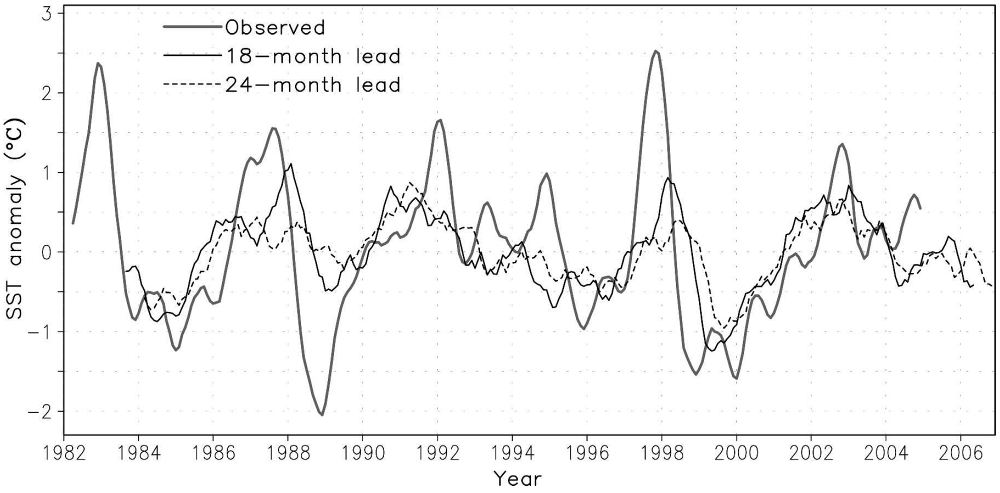

FIG. 3. SST anomalies averaged in the Niño-3.4 region (5°S–5°N, 120°–170°W). The thick gray curve is observations and black curves are nine-member ensemble-mean retrospective forecasts at 18- and 24-month leads. Results have been smoothed with a 5-month running mean. For the time series predicted up to a 12-month lead, readers are referred to Luo et al. (2005b).

situation in the equatorial Pacific since 2002 is similar to that in the early 1990s; warm SSTs above normal persist in the central Pacific. These anomalies are reminiscent of the tropical Pacific decadal variability with a periodicity of about 12 yr (e.g., Ji et al. 1996; Linsley et al. 2000; Cole et al. 2000; Luo and Yamagata 2001; Luo et al. 2003). Indeed, the model predicts two prolonged warm phases during 1990–92 and 2001–03 at lead times of up to 24 months (see Fig. 3). Another notable feature is that westerly wind bursts in the western equatorial Pacific were very active during the early 1990s and recent years since 2002 (e.g., McPhaden 2004; see also http://www.pmel.noaa.gov/tao/jsdisplay/). How the Pacific decadal variability modulates the intraseasonal disturbances and ENSO behavior or vice versa is an interesting question; it will open a new promising field on the ENSO predictability. We note that the decadal cooling trend during the period 1990–96 is well predicted up to 2 yr ahead in our coupled model (see Fig. 3). This suggests a potential predictability of the tropical Pacific decadal variations.[4] A similar cooling trend, started from 2002, is predicted for coming years.

It has been recognized that ENSO predictability decreases rapidly during boreal spring (e.g., Latif et al. 1994; Chen et al. 2004): useful long-range forecasts must overcome this intrinsic prediction barrier. Figure 5a shows the seasonal dependence of the model skills in predicting the Niño-3.4 SST anomaly up to 24 months ahead. As expected, the skills always decrease rapidly for the forecasts across the spring seasons. Nevertheless, the model can successfully predict ENSO across the first spring barrier with correlations above 0.5 but fails during the second one (see Fig. 5a). We note that correct prediction of subsurface signals in the equatorial Pacific can help to overcome the spring prediction barrier as suggested by some empirical studies (e.g., Clarke and van Gorder 2003; McPhaden 2003; Luo et al. 2005b). It is encouraging that prediction skills for the retrospective forecasts initiated during May–September rebound after crossing the first spring barrier and peak again in the next winter, coinciding with the peak phase of ENSO. ENSO prediction skills for the period 1982–2004 reach about 0.6 (0.5) at 16 (24) month lead with root-mean-square errors less than 0.8°C (Figs. 5b,c). All nine members produce comparable prediction skills among them.[5]

4. Extended predictions of global seasonal anomalies during two specific ENSO years

To show the model's skill in the prediction of spatial patterns, we plot in Figs. 6 and 7 global SST anomalies

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[4] Hindcast experiments over a much longer period are required to make a robust estimation of the predictability. This is beyond the scope of this study.

