Monitoring and Predicting ENSO Events and Sea Temperature Structure of the Warm Pool in the Western Pacific Ocean

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Abstract

Numerous studies were undertaken for scientific support of the APN-funded project of the network system for monitoring and predicting ENSO events and the sea temperature structure of the warm pool in the western Pacific. This paper is a brief summary of scientific highlights derived from this project which include: (1) Development of some new indices for monitoring ENSO events and sea temperatures and associated convective activity over the warm pool in the western Pacific. (2) Development of a number of dynamic and statistical models for prediction of ENSO events on the basis of which multi-model ensemble predictions for both dynamical and statistical models are made. Verfication of predictive skills shows good model performance. (3) A proposal for an air-sea interactive conceptual model applicable to predicting sea temperatures over the warm pool by using the subsurface currents and temperature dataset from the TOGA-TAO array. Observational evidence is presented to reveal the formation mechanism and eastward propagation features of subsurface current anomalies driven by the strong westerly wind anomalies over the warm pool in the western Pacific Ocean.

Key words: APN, ENSO events, multi-model ensemble prediction, warm pool

1. Introduction

It is well known that there is a close relationship between ENSO events and anomalous climates over most of the world. Numerous investigators (Huang & Wu, 1989; Li, 1990; Zhang *et al*., 1996; Huang *et al*., 1999) have shown that ENSO cycles (consisting of El Niño and La Niña phases) have significant relations with and impacts on climates, the environment, and socio-economic aspects of Asian and western Pacific countries and regions, such as Indonesia, the Philippines, Malaysia, Vietnam, Thailand, Australia, Japan, Korea and China. They may cause droughts, floods, cold injuries, heat waves and landfall of typhoons, as well as forest fires in the Asian and Pacific region, thus bringing about huge socio-economic losses and deterioration of the environment in these regions. For instance, recent statistics have shown that the impact of the 1997/1998 El Niño event brought abnormal global and regional climate changes and large-scale severe natural disasters, which left five million persons homeless and brought direct economic losses to US$33.9 billion. It has been found that there are some definite correlative relationships between the onset, maturity and decay of ENSO events and winter and summer monsoon activity over Asia (Wang & Li, 2004).

On the other hand, the sea surface temperature anomaly (SSTA) and associated convective activities in the western Pacific Ocean may exert a teleconnective effect on the weather and climate in East Asia through the PJ (Pacific-Japan) pattern (Nitta, 1987; Huang & Li, 1987). Li *et al*. (1999) also pointed out that the thermal regime of the warm pool and convective activity in the region around the Philippine Sea play important roles in affecting the seasonal and interannual variability of the East Asian summer monsoon. Therefore, from a unique regional viewpoint, it is important to monitor and predict sea temperature of the warm pool in the western Pacific Ocean and their relationship to summer monsoon activity. In order to improve our understanding and knowledge in these fields, it is essential to enhance monitoring and prediction of ENSO events and the SSTA of the warm pool over the western Pacific Ocean on seasonal and interannual time scales with necessary related information, products and data sets distributed to APN countries/regions via the Internet, thus leading to improvement of seasonal and interannual prediction of monsoon activity and significant climate events in this region.

Through three year's efforts (1999-2001), funded by the APN, a network and associated web-page (http://ncc.cma.gov.cn) of APN projects (#99012, #2000-12 & #2001-12) have been successively set up, with their catalogues and information residing in a workstation (Ding, 2002). The National Climate Center (NCC) of the China Meteorological Administration is responsible for maintenance and improvement of this Internet network, as well as collecting necessary information and updating the network on a monthly basis. Other participating countries/regions furnish information and datasets. In the network, a special emphasis is placed on oceanic and meteorological conditions over the warm pool and the South China Sea, the impact of ENSO events and the SSTA of the warm pool on the weather and climate of APN countries (including tropical cyclones and monsoon), which have often been neglected in current global studies and networks. Besides historical perspectives, predictions and outlook for the tropical SSTA and El Niño/La Niña events as well as related data and information associated with the ENSO events and the warm pool have been widely collected, including TOGA-TAO and SCSMEX (the South China Sea Monsoon Experiment) buoy data, oceanic data of the warm pool and the South China Sea, the oceanic observations of Japan along 137°E, and satellite data such as OLR and TBB, and most of these have been put onto the network. This is the first distributed network for climate monitoring and prediction established successfully in the APN region.

2. New Indices for Monitoring ENSO Events and Sea Surface Temperatures (SST) in the Warm Pool

A number of indices have been used to monitor the evolution of ENSO events, including their onset, development, maturity and decay. Among them, the most widely accepted indices are SSTA (SST anomaly) indices in regions Nino1+2, Nino 3 and Nino 4, and the Southern Oscillation Index (SOI). Based on these indices, a set of criteria to define the onset time, duration, intensity and mode or type of development has been developed. By using these indices and criteria, an ENSO event can be identified in early stages. Then, at later stages its intensity and duration may be objectively defined. Here, a new SSTA index (Nino 1+2+3+4 and SOI), the Synthesized Ocean-Atmospheric Index, for ENSO monitoring is suggested. It can be used to define different types of warm episodes which initially occur in either the equatorial central Pacific or the equatorial eastern Pacific. Based on this new index, if the average SSTA in these regions exceeds 0.5°C for at least six months, a warm episode may be defined to occur. In contrast, the criterion for occurrence of a cold episode (La Niña) is set at less than – 0.4°C. Then, the ENSO duration is defined as total number of months from the onset month to ending month of an ENSO event. The mature phase is defined as the time period with SSTA ≥ 1.0°C (SSTA ≤ – 0.8) in Nino 1-4 regions for a warm (cold) event. The regions of initial occurrence of an ENSO event vary from case to case (Rasmussen & Carpenter, 1982), but they generally fall into two types: the eastern onset type with positive SSTA starting from the Nino 1+2 region and the central onset type with positive SSTA starting from the Nino 4 region.

