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NUMERICAL MODELING STUDY OF EFFECTS OF EASTERN PACIFIC WARM POOL ON ENSO

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Abstract: In this study, sensitivity experiments were conducted with the Zebiak-Cane ocean-atmosphere coupled model forced by the wind stress anomaly from the U.S. National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data to study the impacts of eastern Pacific warm pool on the formation and development of ENSO events. The effects of climatological mean sea surface temperature of the warm pool on forecast skill during the ENSO events of 1982–1999 are more considerable that those of climatological mean meridional winds and ocean currents. The forecast skill for the 1997/1998 El Niño event is characterized by sensitivity to climatological mean sea surface temperature and anomalies of northerly winds and currents. The forecast skill is found insensitive to climatological mean northerly meridional winds and currents.

Key words: eastern Pacific warm pool; ENSO event; Zebiak-Cane ocean-atmosphere coupled model; sensitivity experiments

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1 INTRODUCTION

In addition to the well-known western Pacific warm pool, another warm pool is located at 0°–29°N, 120–180°W, with a sea surface temperature (SST) warmer than 27.5°C[1]. This area is known as the eastern Pacific warm pool. With the onset and development of El Niño, the effects of the western Pacific warm pool and associated zonal winds have been the focus of previous research[2–14], whereas the effects of the eastern Pacific warm pool have been seldom studied. However, the effects of meridional winds on El Niño events cannot be ignored[15–26]. Recently, Karnauskas et al.[27] showed that the correlation coefficient between El Niño Southern Oscillation (ENSO) and the inter-annual variability of SST over the eastern Pacific warm pool can be as large as 0.95. Yue et al.[28] analyzed the relationship between ENSO and the eastern Pacific warm pool, the associated meridional winds based on SST from the Lamont-Doherty Earth Observatory (LDEO) of Columbia University, and the 1982–1999 reanalysis data from the U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). They found that climatological mean SST over the eastern Pacific warm pool shows strong seasonal variations. These findings are similar to the evolution of El Niño, including onset in spring, development in summer, maturation in fall, and decay in winter. The meridional wind anomaly and divergence are closely associated with ENSO events. With the same data sets, Yue et al.[29] further examined the physical mechanisms associated with the onset and development of the 1997/1998 El Niño event by analyzing the eastern and western warm pools, as well as the northerly and westerly wind anomalies. The study revealed that the northerly wind anomaly directly leads to the increase in SST over the Niño3 region

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through the southward transport of warm water from the eastern Pacific warm pool to equatorial regions. The effects of the eastern Pacific warm pool and associated zonal and meridional winds on ENSO can be studied using ocean-atmosphere coupled models. In 1980, the Zebiak-Cane coupled ocean-atmosphere model was developed by the Lamont-Doherty Earth Observatory, Columbia University, USA[30]. Yue et al.[31] replaced Florida State University wind stress anomaly with 925 hPa NCEP/NCAR reanalysis wind stress anomaly (NCEP wind anomaly) as the initial forcing of the Zebiak-Cane model (referred to as the ZCW coupled model hereafter). They found that the model improves forecast skill in terms of ENSO events during the last two decades of the 20th century. In particular, the model can successfully forecast the event. Yue et al.[32] also conducted a complete evaluation of the forecast skill of the ZCW coupled model. It is an anomaly model that includes climatologically averaged oceanic and atmospheric factors (i.e., the five climatologically averaged fields: SST, ocean surface upwelling, wind divergence, currents, and winds)[30].

In this study, sensitivity numerical experiments were conducted using the ZCW coupled model to study the effects of climatological means, SST anomalies, ocean surface meridional currents, and winds over the eastern Pacific warm pool on the forecast skill for ENSO events from 1982–1999. These factors are analyzed to reveal their effects on the onset and development of El Niño events. The ZCW coupled model and data used in this study are referred to in Yue et al[31, 32]. The results of the numerical experiments on ENSO for 1982–1999 are discussed in the next section. The results of the experiment on the event are presented in section 3. A summary is provided in section 4.