[5] This is probably related to the fact that all three models with different coupling physics produce realistic ENSO simulations, and climate drifts of each model are not largely different (see Luo et al. 2005a,b). We note that, however, ENSO teleconnections tend to be better simulated and predicted in the models with better coupling physics.

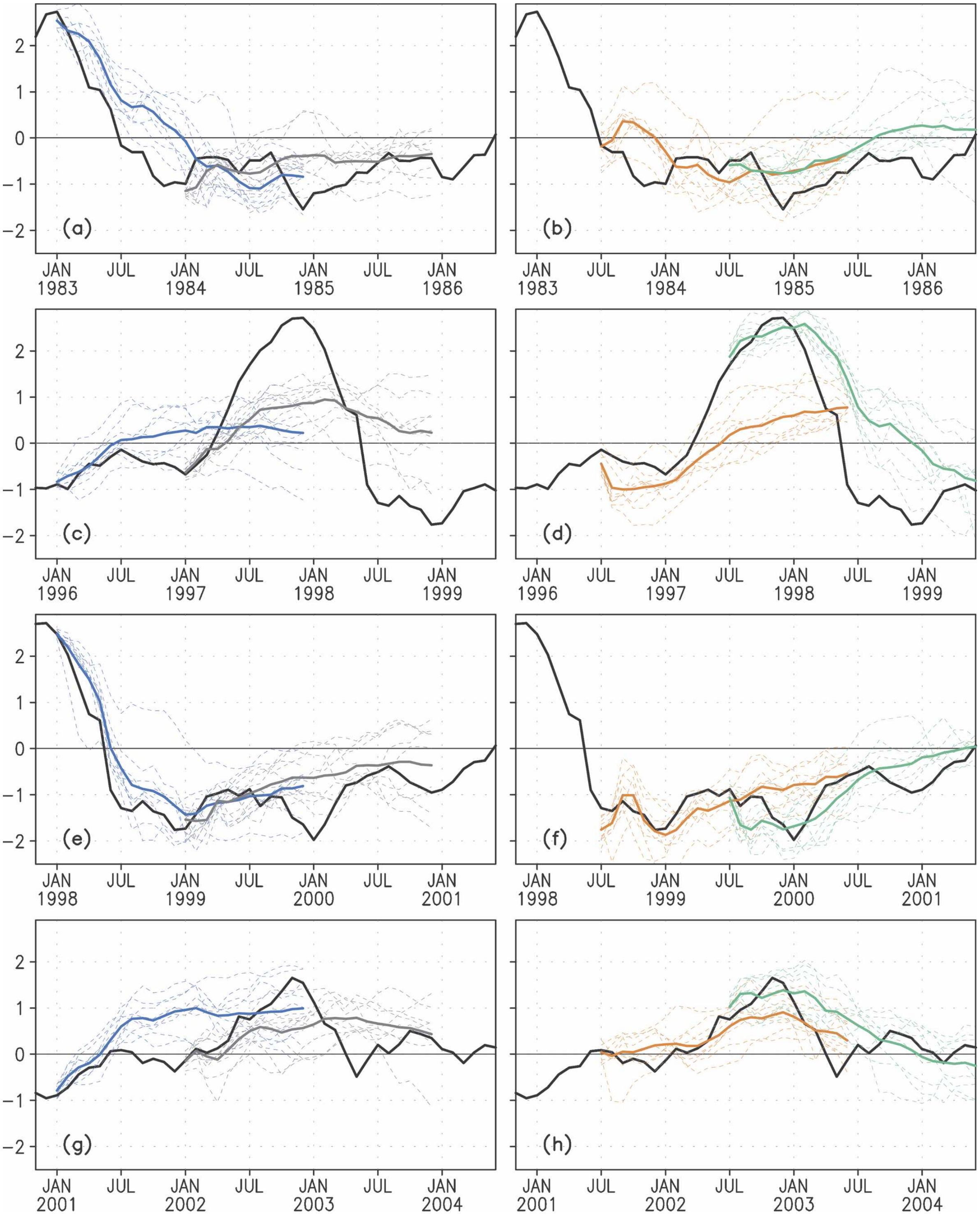

FIG. 4. (a), (b) Prediction plumes of the monthly Niño-3.4 SST anomalies initiated from 1 Jan 1983 and 1984 and 1 Jul 1983 and 1984 (blue, gray, yellow, and green lines) for the 1984/85 La Niña event. (c)–(h) As in (a), (b) but for the predictions of the 1997/98, 1999/2000, and 2002/03 ENSO events, respectively. The thick solid (thin dashed) colored lines show nine-member ensemble-mean (each member) predictions for 24 target months. The thick black curves denote the NCEP monthly analysis.