It can be concluded that the index of Nino 1+2+3+4 can capture all the major features demonstrated separately in regions Nino 1+2, Nino 3 and Nino 4. Therefore, this new index can characterize ENSO events of different regions of origin with a single composed index, without missing any cold or warm episodes. Figure 1 shows an intercomparison among the various ENSO indices used in the monitor-

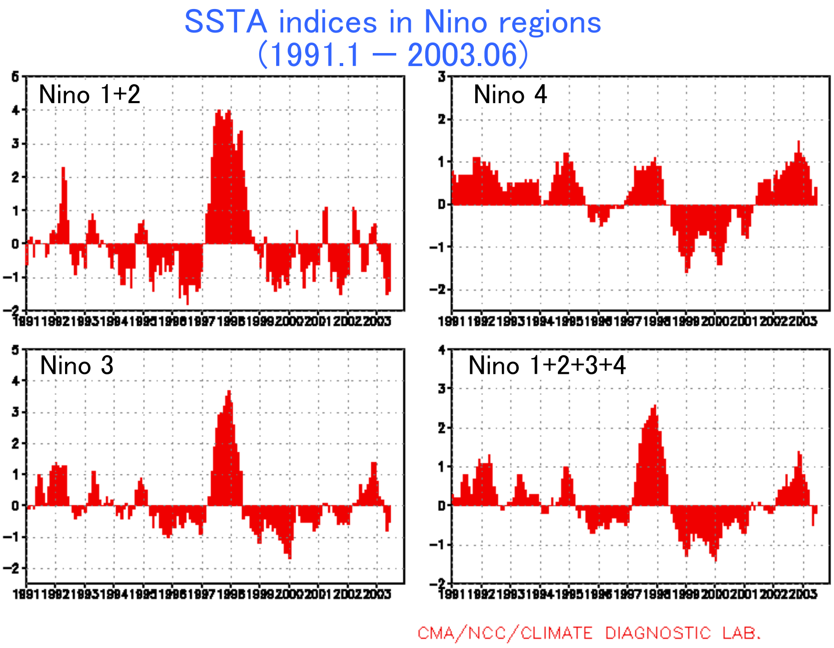

Fig. 1 An intercomparison among the various ENSO indices from 1991 to 2003 (Zhai *et al.*, 2002).

ing and diagnostic study of ENSO events.

The intensity index for ENSO episodes may be defined with this accumulated SSTA of regions Nino 1-4 during the entire period of cold or warm episodes. Based on this index, all the episodes during the past 50 years are classified into different intensity categories. Table 1 indicates the intensity classification and other related parameters of 15 warm episodes and 11 cold episodes.

The connection between convection and SSTAs in the tropical Pacific has been studied, based on satellite measured Outgoing Longwave Radiation (OLR) data and by applying SVD technique. Results have revealed that convection is very closely related to ENSO events. According to a study of typical pattern of OLR fields characterizing convection during ENSO episodes, a convection oscillation index (COI) similar to the SOI has been put forward for ENSO monitoring. The correlation between the COI and SSTA index in the Nino 3 region is higher than that between the SOI and SSTA index of the same region (Fig. 2).

In addition, a synthesized ocean-atmospheric index for ENSO monitoring has also been derived (see SYN. Intensity in Table 1), which is defined as the

Table 1 Classification of ENSO events from 1951 to 2000 (Zhai *et al.*, 2002).

	Onset & end	Duration	Peak SSTA(°C)	Peak Month	SSTA Intensity	SYN. Intensity	Onset Type
WARM EVEETS	1951.06-1952.01	8	1.0	11	W	W	E
	1953.04-1953.11	8	0.9	9	V W	W	E
	1957.04-1953.11	16	1.4	1	S	M	E
	1963.70-1964.01	7	0.8	10	W	W	E
	1965.05-1966.03	11	1.3	12	M	M	E
	1968.10-1970.01	16	1.1	5	M	M	C
	1972.04-1973.02	11	1.9	12	S	S	E
	1976.07-1977.01	7	0.9	10	W	W	E
	1979.09-1980.02	6	0.9	9	V W	V W	E
	1982.05-1983.09	17	2.5	12	V S	V S	C
	1986.09-1988.01	17	1.6	9	V S	V S	C
	1991.05-1992.07	15	1.4	4	S	S	C
	1993.03-1993.11	9	1.1	5	W	M	C
	1994.09-1995.02	6	1.2	12	W	W	C
	1997.04-1998.05	14	2.8	12	V S	V S	E
	1963.70-1964.01	7	0.8	10	W	W	E
	1965.05-1966.03	11	1.3	12	M	M	E
	1968.10-1970.01	16	1.1	5	M	M	C
	1972.04-1973.02	11	1.9	12	S	S	E
	1976.07-1977.01	7	0.9	10	W	W	E
	1979.09-1980.02	6	0.9	9	V W	V W	E
	1982.05-1983.09	17	2.5	12	V S	V S	C
	1986.09-1988.01	17	1.6	9	V S	V S	C
	1991.05-1992.07	15	1.4	4	S	S	C
	1993.03-1993.11	9	1.1	5	W	M	C
	1994.09-1995.02	6	1.2	12	W	W	C
	1997.04-1998.05	14	2.8	12	V S	V S	E
COLD EVENTS	1954.04-1956.04	25	-1.7	11	V S	V S	E
	1956.07-1956.12	6	-0.7	9	V W	W	C
	1964.03-1965.01	11	-1.1	12	M	W	E
	1967.08-1968.05	10	-0.7	2	W	V W	E
	1970.06-1971.12	19	-1.4	12	S	S	E
	1973.06-1974.05	12	-1.4	12	M	S	E
	1974.09-1976.03	19	-1.5	12	S	V S	C
	1984.10-1985.10	13	-0.9	12	M	W	E
	1988.04-1989.05	14	-1.6	12	S	S	E
	1995.09-1996.04	8	-0.5	11	V W	V W	E
	1998.10-2000.03	18	-1.3	1	S	S	C

Remarks: VS-very strong with an intensity index of ≥18.0°C (≤–16.0°C) for warm (cold) episode; VW-very weak with an intensity of ≤4.5°C (≥–3.5°C) for warm (cold) episodes; S- strong with an intensity index of 17.9-14.0°C (–15.9 - –12.0°C) for warm (cold) episodes; M-moderate with an intensity index of 13.9-7.0°C (–11.9 - –6.0°C) for warm (cold episodes); and W-weak with an intensity index of 6.9-4.6°C (–5.9 - –3.6°C) for warm (cold) episodes. E-eastern Pacific onset; C-central Pacific onset.