2 NUMERICAL EXPERIMENTS ON ENSO FROM 1982–1999

Yue et al.[28] analyzed the NCEP/NCAR reanalysis data from 1982–1999 and revealed that the eastern Pacific warm pool and associated meridional wind anomaly play important roles in the onset and development of ENSO events. The correlation coefficients of the Niño 3 region were then calculated between the experiments, determined with the ZCW coupled model, and those observed in 1982–1999. The results of the experiments were then compared with the correlation coefficients of the Niño 3 region between the forecasts from the experiments without any modifications or observations. The variables tested included SST, ocean surface meridional currents, and winds over the eastern Pacific warm pool at 0°–29°N, 120°–80°W.

Ten experiments were conducted in this study with T0 as the control experiment. Climatological mean SST, meridional current, and meridional wind in the ZCW coupled model over the eastern Pacific warm pool were set to zero in T1, T3, and T5, respectively, and were increased by 10% in T2 and 100% in T4 and T6, respectively. The anomalies of the meridional currents and winds over the eastern Pacific warm pool were set to zero during the integrations of the ZCW coupled model in T7 and T9, respectively, and were increased by 100% in T8 and T10.

Figure 1a shows the correlation coefficients of Niño3 predicted by the ZCW coupled model in T0 and T1 for the preceding 24 months and corresponding observations. The correlation coefficients in T1 decrease dramatically from 0.8 to -0.6 when the prediction is made less than three months in advance; the correlation coefficients also tend to be around zero, suggesting that a crucial role is played by the SST of the eastern Pacific warm pool in determining the performance of the ZCW coupled model in forecasting ENSO. The correlation coefficients in T2 are similar to those in T0 in the prediction made less than six months in advance; the values tend to be smaller than T0 for the predictions made more than six months in advance. This indicates that a 10% increase in climatological mean SST does not affect the forecast skill for ENSO made less than six months in advance; the increase also gradually reduces the forecast skill for predictions made more than six months in advance. T3 shows a correlation coefficient similar to that of T0 for forecasts made less than four months in advance, and has a smaller correlation coefficient than T0 when the prediction is made more than four months in advance (Fig. 1b). This result indicates that the climatological mean meridional current influences ENSO predictions to some extent. The similarity of correlation coefficients between T4 and T0 implies that a 100% increase in the climatological mean meridional current has no effect on the ENSO prediction made less than 24 months in advance. Generally, T5 has similar correlation coefficients as T0, suggesting that the climatological mean meridional wind has no impact on the ENSO forecast (Fig. 1c). T6 has similar correlation coefficients to T0 when the precipitation is made less than 10 months in advance, but it has a smaller correlation coefficient than T0 when the forecast is made more than 10 months in advance. The 100% increase in climatological mean meridional winds can reduce the forecast skill of ENSO by more than 10 months in advance.

T7 has correlation coefficients similar to those of T0 when the forecast is made less than four months in advance (Fig. 1d). The correlation coefficients in T7

are slightly smaller than those in T0 when the prediction is made 5–10 and 18–24 months in advance, and are slightly larger than those in T0 when the forecast is made 12–17 months in advance. The correlation coefficients in T8 are similar to or larger than those in T0 when the prediction is made less than 14 months and more than 21 months in advance, respectively, whereas the correlation coefficients are less than those in T0 for the prediction made 15–20 months in advance. T9 has correlation coefficients similar to those of T0 when the prediction is made less than four months in advance (Fig. 1e). The correlation coefficients in T9 are considerably smaller than those in T0 for the forecast made 5–20 months in advance, indicating an important role of the anomaly of meridional winds over the eastern Pacific warm pool. The similarity of correlation coefficients between T10 and T0 for predictions made less than 14 months in advance suggests that a gradual 100% increase in the anomaly of meridional winds has no effect on ENSO during the integration. Such increase may diminish forecast skill when the prediction is made 15–22 months in advance.

