Research Development of 4-Dimensional Data Assimilation System using a Coupled Climate Model and Construction of Reanalysis Datasets for Initialization

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By using a 4-dimensional variational (4D-VAR) coupled data assimilation system exploited at JAMSTEC for the first time, a newly developed reanalysis dataset has been constructed to better define seasonal to interannual (S-I) climate variations. The analysis field well reflects most of the familiar gross features of observed climatological states. The time-series of the analysis fields also exhibit realistic features of important climate events such as the El Niño and the Asian Monsoon evolution and thereby have the ability to provide physical insight into the dynamic nature of S-I coupled phenomena. The forecast result using an initialization procedure by our 4D-VAR coupled data assimilation demonstrates the capability of one-year-lead prediction of the 1997/1998 El Niño event. These results reveal that our system can provide greater information content and forecast potential than do models or data alone.

Keywords: Coupled Data Assimilation, State Estimation, Seasonal to Inter-Annual Variability, El Niño Prediction

1. Introduction

Modeling studies using a coupled general circulation model (CGCM) represent a useful means of investigating the physical mechanisms responsible for climate variabilities generated by atmosphere-ocean interactions (e.g., Wang et al., 2004). However, current CGCMs are still at insufficient levels of performance to provide fully comprehensive descriptions of the important physical processes involved in climate variations. In particular, realistic simulation of the seasonal to interannual (S-I) variations such as the monsoon and the El Niño Southern Oscillation (ENSO) represents one of the toughest challenges of the modeling community (e.g., Sperber and Palmer, 1996; Annamalai and Murtugudde, 2004).

Recently, a 4-dimensional variational (4D-VAR) data assimilation system has gathered much attention in the modeling and the data analysis studies as an important tool of improving the representation of S-I climate processes. In fact, Mochizuki et al. (2007a) successfully reproduced the Asian summer monsoon development by optimizing the bulk adjustment factors required in the calculation of air-sea flux values for use in a CGCM by using a 4D-VAR technique. In the present study, we perform further coupled data assimilation experiments to make a better reanalysis dataset than earlier results and to improve the CGCM simulations for major processes during 1997–1998. In these years, the strongest ENSO and Indian Ocean Dipole Mode (IODM) events take place. A better definition of the clomatological features and accurate estimates of S-I variations of such important climate events strengthen our understanding of the underlying physical mechanisms, since the reanalysis data derived from our 4D-VAR data assimilation technique offer dynamically and thermodynamically self-consistent information on the air-sea coupled system.

Here, in line with our earlier work (e.g., Mochizuki et al, 2007a; b), we optimize the initial conditions together with the bulk adjustment factors using a 4D-VAR assimilation approach.

2. Model and assimilation experiment

The CGCM employed here in the atmosphere-ocean-land surface coupled data assimilation system is the coupled model for the Earth Simulator (CFES) (Ohfuchi et al., 2004; Komori et al., 2005) and the adjoint code is obtained on the basis of the Tangent linear and Adjoint Model Compiler (Giering and Kaminski, 1998) and the Transformation of Algorithms in Fortran compiler (Giering and Kaminski, 2003). The radiation code of the atmospheric component has been updated using the MstrnX system (Nakajima et al., 2000) and a simple diagnostic calculation of marine stratocumulus cloud cover has been newly implemented (Mochizuki et al., 2007b). The ocean mixed-layer scheme also has been updated using the method of Noh (2004). The resolution of the atmospheric model is horizontally the same as the commonly-used T42 spectral model and has 24 layers in the vertical σ coordinate. The resolution of the ocean-sea ice model is 1° in both latitude and longitude and has 45 vertical layers. A rather coarse resolution has been employed in order to restrict the computational load required by the coupled 4D-VAR experiment.

The latent heat, sensible heat, and momentum fluxes are determined here as $\alpha_i F_i$; $F_i(x, y, t)$ and $\alpha_i(x, y, t)$ represent the surface flux values calculated from the bulk formulae in the CFES model and the adjustment factors introduced into each bulk formula, respectively. These bulk adjustment factors are chosen as control variables along with the oceanic initial conditions in this study. Note that each value of α_i is optimized at each grid point as a 10-day mean value by the present coupled assimilation experiments. The cost function J is composed of background and observational terms (not shown), and the minimization of J is performed for the optimization of the control variables by using the 10-day mean values of the modeled variables and the observational data to improve the S-I component. Thus, shorter timescale fluctuations and the climatological monthly-mean fields are not directly corrected in our assimilation approach. In addition, the error covariance matrices for the control variables and observational data are assumed to be diagonal for convenience.