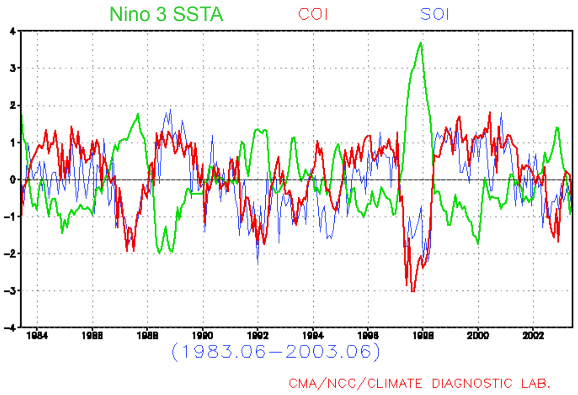

Fig. 2 Time series of the SSTA index in Nino 3, SOI and COI. SSTA index in Nino 3: equatorial Pacific sea surface temperature anomaly index averaged over the area for Nino 3 region 90°W-150°W, 5°N-5°S (green). COI: Convective activities oscillation index over equatorial Pacific (red). COI = standardized (standardized (ECI) – standardized (WI)). ECI stands for the OLR anomaly index over the equatorial eastern and central Pacific (5°N-5°S, 170°E-90°W) and WI stands for the OLR anomaly index over the equatorial western Pacific (5°N-5°S, 110°E-140°E). Anomalies are departure from the averages of the 1979-1998 period. SOI = standardized (standardized (SLPA (TAHITI)) – standardized (SLPA (DARWIN)) (blue)).

difference between the normalized accumulated monthly SSTAs of the Nino 1-4 regions and the normalized accumulated SOI. This index reflects the combined effect of the SSTA and the large-scale surface pressure fields. Intensity categories of ENSO events classified with this index show some differences from the results derived with SSTA Intensity, as indicated in Table 1.

The interannual variability of SSTs in the warm pool region is very small, but the spatial coverage of the warm pool changes significantly. A new index related to the areal extent of SST greater than 28°C and the SST departure from 28°C were calculated to measure the intensity of the warm pool. They are named the area index and the intensity index of the warm pool, respectively. Figure 3 shows time series of these two indices since 1991. It can be seen that the intensity index and the area anomaly index have good positive correlation, i.e., the expansion of area of the warm pool corresponds to stronger anomaly indices. These two indices also show an obvious decadal variability, with positive anomalies found in the period from 1994-2003 and negative anomalies found before 1994. Anomalous warming and an expanding warm pool can exert an important effect on the teleconnective mode by exciting active convective activity (Nitta, 1986; Huang, *et al*., 1987). In the past decade, the major seasonal rain belt in China has shifted to the region of the Yangtze River basin and South China. It

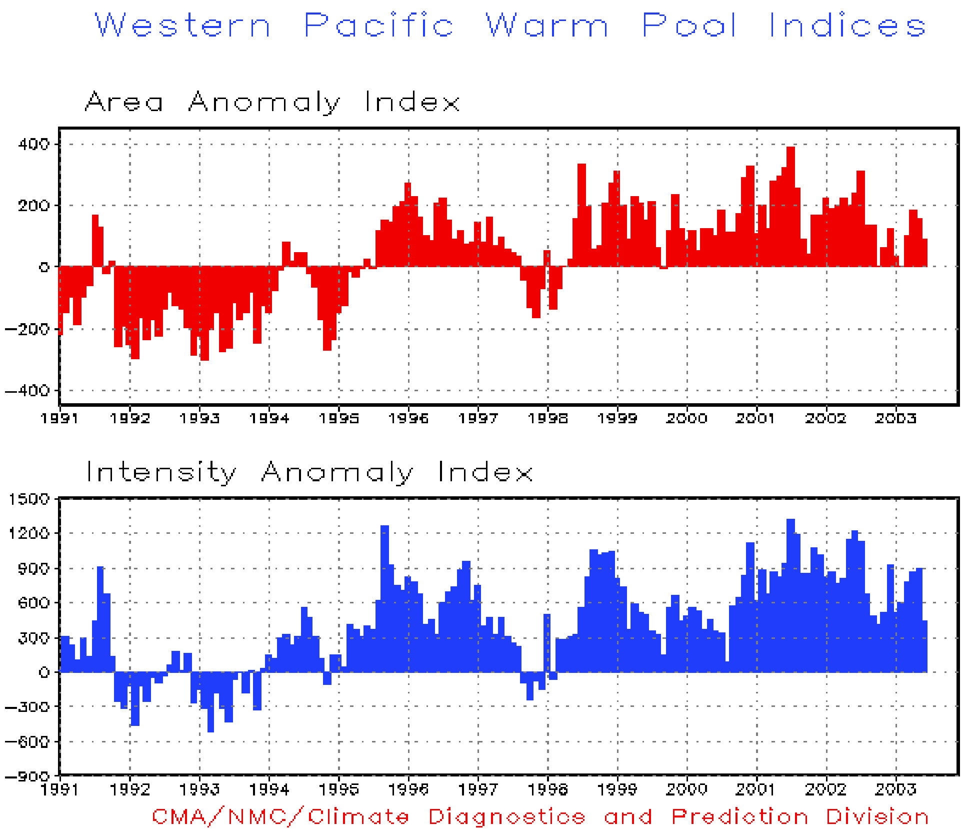

Fig. 3 Time series of the area anomaly index (upper panel) and intensity anomaly index (lower panel) from 1991 to 2003.

is not clear yet whether they have a possible correlative relationship on an interdecadal time scale. This problem needs to be further studied. However, for some individual years, one does observe remote effects of convective activity over the warm pool. As shown in Fig. 4, in the summer of 2004, the surface air temperature anomaly was characterized by a northeast-southwest-oriented ‘sandwich’ pattern, namely above normal over the southeast coast of China, below normal over central China and above normal over Northeast China and Northwest China. In particular, the southeast coast of China suffered from a severe hot wave this summer, which was probably associated with active convective activities in subtropical region of the northwest Pacific Ocean (Fig. 5). That large-scale convection persisted throughout the whole summer, which induced a JP pattern-like teleconnective mode over East Asia, with a compensative subsidence to the north of the active convective region in the warm pool. Such thermal forcing enhanced the subtropical high over the West-Pacific and associated subsidence which is attributed to occurrence of the hot wave over the southeast coast of China and lower valley of the Yangtze River (Fig. 6).