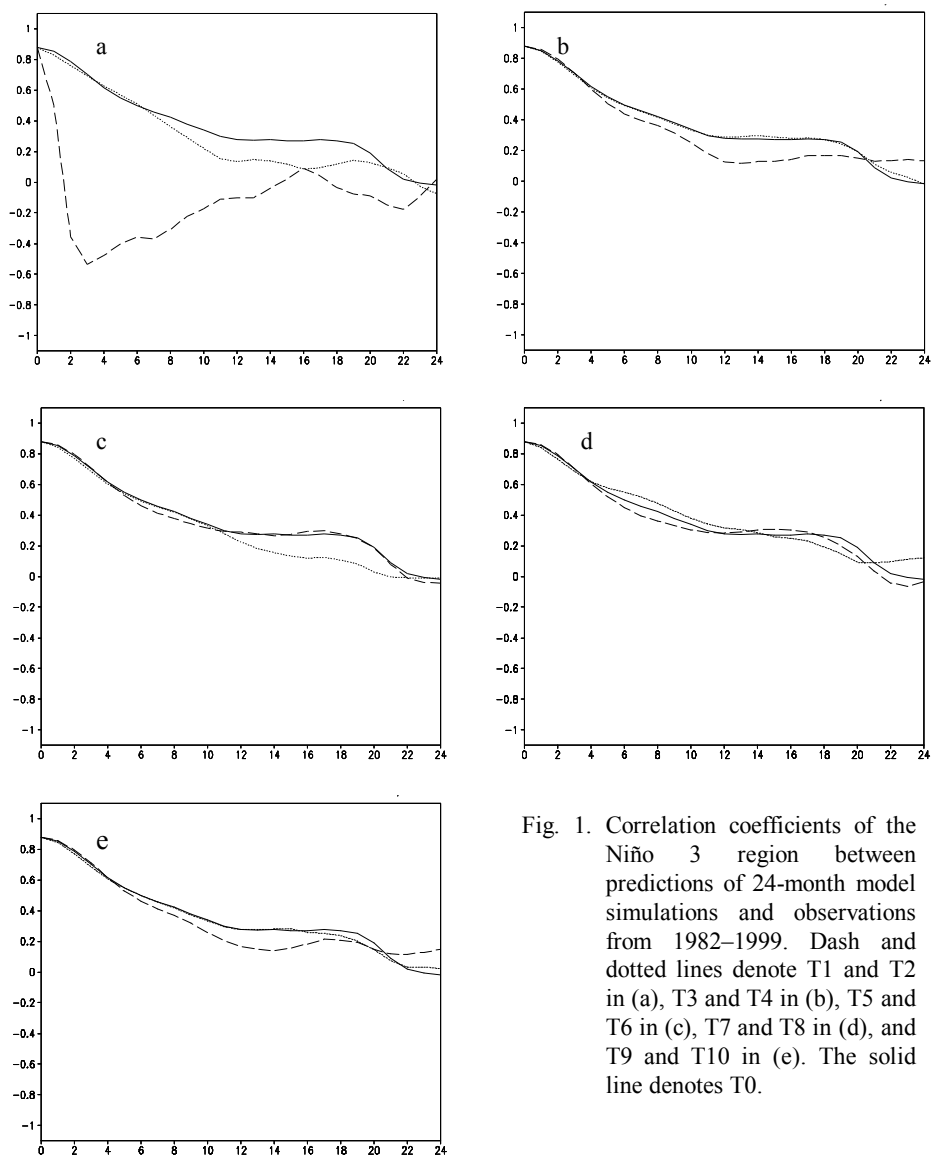


Fig. 1. Correlation coefficients of the Niño 3 region between predictions of 24-month model simulations and observations from 1982–1999. Dash and dotted lines denote T1 and T2 in (a), T3 and T4 in (b), T5 and T6 in (c), T7 and T8 in (d), and T9 and T10 in (e). The solid line denotes T0.

The results of the sensitivity experiments show the effects of climatological mean SST, meridional currents and winds, and anomalous meridional currents and winds over the eastern Pacific warm pool on the forecast skill of the ZCW model in the prediction of ENSO made less than 24 months in advance. In addition, the experiments for 1982–1989 and 1990–1999 were also analyzed, with results close to those from the analysis of experiments in 1982–1999, indicating no significant inter-annual variability in correlation analysis. The event, strongest in the 20th century, will be discussed later.