The assimilation experiments are performed for the 3-year period from January 1996 with a 9-month assimilation window. First guess values of the initial oceanic conditions are derived using the Incremental Analysis Updates (IAU) method (Bloom et al., 1996) and those of the bulk adjustment factors are set to unity. Thereafter the initial oceanic conditions and the bulk adjustment factors are optimized in every assimilation cycle of both the 9-month-long forward run and the subsequent 9-month-long backward run using the adjoint codes. The iterative procedure with the forward and the back run for each cycle is continued until the cost function value reduces to a level that is almost equivalent to the errors in the assimilated input fields in this study. This reduction proves that the correction of the model fields in the CGCM simulation is meaningful in a statistical sense, although the repetition of the adjoint calculation may not be sufficient to obtain an optimum solution. Further details of the experimental design will be documented in Sugiura (in preparation).

3. Results

3.1 Climate fields in 1997 and 1998

Here, we direct our attention to the S-I processes in the specific years from 1997 to 1998 when several important climate events took place. Firstly, to examine the effects of the optimization of bulk adjustment factors and initial oceanic conditions on the representation of climate fields, we analyze the ensemble-mean fields (referred to as CTL and ADJ) of 11 ensemble control simulations with different atmospheric initial conditions, since the shorter timescale atmospheric disturbances that are not directly assimilated in this study lead to an intrinsic limit in the effectiveness of monsoon predictability.(e.g., Palmer and Anderson, 1994). In the CTL simulations, the values of bulk adjustment factors are set to be uniformly 1 and those of oceanic initial conditions are derived from the IAU method, while those in the ADJ run are set to the optimized values from the assimilation.

The large differences observed in summertime SST between 1997 and 1998 can be interpreted as related to the IODM and the ENSO phenomenon (Fig. 1a). When compared to 1997, colder water is observed over the western equatorial pacific and the western equatorial Indian ocean during June-July of 1998, while warmer water spreads around the maritime continent and over the northwestern Pacific. These SST anomalies are better defined in the ADJ data (Fig. 1b), while the CTL case fails to simulate the warm SST anomalies, particularly to the west of Sumatra Island and southeast of Japan (Fig. 1c). We also perform two additional runs in which optimized values of either the initial oceanic conditions (Experiment ADJ*init*) or the bulk adjustment factors (Experiment ADJ*alpha*) are used. The ensemble-mean fields derived from these additional runs (Fig. 1d,e) offer less favorable comparisons with observations (Fig. 1a) than the ADJ run (Fig. 1b), although the presence of unrealistically cold water west of Sumatra Island is now largely removed and the weak warm SST anomaly southeast of Japan is enhanced in comparison to the CTL run (Fig. 1c). These results suggest that the optimization of initial oceanic conditions in conjunction with the bulk adjustment factors is able to improve the modeled SST fields.

In the summers of 1997 and 1998, the difference plot between the ADJ data and the CTL data displays large-scale patterns rather than localized patches (Fig. 2), whereas the control variables are optimized at each grid point. Although the assimilation experiments are performed independently in 1997 and 1998, the spatial pattern in SST difference in 1997