3. ENSO Predictions and Verifications

A simplified air-sea dynamical model system (SAOMS) of the ZC type (Zebiak & Cane, 1987) and a statistical model system have been developed and used to predict sea surface temperature anomalies over the tropical Pacific Ocean. The dynamical model system includes three components: initialization, modeling, and prediction and verification. In this system,

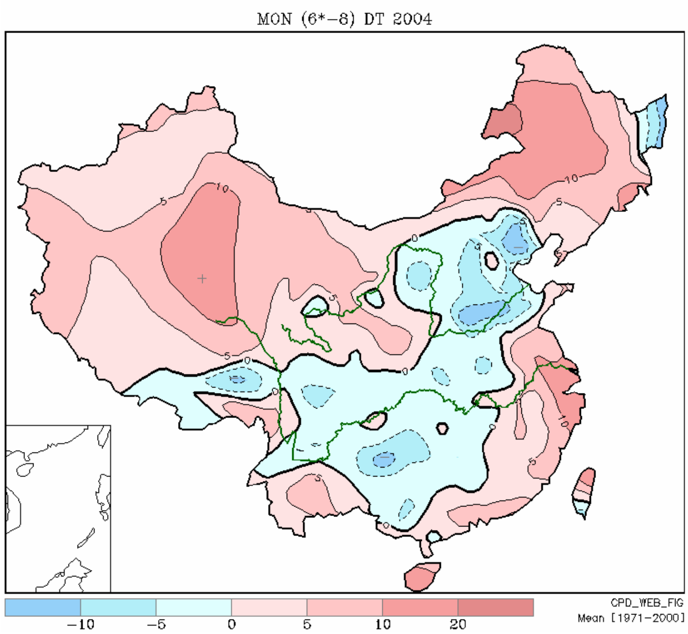

Fig. 4 Surface air temperature anomalies (unit: 0.10^{o}C) in June, July and August (JJA) of 2004 (from the Division of Climate Diagnosis and Prediction of National Climate Center, China Meteorological Administration).

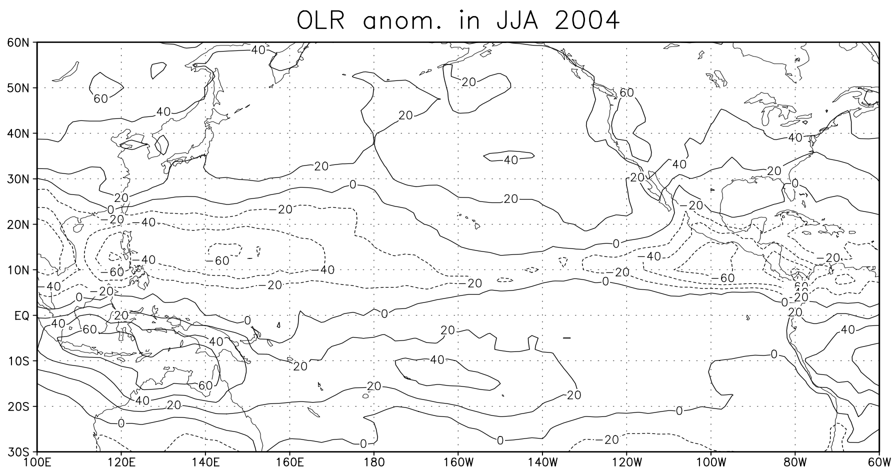

Fig. 5 Outgoing Longwave Radiation (OLR) anomaly (Unit: W/m^2) in JJA of 2004.

five dynamic models (NCCo, NCCn, NCC/STI, NCC/NIM and CAMS/NJU) are used to make ensemble predictions of ENSO events.

The model NCCo is based on the ZC87 model (Zebiak & Cane, 1987). Several computational functions have been changed. Both pre- and post-processing procedures have been constructed. A new initialization has been used in the NCCo, i.e., both computed SSTA and wind stress anomalies are replaced by the observed values during the initialization (Li & Zhao, 2000). The model NCCn has been modified based on the NCCo without initialization. In particular, the upwelling and advection in the oceanic component of the NCCo have been improved (Zhang & Zhao, 2000). The model NCC/STI was based on the NCCo without initialization. An adjoint assimilation has been created and used to perform multiple-seasonal predictions (Duan *et al*., 2000). The model NCC/NIM is based on an Oxford model (Balmaseda *et al*., 1994). Both the climate background and the heat flux estimate in the atmospheric component of the model have been improved (Zhang & Ding, 2000). The dynamic framework of the model CAMS/NJU is based on the ZC87. It covers three oceanic basins (the tropical Pacific Ocean, Indian Ocean and tropical Atlantic Ocean). New parameters in the Indian Ocean and Atlantic Ocean have been selected after several experiments (Yin *et al*., 2000).

A hindcast experiment from 1980 to 1996 was carried out to test the performance of the SAOMS in comparison with the persistent prediction (Fig. 7). It can be seen that the model system shows a certain skill at predicting the SSTA over the tropical Pacific Ocean, for 6-12 months in advance, with correlation coefficients considerably exceeding the persistence prediction. Particularly for predictions with a lead time of 9-12 months, all the models perform better than the persistence prediction. In this hindcast experiment, three El Niño events (1982/83, 1986/87, 1991/92) and three La Niña events (1984/85, 1988/89 are 1995/96) were included. Therefore, the prediction skill shown in Fig. 7 mainly reflects the predictive performance for ENSO events.

Figure 8 shows real-time prediction results for the SSTA in the Nino 3 region during 1997-2004. Multi-model ensemble predictions were made based on five models which started from January of 1997 to 2004. It can be seen that the model system predicted both El Niño (1997/98) and La Niña (1998/2000) events reasonably. Among the five models, only one model (NCC/STI) captured the 2002 El Niño event, whereas the other four models missed this El Niño event. Thus, the multi-model ensemble prediction also

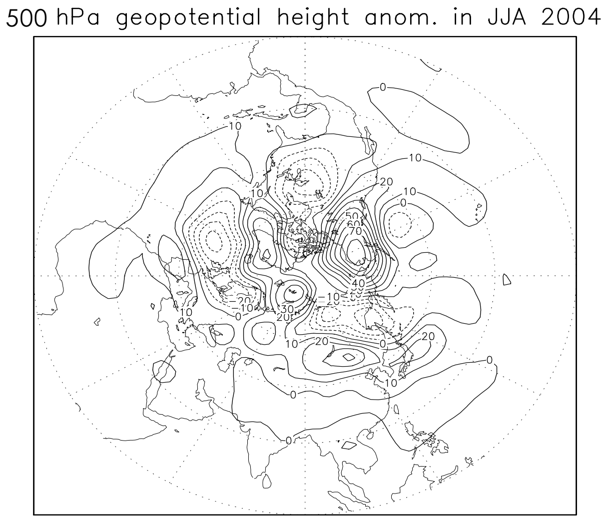

Fig. 6 500 hPa geopotential height anomaly (unit: 10 gpm) in JJA of 2004.