3 ANALYSIS OF EXPERIMENT ON 1997/1998 EL NIÑO EVENT

Previous studies[29] revealed that the eastern Pacific warm pool and northerly wind anomalies are closely associated with the development of the event. To examine the effects of the eastern Pacific warm pool on the forecast of the event using the ZCW coupled model, the sensitivity numerical experiments focused on the pre- (August–October 1996), onset (November 1996–January 1997), and development (March–May 1997) stages of the El Niño[33]. Experiments C0–C10 are identical to T0–T10, respectively, except that Experiments C0–C10 predict the event as well as the northerly meridional winds and currents. In C0–C10, the ensemble forecasts of the El Niño event were conducted using the ZCW coupled model with the initial month set at six consecutive months from August 1996–January 1997, February–July 1997, and August 1997–January 1998.

C1 fails to make an ensemble forecast of the event for August 1996–January 1997 (Fig. 2a). C2 makes an ensemble forecast of the Niño3 index at only 1°C, which is significantly lower than that of C0 (2.6°C) and the observation. For February–July 1997 (Fig. 2b) and August 1997–January 1998 (Fig. 2c), C1 fails to make a seasonal ensemble forecast, whereas the Niño3 index predicted by C2 is closer to the observation compared with C0. The removal of the climatological mean SST of the eastern Pacific warm pool in C1 leads to the failure of the forecast of the event, indicating the importance of climatological mean SST in determining the forecast skill for El Niño events. The 10% increase in climatological mean SST of the eastern Pacific warm pool does not have any effect on the improvement of forecast skill for the event in the pre- and onset stages of the El Niño; instead, it leads to a marked improvement in the forecast skill for the event after February 1997.