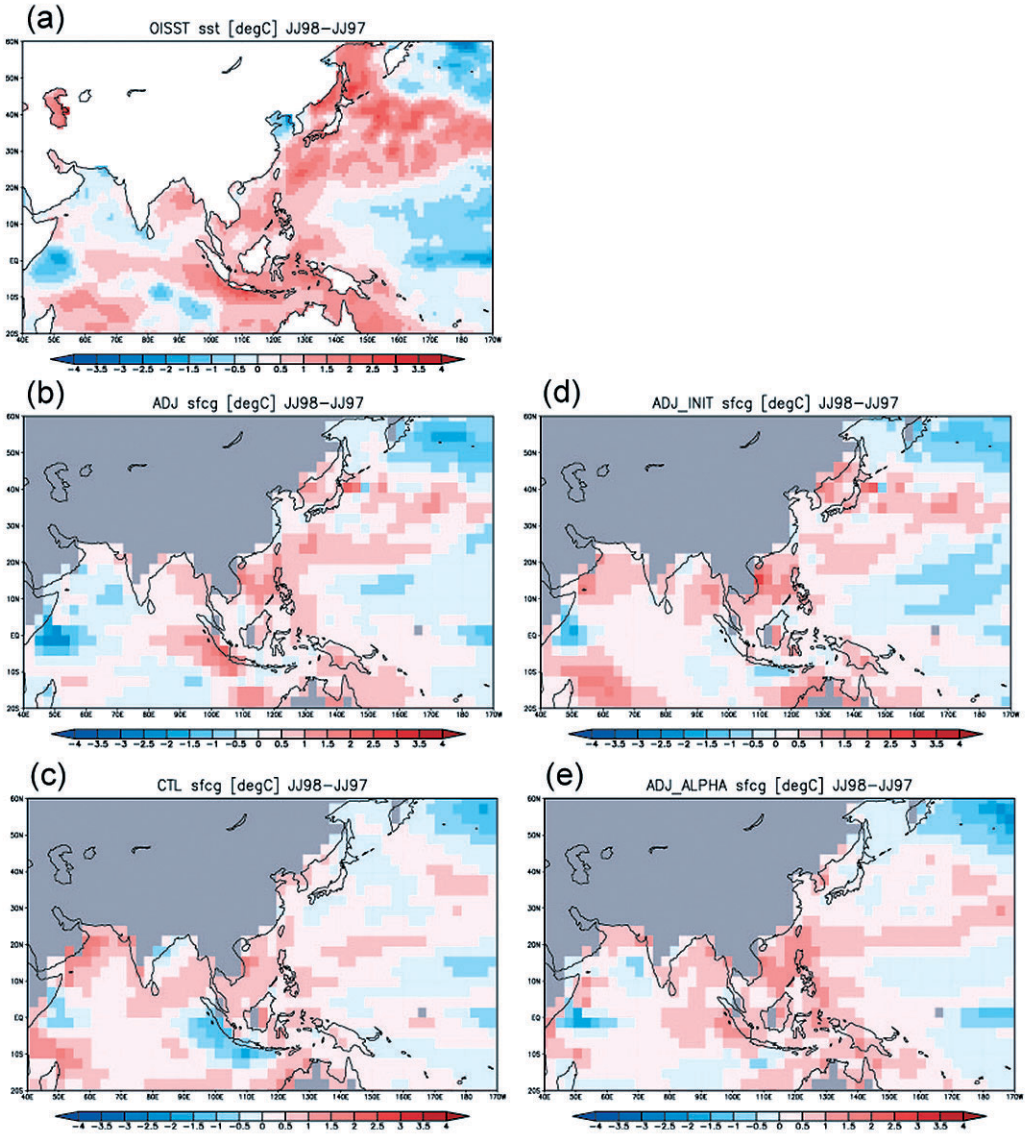

Fig. 1 Summertime SST differences between 1997 and 1998 (averages over June-July) of (a) OISST observation, (b) ADJ data, (c) CTL data, (d) ADJ_{init} data and (e) ADJ_{alpah} data, respectively.

is almost the same as in 1998 (Fig. 2b,d). This suggests that our coupled assimilation primarily improves the model climatologies.

In addition to these improvements in climatological features, the 1997/1998 IODM event is also better reproduced in the ADJ data. For example, the observed SST anomalies relating to the IODM event in the equatorial Indian ocean rapidly decay in early summer of 1998 (e.g., Sadi et al., 1999). The relatively warm water west of Sumatra Island in Fig. 2d suggests that the IODM event in the ADJ data is realistically terminated in early summer of 1998, while that in the CTL data persists for an excessively long time. The dominant spatial pattern of differences in precipitation (Fig. 2c) is similar to that typically observed during a negative IODM year.