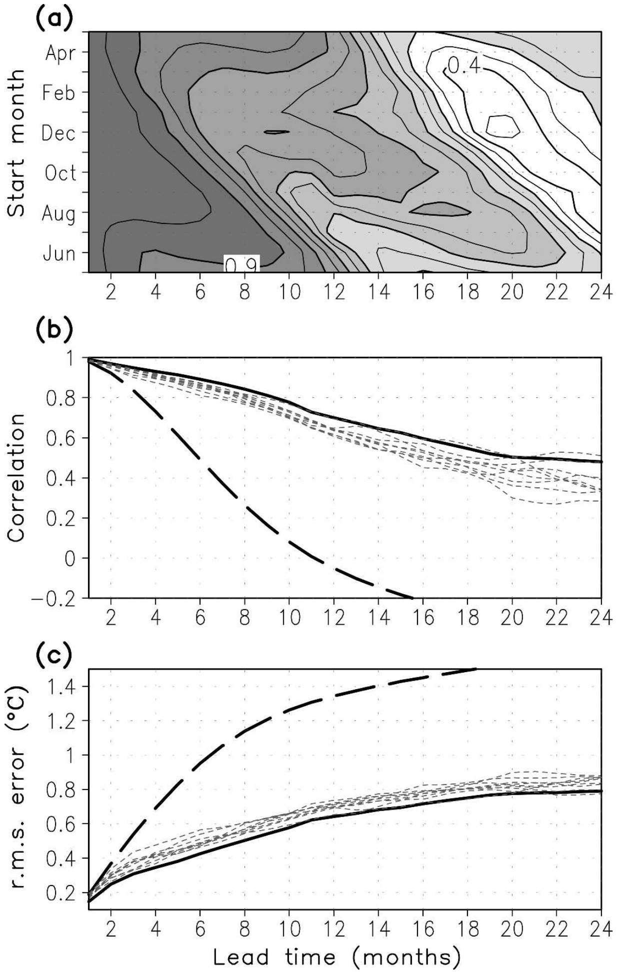

FIG. 5. (a) As in Fig. 2, but for Niño-3.4 SST anomaly correlations between the observations and nine-member ensemble-mean predictions up to a 24-month lead. These are shown as a function of start month and lead time. Contour interval is 0.05 and regions with values above 0.5 are shaded. (b) As in (a), but for the anomaly correlations calculated with no seasonal dependence. The thick solid (dashed) curve is nine-member ensemble-mean (persistence) forecasts. The gray dashed lines denote individual member forecasts. (c) As in (b), but for the rms errors.