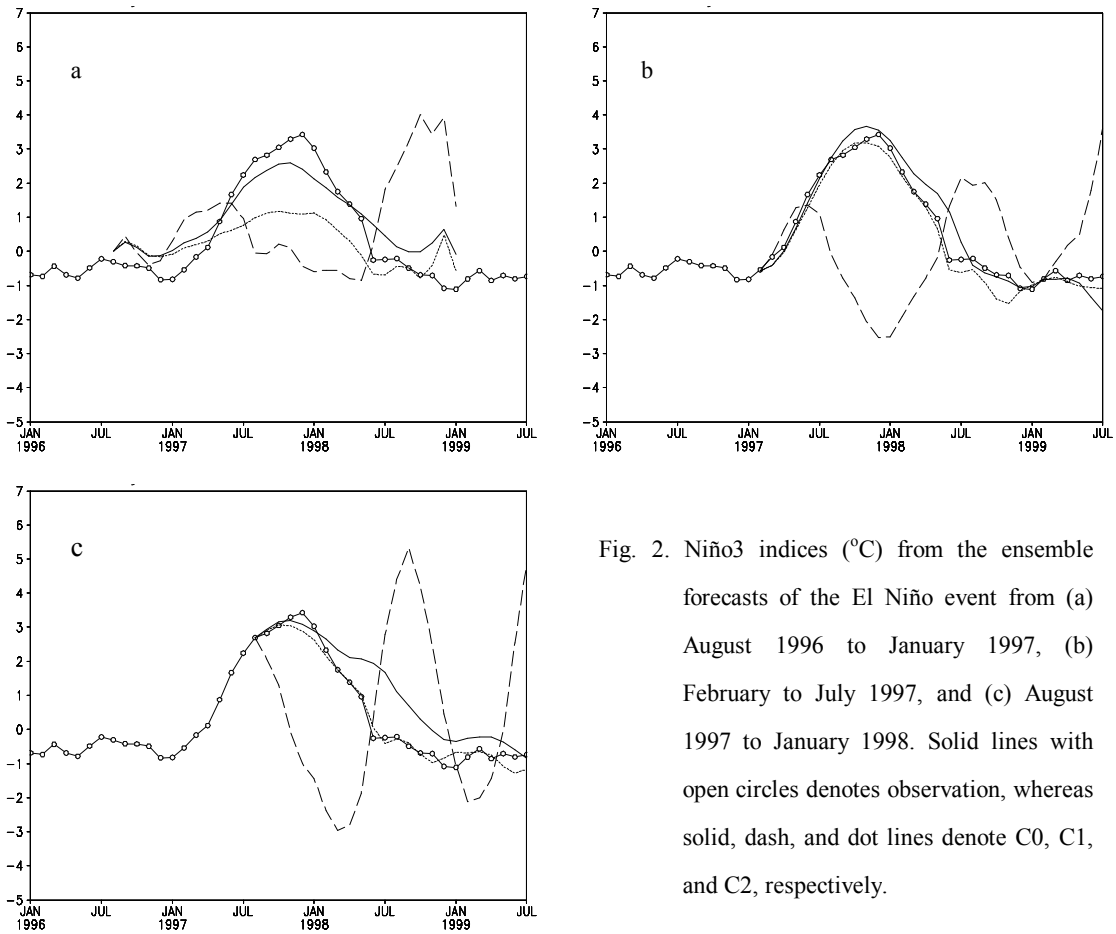
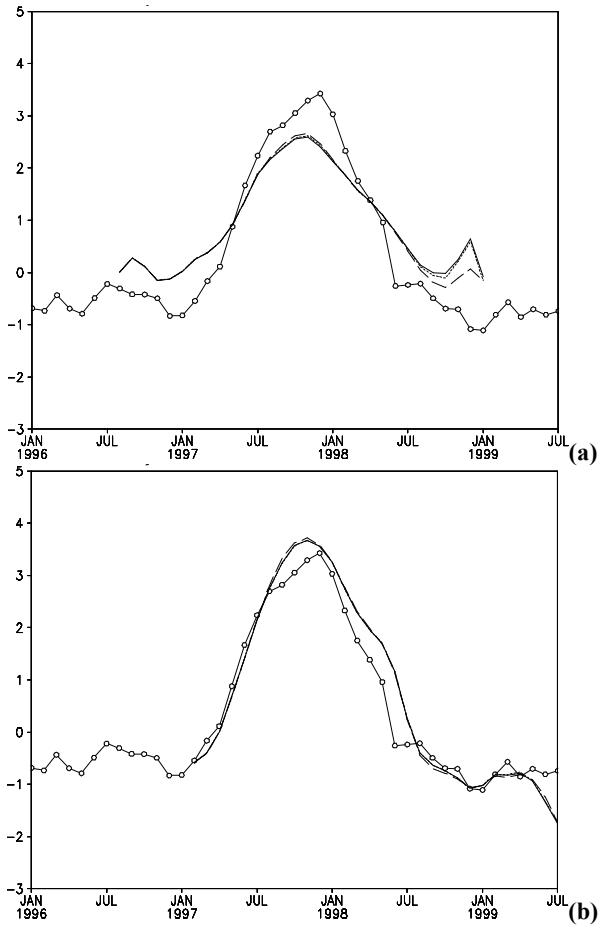


Fig. 2. Niño3 indices (°C) from the ensemble forecasts of the El Niño event from (a) August 1996 to January 1997, (b) February to July 1997, and (c) August 1997 to January 1998. Solid lines with open circles denotes observation, whereas solid, dash, and dot lines denote C0, C1, and C2, respectively.

The eastern Pacific warm pool affects the SST over the Niño3 region mainly through the northerly currents and winds[28, 29]. The ZCW coupled model includes imposed climatological mean northerly winds and currents, as well as prognostic anomalies of northerly winds and currents. Their effects on forecast skill will be discussed afterwards.

During the pre-, onset, and development stages of the El Niño, the Niño3 predicted by C3 and C4 (Fig. 3), as well as C5 and C6 (not shown) is very similar to that predicted by C0, suggesting that the forecast skill for the event is not sensitive to the removal of or

increase in climatological mean northerly currents and winds. The change in the climatological mean SST of the eastern Pacific warm pool has a considerable effect on the forecast skill for the event. This implies that the climatological mean SST of the warm pool is a crucial factor in the formation of the model El Niño event, and the warm pool is an important physical factor in the formation of the event. The changes in climatological mean northerly winds and currents do not affect the forecast skill for the event. This suggests that the effects of the eastern Pacific warm pool on the event may not be exerted through climatological mean northerly winds and currents. The effects of the anomalies of northerly winds and currents of the eastern Pacific warm pool on the event are analyzed next.