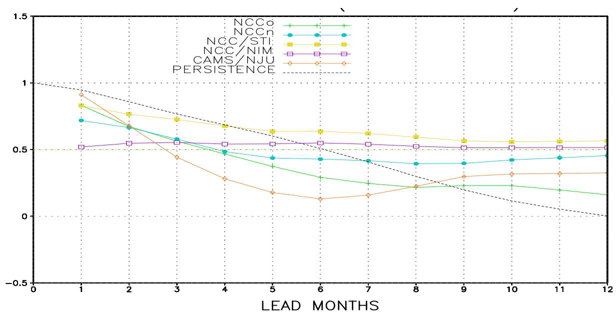

Fig. 7 Temporal correlation coefficients between observed and predicted Nino3 SSTA in 1980-1996 by the SAOMS.

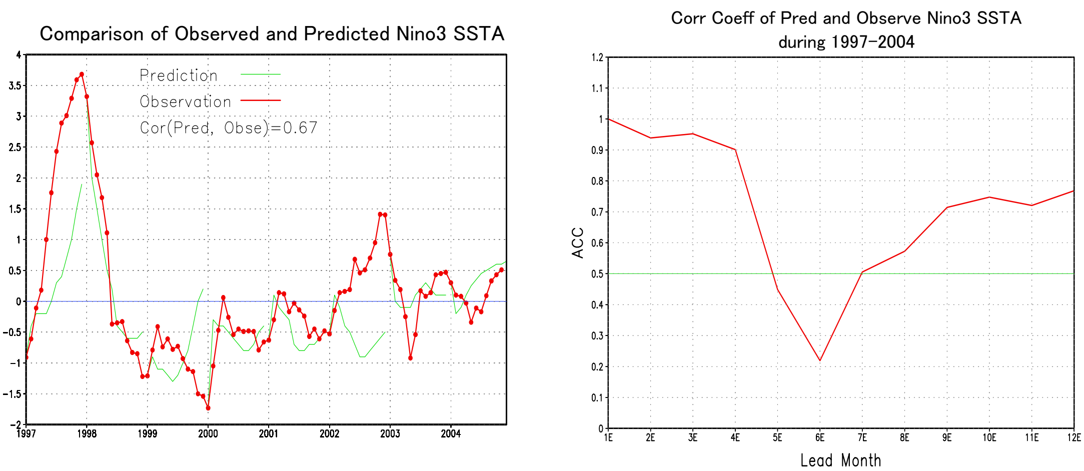

Fig. 8 Verification of predictions starting from January of 1997-2004 (left) and anomaly correlation coefficients between prediction and observation (right).

missed the forecast of the 2002 warm episode in early 2002. In January 2004, the SAOMS predicted that Nino 3 SSTA might increase in the following seasons (see Fig. 8). Although the predicted warming occurred three months earlier than observations, the prediction captured the weak warm process in 2004. During 1997-2004, the correlation coefficient between the multi-model ensemble predictions and observations was 0.67. The correlation coefficients at 1-3 and 6-11 lead months were all above 0.5 (see Fig. 8).

The statistical model system consists of four statistical models (PC-CCA, SSA, ANA and FLT). An ensemble prediction can be made based on individual predictions derived from different statistical models. The Principal Component Canonical Correlation Analysis Model (PC-CCA) has been established by applying EEOF, the PRESS principle and ensemble forecast techniques (Jiang *et al*. 1999). In the Maximum Entropy Singular Spectrum Analysis Model (SSA), principal components with significant periods have been generated, so the ENSO cycle has been reconstructed by using singular spectrum analysis (Zhai, 2000). This maximum entropy singular spectrum analysis model was established after applying the maximum entropy AR (p) technique. In the Analogue Prediction Model (ANA), firstly ten simple indices for original series similarity, trend similarity and acceleration similarity were designed on the basis of the dynamic analysis of ENSO cycle. Then a synthetic index was generated from the ten simple indices, establishing the so-called analogue forecast model (Ren & Zhou, 2000). The idea of the Optimum Filtering Assembly Model (FLT) was based on an ENSO component analysis theory, in which the ENSO cycle was separated into three time-scale oscillations – QBO, low frequency mode of 3-5 years and interdecadal variance using filtering techniques. A new statistical ENSO model, the optimum filtering assembly model, was established by applying four statistical time series analysis models (Ren *et al*., 1998). The statistical model system is used to perform real-time operational forecast of Nino 3 SSTA each month at the National Climate Center of China. Figure 9 shows the individual predictions of Nino 3 SSTAs for the subsequent year (from July 2003 to July 2004) using four statistical models and the multi-statistical model ensemble