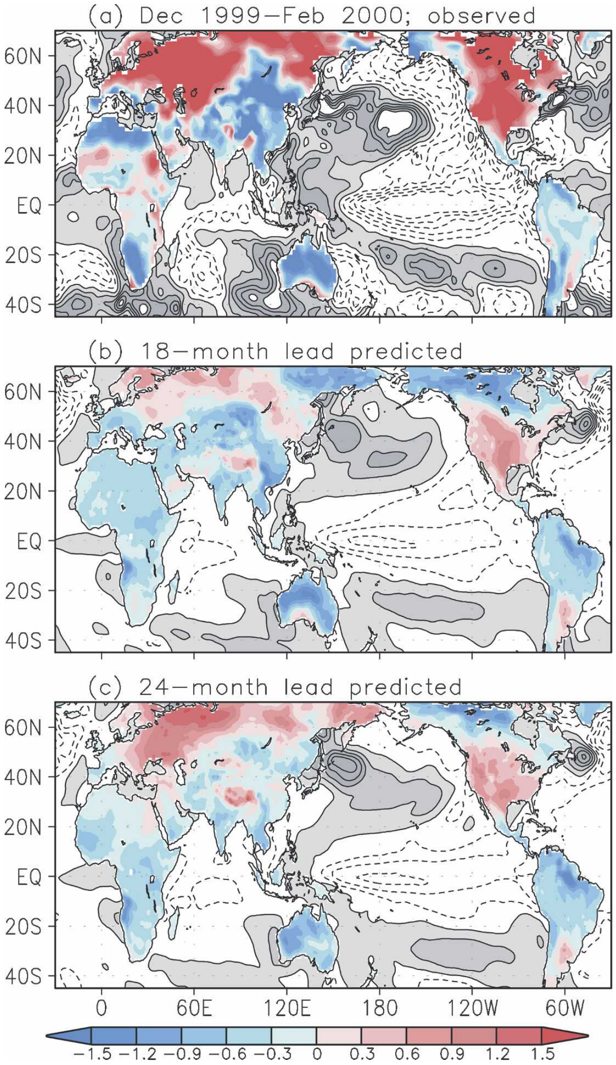

FIG. 6. Seasonal-mean SST anomalies (contour interval: 0.3°C) and terrestrial 2-m air temperature anomalies during the period from December 1999 to February 2000. These are produced by (a) NCEP reanalysis and predicted at (b) 18- and (c) 24-month leads. SST anomalies are spatially smoothed with nearby nine points for clarity, and regions with positive values are shaded.

predicted at 18- and 24-month leads during the peak phases of the highly predictable 1999/2000 La Niña and 2002/03 mild El Niño–like episodes. Compared with the NCEP SST observations, the spatial patterns of both events in the Pacific Ocean are well predicted except for some local discrepancies. The broad meridional structures of the SST anomalies in the tropical Pacific are well captured, but the magnitudes are only about 40%–60% of the observed ones. Besides, ENSO-related SST anomalies in the tropical Indian Ocean are also captured; this is related to the model's good performance in simulating SST signals in the Indian Ocean (Luo et al. 2005a,b; Behera et al. 2005).

Potential predictability of seasonal climate (atmospheric states) is largely determined by the slow variations in the surface boundary forcings, in particular, the tropical SST anomalies associated with ENSO (e.g., Brankovic et al. 1994; Barnett et al. 1994; Shukla et al. 2000). Numerical studies show evidence of links between the tropical SST anomalies in the Indo-Pacific sector and the widespread drought and warm climate in the United States and southern Europe during 1998–2002 (Hoerling and Kumar 2003). Given the well-predicted SST anomalies in the Indo-Pacific region, the 1999/2000 above-normal winter temperatures in the United States and northern Eurasia can be predicted

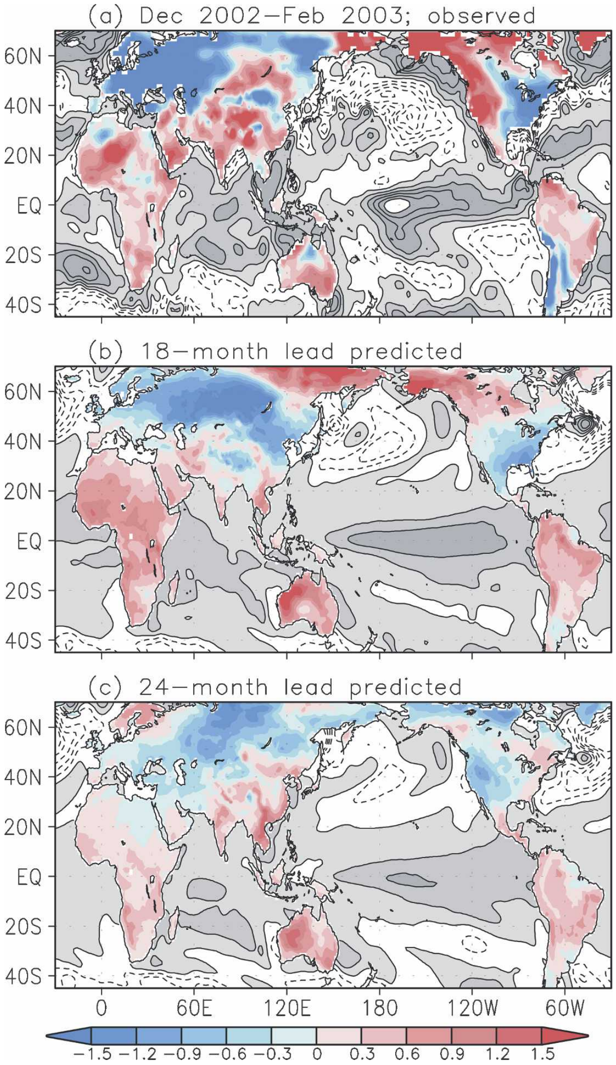

FIG. 7. As in Fig. 6, but for the period from December 2002 to February 2003.