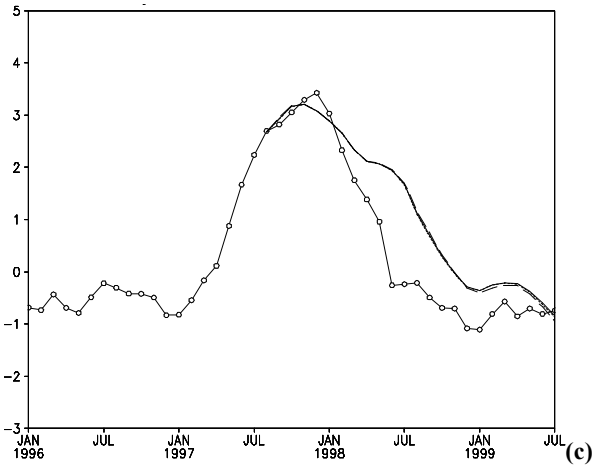


Fig. 3. As in Fig. 2 except for C3 and C4

Figure 4 shows distinct differences of the Niño3 index among C7, C8, and C0 predicted within the period of August 1996–January 1997. The warm phase in C7 is weaker than that in C0 and differs from the observation, whereas the warm phase in C8 is stronger than that in C0 and is close to the observation. The differences of Niño3 index predicted within February–July 1997 become smaller, and the indices predicted within August 1997–January 1998 are similar to each other.

Before the development of the El Niño event, the gradual removal and addition of the anomaly of northerly currents over the eastern Pacific warm pool appreciably affect the prediction of the Niño3 index with the ZCW coupled model. After the development of the El Niño event, the forecast skill is found to be insensitive to the anomaly of northerly currents. This implies that the anomaly of northerly currents over the warm pool enhances the development of the warm event during the pre- and onset stages of the El Niño, whereas the effect becomes weaker during the development stage.

The warm event predicted during August 1996–January 1997 in C9 (1.1°C) is much weaker than that in C0 (2.5°C), and deviates from the observation (3.5°C) (Fig. 5). The warm event predicted in C10 is much stronger than that in C0, and is close to the observation. The warm events predicted during February–July 1997 and August 1997–January 1998 in C9 and C10 are respectively weaker and stronger than those in C0.

The predicted Niño 3 index in C9 is smaller than in C0; C9, in particular, fails to predict the event. The predicted Niño 3 index in C10 is larger than that in C0; the predicted intensity in C10 is closer to the observation than that in C0. This suggests that the anomaly of northerly winds over the eastern Pacific warm pool can affect the forecast skill of the ZCW coupled model. During the pre-Niño stage, the gradual

removal of the anomaly of northerly winds leads to the failure of prediction of the event by the ZCW coupled model. The increase in the anomaly of northerly winds forces the predicted intensity of the warm event to become close to the observation.