Our optimization improves both the climatological seasonal cycle and the interannual variation of the Asian monsoon dominating in seasonal variations. For example, the heavy-rainfall areas over the Indochina Peninsula in the ADJ data rapidly migrate northward in mid-May in agreement with observations, while south northward migration in the CTL case takes place in June. Mochizuki et al. (2007a) reported a similar improvement on the timing of the climatological monsoon onset by a coupled assimilation. Note that the precipitation data are not directly assimilated in our experiments.

These improvements are realized by optimization of both the bulk adjustment factors and the oceanic initial conditions. The optimized α_i values in 1997 display similar spatial variations to those in 1998 (not shown). This again suggests that our assimilation primarily improves the model climatologies.

The optimized oceanic initial condition is also a major contributor to the better definition of S-I climate variations using the CGCM. Large changes in initial water temperature are evident around the thermocline of the equatorial Indian ocean, particularly in 1997 (Fig. 3). In the ADJ data, well

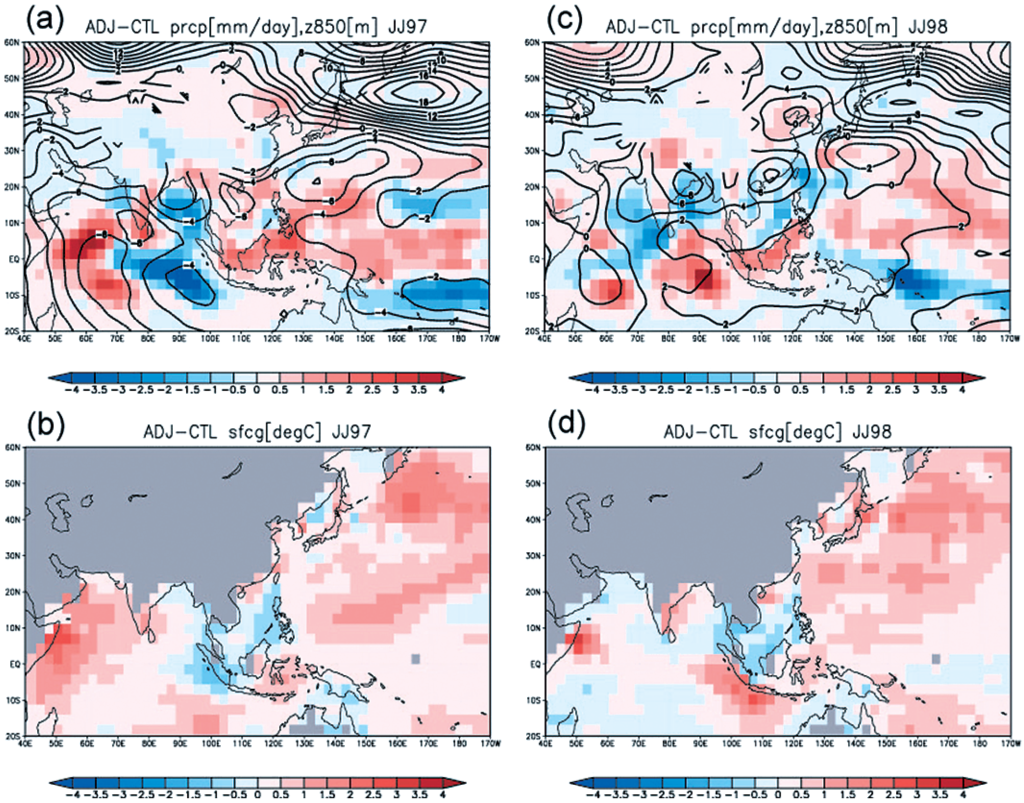

Fig. 2 Summertime differences between ADJ data and CTL data (averages over June-July) of 1997 (left) and 1998 (right). Lower panels denote SST values (shade) and upper panels denote precipitation rate (shade) and 850hPa geopotential height values (contour), respectively.