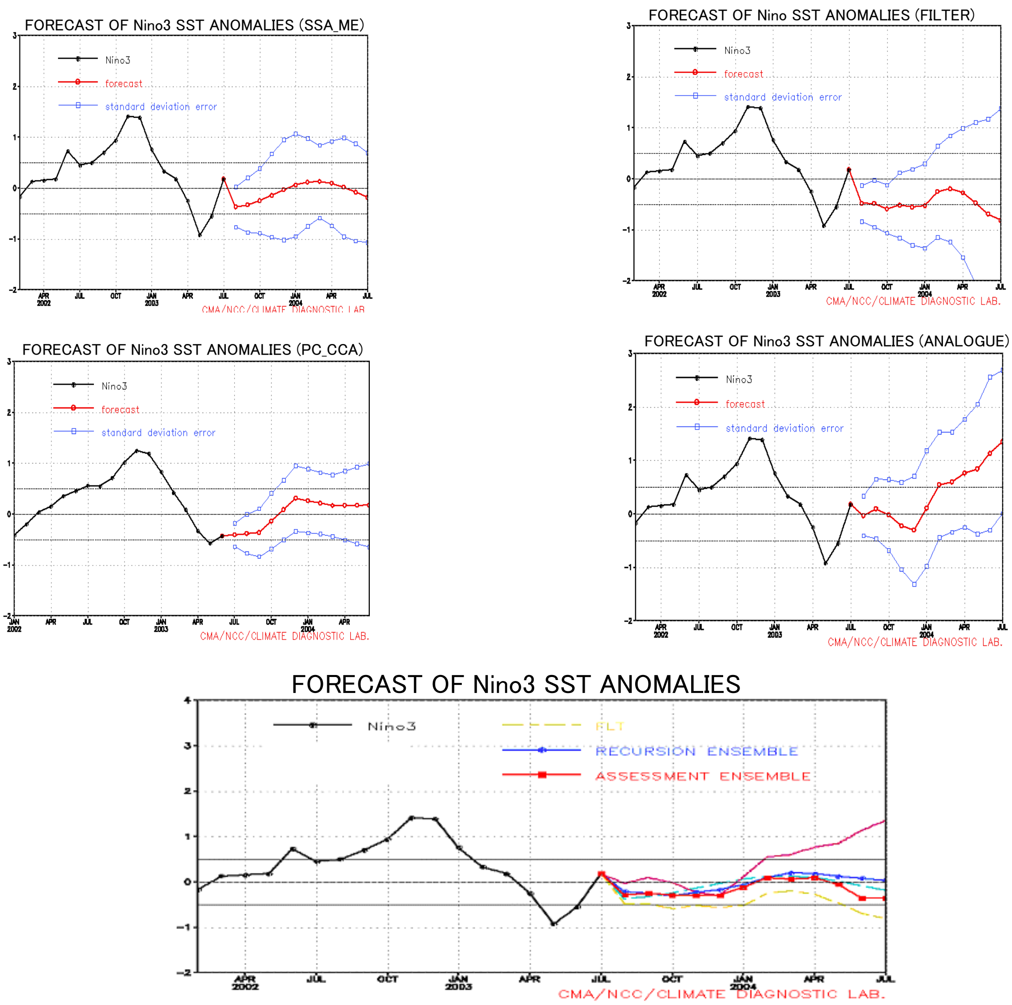

Fig. 9 Real-time forecasts of the Nino 3 SSTA using 4 statistical models and the ensemble of multi-statistical model forecasts. Singular Spectral Analysis (upper left), Canonical Correlation Analysis (lower left), Analogue Prediction (lower right), Optimum Filter Assembly (upper right), and the ensemble prediction (bottom).

prediction. It seems that for the future 12 months, the SSTA in the Nino 3 region will stay at a normal condition. This is the same as the general trend predicted by the Australian National Climate Center Coupled model. At least 30 forecasts of Nino 3 SST anomalies, which started from July-August 2003, have predicted a neutral condition (–0.8-0.8°C). Most SSTA predictions made by dynamic and statistical models around the world starting from August 2003 such as CPC, COLA(2), ECMWF, LDEO(4), NCEP, NOAA Linear Inverse, Seripps/MPI, NSIPP/NASA, JMA and CLIPER have predicted a neutral condition through April 2004 (NOAA/NCEP, 2003).

4. An Air-sea Interactive Conceptual Model Applicable to Predicting the Sea Temperature Structure Over the Warm Pool

The warm pool is located in an extensive tropical oceanic region extending from the Philippines to the dateline, with the maximum SSTs observed. During a warm episode, adjustment of the thermocline results in enhanced negative SST anomalies in the equatorial western Pacific, while, during a cold episode, the opposite situation occurs in the equatorial western Pacific. Therefore, in order to predict SSTAs and subsurface sea temperatures over the warm pool, the physical processes responsible for thermocline adjustment must be studied. This problem is closely related to air-sea interaction between the wind field and the thermocline. A longer time series of the oceanic datasets for the equatorial ocean current profile and thermocline depth (from 1988 to 2001), derived from the in site TOGA-TOA buoy array (McPhaden, 1995) was employed to investigate the ENSO-related atmosphere-ocean interaction in this region.

To highlight the effects of low-level wind anomalies on the subsurface ocean, the mature phases of cold and warm episodes, *e.g*. December 1996 and December 1997, were chosen for investigating potential linkages between atmospheric wind anomalies and thermodynamic variations in the equatorial ocean profile (Fig. 10). Anomalies of all elements here are relative to the 1992-2001 climatological average. At the end of 1996, enhanced trade winds met anomalous