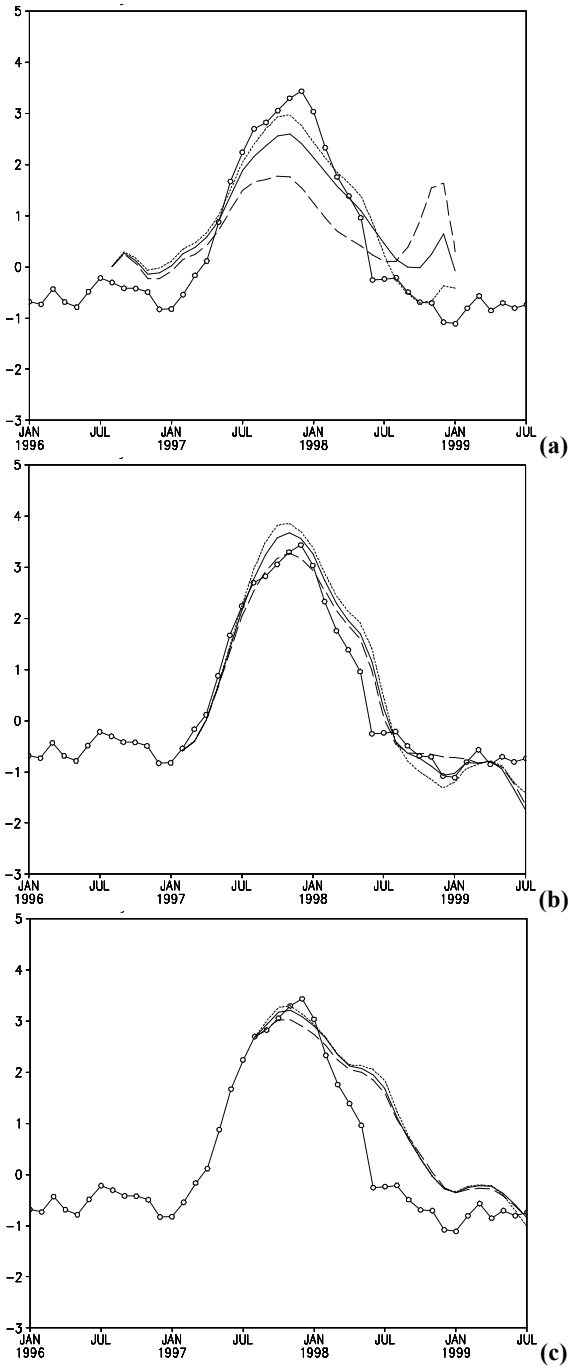


Fig. 4. Similar to that in Fig. 2 except for C7 and C8

The sensitivity experiments revealed that the forecast skill for the event using the ZCW coupled model is sensitive to the anomaly of northerly currents of the eastern Pacific warm pool, especially before the development of the event. The forecast skill for the 1997/1998 El Niño event is also sensitive to the anomaly of northerly winds of the warm pool, particularly during the pre-Niño stage. This implies that the eastern Pacific warm pool affects the SST over the Niño3 region mainly through the anomalies of northerly winds and currents.

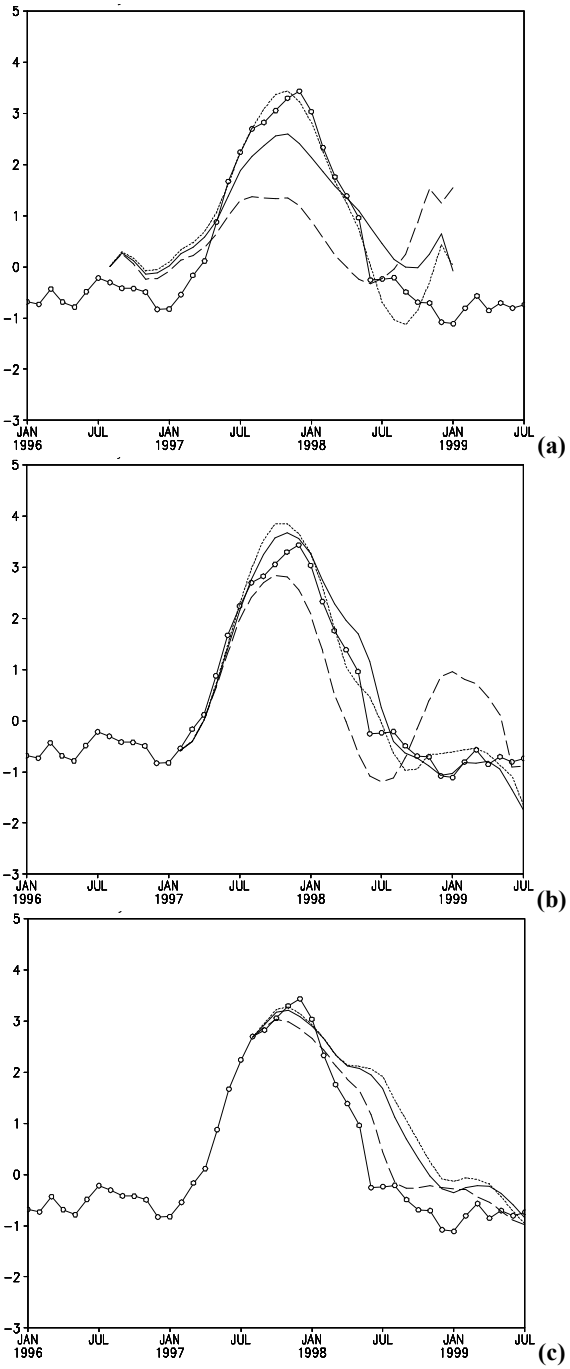


Fig. 5. Similar to that in Fig. 2 except for C9 and C10

The effects of the anomaly of northerly winds of the eastern Pacific warm pool on the forecast skill for the 1997/1998 El Niño event using the ZCW coupled model are larger than those of the anomaly of northerly currents because the latter transports the warm water of the eastern Pacific warm pool from north to south and