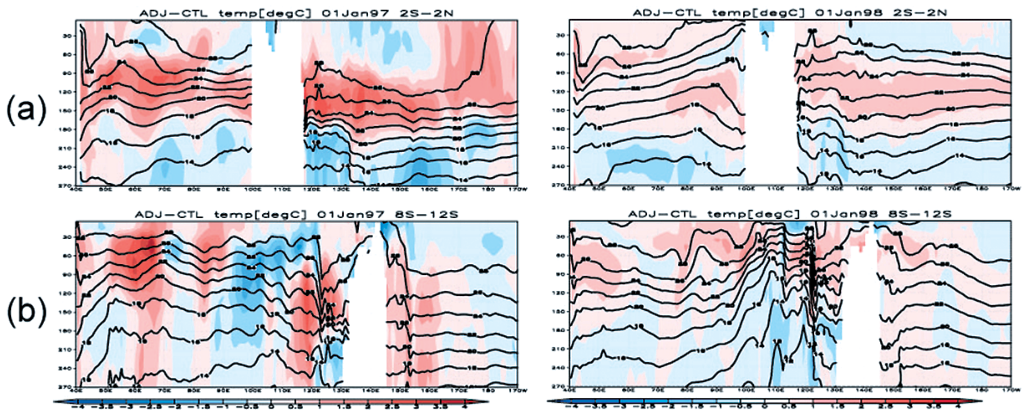

Fig. 3 Longitude-depth section of initial water-temperature differences between the optimized values derived by our assimilation (ADJ case) and the IAU-derived values (CTL case), for (a) along the equator and (b) along 10˚S. Left and right panels denote these values for 1997 and 1998, respectively.

initialized water-temperature anomalies propagate as tropical waves over the topical Indian ocean and make the thermal conditions in the upper ocean more realistic throughout the assimilated period. In fact, along 10˚S in 1997, in the ADJ data, the initial warmer water in the central Indian ocean is transported towards the west through an oceanic Rossby wave action and consequently the upper ocean temperature in the western equatorial Indian ocean attains an above-normal values in autumn when these waves reach the east coast of Africa (not shown). Such westward propagation of warm water along 10˚S is a key process in the development of the 1997/1998 IODM event (e.g., Xie et al., 2002).

3.2 El Niño reanalysis and predictability

Using one member of the ADJ run, we assess the El Niño phenomenon which is one of the most dramatic climate events in the Pacific ocean. Figure 4 shows the time series of SST values averaged in Niño 3.4 region (5˚N–5˚S, 170˚W–120˚E) in which the ADJ data are quite similar to the observed data. The root mean square difference of the SST values between the ADJ run and the observations is approximately 0.53K during the period of 1996–1998, while

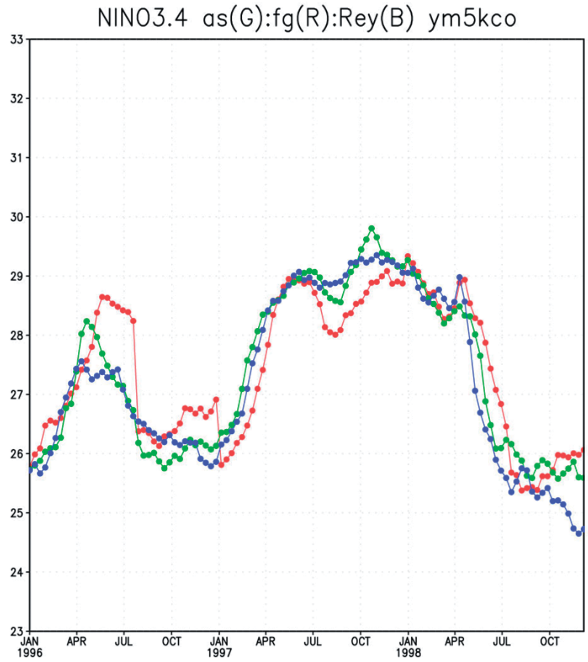

Fig. 4 Time change of Niño 3.4 SST from 1996 to 1998 for the first guess (red curve ; CTL data), the analysis (green curve ; ADJ data), and Reynolds product (blue curve). The unit is in ˚C.