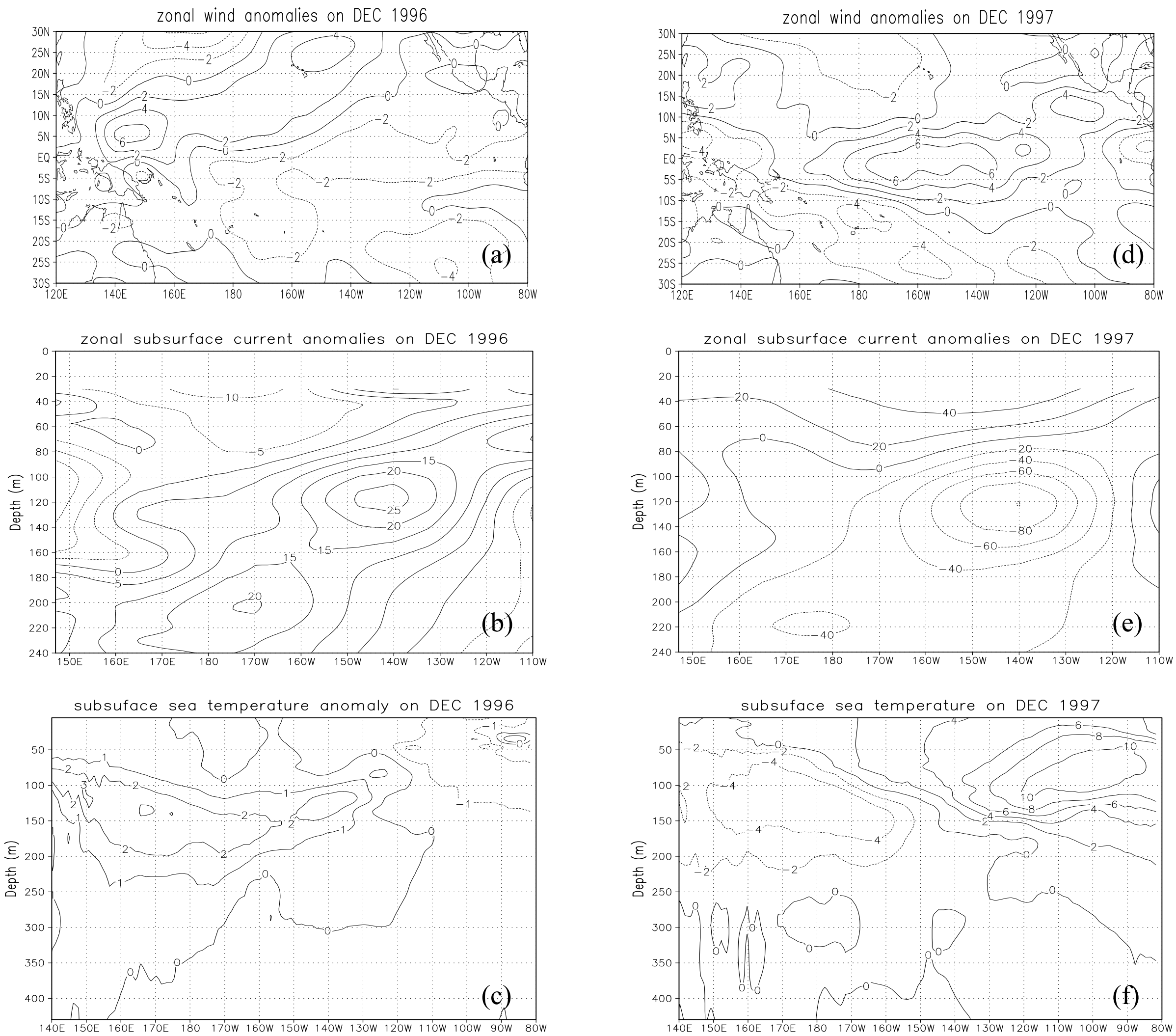

Fig. 10 Monthly 850 hPa zonal wind anomalies over the tropical Pacific (upper panels, m/s), equatorial profiles of anomalous ocean currents (middle panels, cm/s) and of sea temperature anomalies (bottom panels, °C).

westerly winds over the warm pool area. As a consequence, the upper-layer of water in the central and equatorial eastern Pacific was driven westward, whereas the western counterpart moved in an opposite direction. A pile-up of warm water occurred in the vicinity of the dateline. Therefore, a subsidence of upper-layer water would be expected, reducing such a peaking tendency of the sea surface level. Owing to a weak vertical temperature difference in the mixed layer, it was possible for the upper-layer of sea water to descend to a deeper level in the mixed layer. However, in the neighborhood of the thermocline, where the environmental sea temperature drops sharply with depth, further subsidence in the mixed layer was greatly hampered by rapidly increasing upward buoyancy. In this case, the sinking water had to diverge over the sloping thermocline surface. This is why the zonal currents below 80 meters were almost the reverse of those above that level, as shown in Fig. 10b. On the other hand, the subsidence of the upper layer of water not only caused a warm advection to the bottom of the mixed layer, but also reduced the upwelling of cold water below the mixed layer, ultimately inducing a depressed thermocline. This illustration gives a reasonable interpretation for the emergence of a positive temperature anomaly maximum sloping from west to east across the equatorial basin in Fig. 10c.

As shown in the right-hand column in Fig. 10, the case of 1997 was almost the mirror of that in 1996. A record-breaking strong El Niño reached maturity at the end of 1997. A dominant westerly anomaly prevailed over nearly the entire equatorial Pacific except for west of 150°E. Consistent with the low-level winds, the upper-layer of water over the whole equatorial Pacific traveled eastward, with a speed core of 40 cm/s observed to the east of the dateline. This means that, despite the anomalous zonal winds and the upper-layer zonal current, a true zonal divergence was found to the west of the dateline, which induced an opposite flow in the layers below 80 meters (Fig. 10). This pattern favored an upwelling in the mixed layer and a consequently shoaled thermocline, which created a cold water core as much as 4°C lower in the 80-180 m layer of the warm pool.

Figure 11 shows temporal evolutions of low-level zonal winds and related zonal divergence ($\partial u/\partial x$), and of the thermocline depth anomaly, which represents the thermal condition of the subsurface ocean or the mixed layer thickness. As shown in Fig. 11, considerable temperature anomalies in the subsurface warm pool occurred unexceptionally before the onset of each ENSO event. Of great importance is that the variation in zonal wind divergence, rather than the zonal wind anomaly itself, matches that of the warm pool subsurface thermal conditions well. Although westerly anomalies remained over the warm pool from 1992 through 1994, as an example, the original thin mixed layer became thicker than normal in early 1994. In fact, the centers of the westerly winds were located to the east of the warm pool during the period of 1992 to 1993, thus zonal divergence did prevail at that time, favoring an upwelling in the mixed layer and an uplifted thermocline. In early 1994, recovering trade winds in the central Pacific resulted in the replacement of zonal divergence with zonal convergence, a sign that a change in the mixed layer thickness anomaly would take place in the warm pool soon.

Considerable disagreement between changes in zonal wind anomalies and subsurface thermal conditions have been found in recent years. Westerlies in the western Pacific were replaced by easterlies in late 1997, while the thermocline was not pushed down to a level below normal until one year later. In the spring of 2001, the original easterly wind anomaly sustaining over the warm pool for three years came to an end, but the depressed thermocline persisted till the summer of 2002. Thermal variations in the warm pool subsurface ocean can be easily explained from the viewpoint of zonal wind convergence. In the boreal winter of 1997/98, the easterlies to the east of 160°E which brought the 1997/98 El Niño to an end several months later, together with the westerlies west of 160°E, caused zonal divergence over the warm pool, so the subsurface ocean stayed in a cold condition. By the autumn of 1998, a newly developed cold episode triggered a reversal of the zonal wind anomalies over the central and eastern Pacific, and thus a consequent zonal convergence and thickening of the mixed layer commenced in the warm pool region. In the spring of 2001, westerlies appeared again over the western Pacific, but the zonal confluence still remained, except for a slightly eastward shift, because of the persistence of above-normal trade winds east of the dateline. In this regard, the thermocline did not uplift to a shallower-than-normal depth until the spring of 2002 when the westerlies migrated eastward and associated zonal divergence occurred east of 160°E. In October 2002, a flattened thermocline along the equator was built up.