affects the SST over the Niño3 region. The increase in SST over this region is associated with the increase in warm water transported from the warm pool to the Niño3 region, which is related to the increase in the anomaly of northerly currents. If the anomaly of northerly currents of the eastern Pacific warm pool is reduced or removed, the transport of warm water from the warm pool to the Niño3 region is decreased, the increase in SST over the Niño3 region becomes smaller, and the probability of a warm event becomes lower. The marked effects of the anomaly of northerly currents on the forecast skill of the event for the pre- and onset stages of El Niño are related to the increase of SST over the Niño3 region as a result of the transport of warm water from the eastern Pacific warm pool to the Niño3 region. After the development stage, other processes for the increase in SST over the Niño3 region become important, weakening the effects of the anomaly of northerly currents on the warming of the Niño3 region. The anomaly of northerly winds of the eastern Pacific warm pool affects the SST in the Niño3 region by changing the anomaly of northerly currents and suppressing the upwelling near the equator through the convergence of meridional winds. Thus, the effects of the anomaly of northerly currents on the warming of the Niño3 region are determined by the effects of the anomaly of northerly winds, leading to the anomaly of northerly winds having a larger influence on the SST of the Niño3 region than the anomaly of northerly currents.

4 SUMMARY

The major results from the sensitivity experiments are summarized as follows:

(1) The forecast skill for the ENSO events in 1982–1999 by the ZCW coupled model is sensitive to both the removal and increase of the climatological means of SST and the meridional winds and currents of the eastern Pacific warm pool. The removal can lead to the complete failure of forecast of ENSO events, reduction of prediction ability (by four months in advance), and general absence of adverse effects. The 10% increases in climatological mean SST, 100% increases in climatological mean meridional winds, and 100% increases in climatological mean meridional currents can lead to the reduction of the forecast skill (by six months in advance), general absence of adverse effects, and the reduction of forecast skill (24 months later), respectively.

(2) The forecast skill for the ENSO events in 1982–1999 by the ZCW coupled model is sensitive to the gradual removal and increase of the anomalies of meridional winds and currents of the eastern Pacific warm pool. The gradual removal of the anomalies of meridional winds and currents weakens the forecast skill for ENSO events. The gradual 100% increase in the anomaly of the meridional currents can improve the forecast skill for ENSO events by less than 14 months in advance, whereas the gradual increase in the anomaly of meridional winds does not influence the forecast skill.

(3) The forecast skill for the 1997/1998 El Niño event by the ZCW coupled model is sensitive to the removal and increase of climatological means of SST, but is not sensitive to the meridional winds and currents of the eastern Pacific warm pool. The removal of climatological mean SST leads to the complete failure of the forecast. The 10% increase in climatological mean SST markedly improves the forecast skill after February 1997, but reduces the forecast skill during the pre- and onset stages of El Niño.

(4) The gradual removal and increase of the anomaly of northerly currents of the eastern Pacific warm pool considerably improve the forecast skill of the ZCW coupled model for the 1997/1998 El Niño event before the development stage, but do not pose any influence on the forecast skill after the development stage. The gradual removal and increase of the anomaly of northerly winds of the eastern Pacific warm pool affect the forecast skill. In particular, the removal leads to the failure of forecast whereas the increase improves the forecast.

Note that the physical mechanisms, responsible for the effects of various physical factors and processes over the eastern Pacific warm pool on the prediction skill of ZCW coupled model for ENSO events, were not examined in this study, particularly with regard to the in-depth analysis of the sensitivity of forecast skill to northerly currents and wind anomalies over the eastern Pacific warm pool. These areas still require further study.

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