the difference for the CTL case is 0.86K. Figure 5 shows the longitude-time section of absolute SST values averaged in a zonal band between 2˚N and 2˚S. Note that accurate estimates of absolute SST values are quite important in identifying and predicting realistic air-sea interactions (e.g., Gadgil et al., 1984). The time evolution of SST in the ADJ data well reflects the observed features about the 1997/1998 El Niño (Picaut et al., 2002). For example, the El Niño onset is triggered by strong westerly bursts in the spring of 1997 and the peak value of SST in the central equatorial Pacific reaches about 30˚C in October of 1997 (Fig. 5). In the CTL data (first guess field), such a familiar gross feature is not well presented (Fig. 5a). In addition, the time series of the equatorial zonal wind stresses averaged between 2˚N and 2˚S in the ADJ data (Fig. 6) exhibit the occurrence of a couple of westerly bursts observed in the spring of 1997 that initiated the 1997/1998 El Niño. The wind stress distribution in the mature phase of the El Niño is also corrected in the ADJ data when compared with observations. The successful reproduction of wind stress fields leads to a better time trajectory of the main thermocline (thus, upper ocean heat stor-

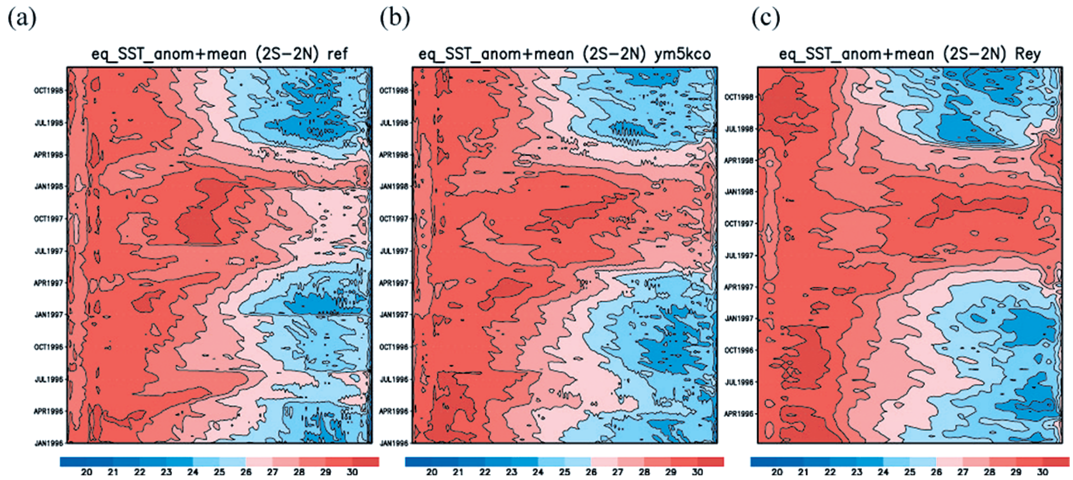

Fig. 5 Longitude-time section of SST along the equator averaged in 2˚S–2˚N from 1996 to 1998 : (a) first guess field (CTL data), (b) analysis field (ADJ data), and (c) Reynolds product. The unit is in ˚C.

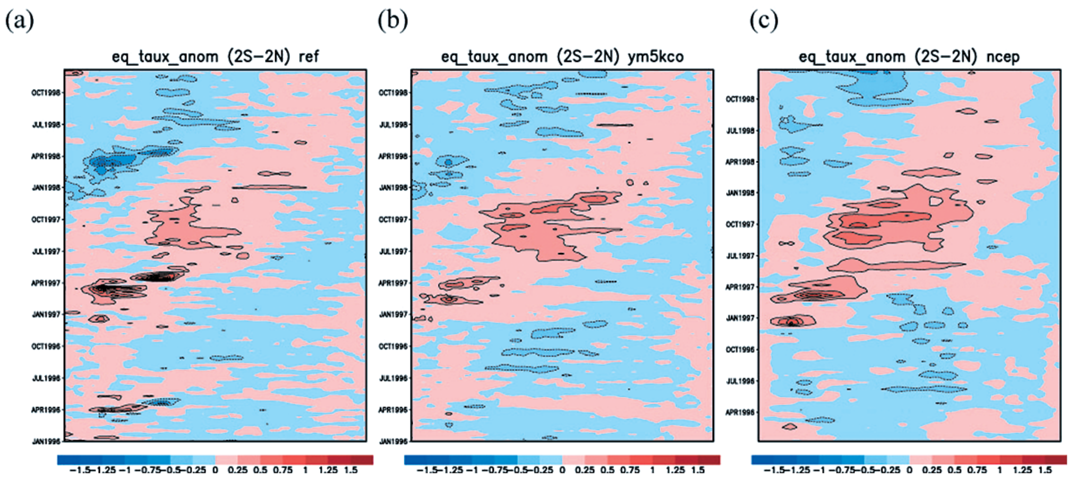

Fig. 6 Same as Fig. 5 but for zonal wind stress anomaly. The unit is in Nm^{-1}.

age and sea surface height) (Hirst, 1986). Further, associated with the improved ENSO process, the Pacific-North America teleconnection pattern is better represented in the ADJ data than in the CTL data (not shown).