even at 18- and 24-month leads (Figs. 6b,c).[6] Moreover, the cold surface air temperature anomalies are also predicted realistically over large parts of Africa, Asia, Australia, and South America, consistent with the NCEP reanalysis data (Fig. 6a; Kalnay et al. 1996). We note that 18- and 24-month lead predicted SST anomalies in the Indo-Pacific sector and the global 2-m temperature anomalies associated with the 1984/85 La Niña event bear a good resemblance to those of the 1999/2000 event (not shown). Associated with the 2002/03 mild El Niño–like event, the model predicts similar global winter climate anomalies but with an opposite polarity in general (Fig. 7).[7] This implies that the model captures the intrinsic impacts of ENSO on the global winter climate (Luo et al. 2003). The terrestrial air temperature anomalies predicted at 18- and 24-month leads are also close to the NCEP reanalysis over most parts of the globe except for North America (Figs. 7b,c). The model predicts the winter climate anomalies in that region reasonably well at an 18-month lead but fails at a 2-yr lead.

5. Summary and discussion

As far as we know, this is the first report on the success of a fully coupled ocean–atmosphere GCM in predicting ENSO and its related global seasonal climate anomalies at lead times of up to 2 yr. The El Niño condition in the 1997/98 winter can be predicted to some extent up to about a 1½-yr lead but with a weak intensity and large phase delay in the prediction of the onset of the strongest warm event. This is attributed to the impacts of a sequence of several strong stochastic westerly wind bursts during late 1996 to mid-1997, which are basically unpredictable at seasonal time scales. The results suggest that both the large-scale ENSO dynamics and the pronounced westerly wind bursts are important to the development of the unprecedented 1997/98 El Niño event (e.g., Fedorov et al. 2003). The cold conditions during the 1984/85 and 1999/2000 winters (i.e., the peak phases of the past two long-lasting La Niña events) are predicted well up to a 2-yr lead; this is consistent with the classical ENSO theory. Interestingly, the mild El Niño–like event of 2002/03 is also predicted well up to a 2-yr lead; this seems to be related to the tropical Pacific decadal variability. The results do not support the idea that strong El Niño events are more predictable than mild ones and La Niña events as was put forward using a simple dynamical model (e.g., Chen et al. 2004). Individual ENSO events can be highly predictable depending on whether the forecast system is able to capture the main multiscale interactions in the climate system.

One advantage of the GCM-based prediction system is that it provides dynamically consistent forecasts of terrestrial seasonal climate anomalies, while other methods resort to empirical relations. It seems that the

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[6] Large ensembles are required to make reliable probabilistic predictions of the seasonal climate anomalies in the extratropics owing to the strong internal atmospheric variability there. Here, however, we limit our attention to the ensemble mean anomaly based on only nine available members. The mean anomaly tends to have the maximum likelihood of occurrence (e.g., Barnston et al. 2005).

[7] We note that teleconnections associated with El Niño and La Niña events do not always bear an opposite polarity owing to the nonlinearity of the climate system.

global seasonal climate predictability can be much higher than what we have thought, especially during periods when the SST anomalies in the tropical Indo-Pacific sector are highly predictable. It is worth noting that the current GCM prediction system still suffers from model biases, such as the semiannual SST cycle in the eastern Pacific (Luo et al. 2005a,b). Considerable efforts are required to improve the model performance in climate simulations, to assimilate both atmosphere and ocean observations suitably into the forecast system,[8] and to reduce the systematic forecast errors. Further research will tell us whether skillful long-lead predictions of ENSO and its related climate variations can be made in the future with increased anthropogenic impacts and in the past decades before 1982. Since our model assimilates only SST information, retrospective forecasts with larger ensemble members over the past five decades or even one century are feasible by use of the Earth Simulator.

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