The good representation of Niño 3.4 SST and wind stress fields in the ADJ data implies the enhancement of El Niño predictability, since previous studies have shown the effectiveness of the appropriate initialization for the upper ocean on the ENSO prediction (e.g., Ji and Leetma, 1997; Alves et al., 2004). Note that the SST nudging method often used for initialization of forecasts inevitably contaminates the forecast field leading to less predictability than sophisticated assimilation methods such as the 4D-VAR technique. Considering these facts, we have attempted the 1997/98 El Niño forecast experiments using the 4D-VAR coupled data assimilation system. Figure 7 shows the forecast result in terms of the time series of the Niño 3.4 SST. This result demonstrates the success of about one-year-lead prediction of the El Niño evolution process. This is an appropriate benchmark for the advantage of our 4D-VAR coupled data assimilation approach in initializing the El Niño prediction and thereby demonstrates greater forecast potential of our system than earlier results.

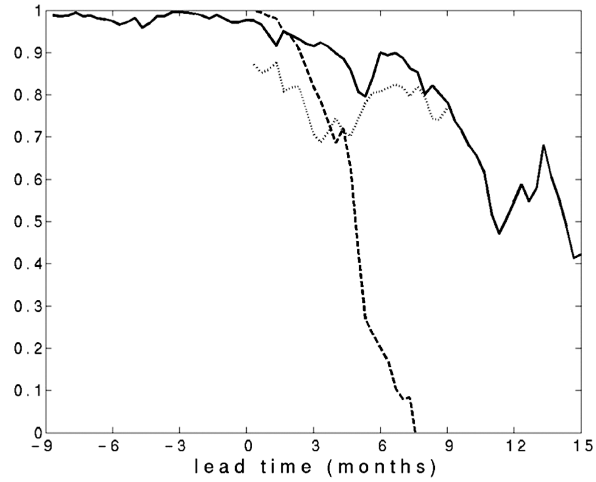

Fig. 7 NIÑO 3.4 SST anomaly correlation coefficient for prediction experiments. Solid line: extended integration from optimized oceanic initial condition given by ADJ data, dotted line: prediction from oceanic initial condition by IAU, dashed line: persistence. The statistics is from 6 cases of ensemble runs starting from October and April of 1996 to 1998 (each with 11 different atmospheric initial conditions).

4. Concluding remark

By developing the 4D-VAR coupled data assimilation system for the first time, we have obtained dynamically self-consistent reanalysis dataset suited to applications in climate variation. The dataset shows consistency with previous knowledge of seasonal to inter-annual climate changes. Analysis and prediction using the reanalysis dataset confirm that our 4D-VAR coupled data assimilation system has more ability than earlier systems and, further, create new information for the understanding of climate change mechanisms. These results underline its usefulness in formulating accurate forecasts.

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フル結合四次元データ同化システムの研究開発と初期値化・再解析データの構築

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「人・自然・地球共生」課題7で開発した四次元変分法結合データ同化システムを適用してアンサンブル気候値再解析及び顕著年再解析実験を行い、大気海洋相互作用パラメータである水・熱・運動量交換のバルク係数を最適化することによって、季節～経年変動過程の再現性を整合的に向上させることに成功した。具体的には、アジアモンスーンやインド洋ダイポールモード現象、ならびにエルニーニョ現象の進化過程を精緻に記述する再解析データセットを作成して、それを初期値化に使用することにより、1997–1998年に発生した史上最大のエルニーニョの発展過程の1年先行予測に初めて成功した。

キーワード：結合データ同化, 状態推定, 季節・経年変動, エルニーニョ予測