Finally, a schematic illustration of the atmosphere-ocean coupling process along the equatorial Pacific, with the mature phase of La Niña as an example, is shown in Fig. 12. An intensified Walker Circulation and active western Pacific convection created a positive feedback to zonal convergence of low-level wind stress over the warm pool. More surface layer water is transferred to the warm pool by the wind stress-induced ocean current, favoring the subsidence of surface layer water. Due to the relatively weak sea temperature difference with depth in the mixed layer, at the depth A, the imposed buoyancy on the sinking water is not strong enough to counteract its further drop. However, in the vicinity of the thermocline, that is, depth B, the upward buoyancy increases rapidly because of the strong vertical temperature gradient, which finally exhausts the sinking momentum of the water. In this case, the thermocline, something like a rigid boundary, impels the subsiding water to diverge

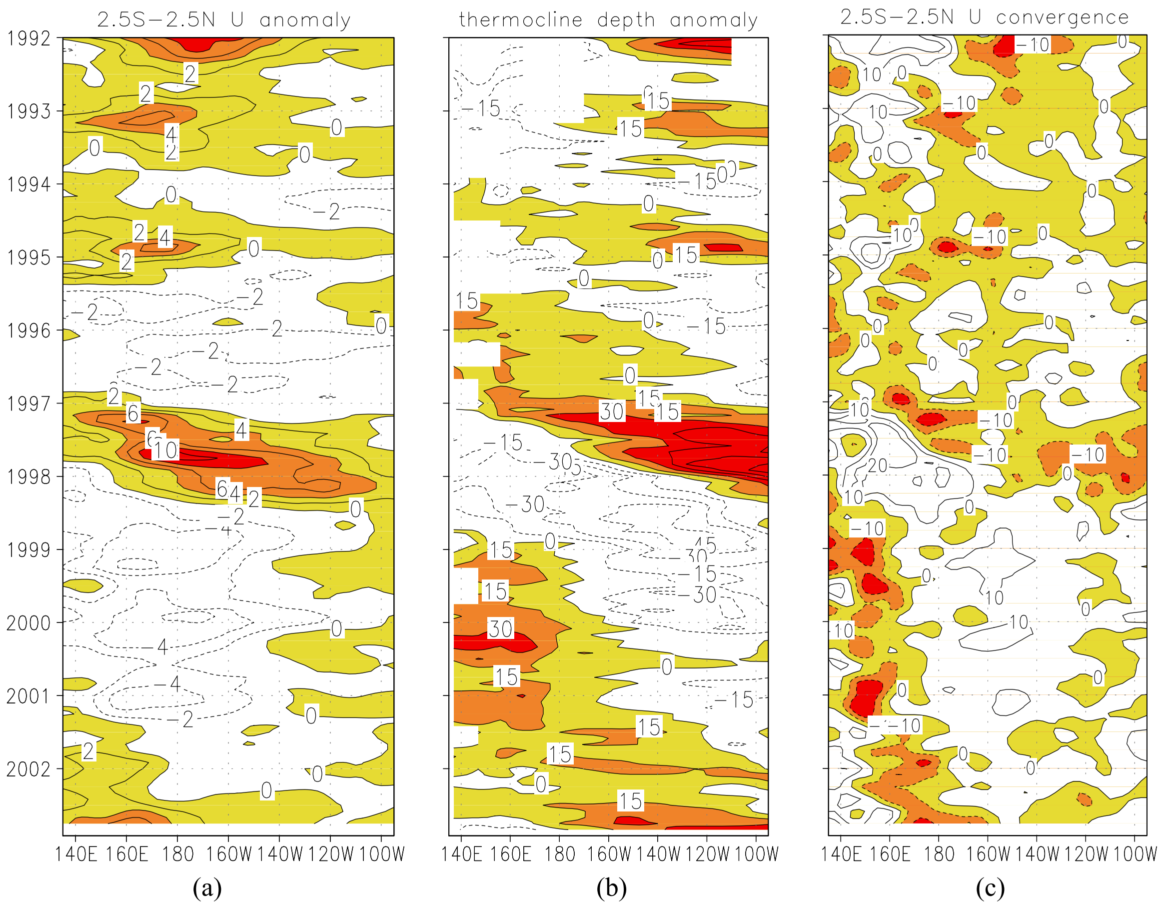

Fig. 11 1992-2002 longitude-time cross sections of near-equatorial (a) 850 hPa monthly zonal wind anomalies (m/s), (b) thermocline depth fluctuation (m), and (c) the 9-point-smoothed zonal difference $\partial u/\partial x$ (10^{-7}/s).

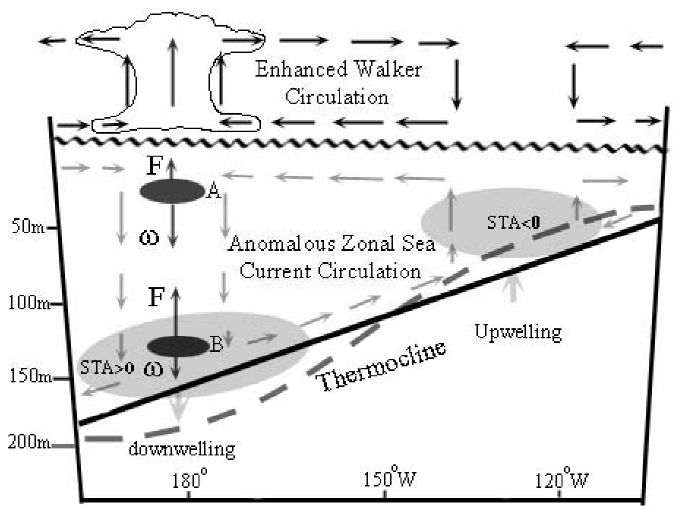

Fig. 12 Schematic illustration of the equatorial Pacific atmosphere-ocean interaction during the mature phase of La Niña event. The letters of A and B denote different depths of the dark shaded water box. ω and F represent the downward velocity of the water box and the buoyancy imposed on it by the surrounding ocean, respectively. Lengths of the arrows indicate the intensities of factors. The solid thick line and the dashed line stand for the climate average and anomalous states of the thermocline, repectively.

over its own sloping surface. The consequent ocean current profile in the equatorial mixed layer, convergence in the upper layer and divergence in the deeper layer, produces persistent downwelling and reduces colder water upwelling beneath the mixed layer, ultimately inducing the maximum temperature anomaly at the climatological depth of the thermocline.

5. Concluding Remarks

In recent years, NOAA of US, JMA, the Bureau of Meteorology of Australia and the National Climate Center of China have made considerable progress in the monitoring and prediction of ENSO events. They issue operational oceanic and atmospheric products with regard to the tropical Pacific Ocean and carry out monthly, seasonal, and interannual prediction of SSTA using both statistical methods and dynamic models on a regular basis. These products provide useful guidance for other countries. The focus of most of their monitoring and prediction, however, is placed on the equatorial central and eastern Pacific Ocean, with less attention paid to monitoring and prediction of the western Pacific warm pool or the impacts resulting from the warm pool SSTA and ENSO. In 1999, under the support of the APN, China, Japan, Korea, the Philippines, Thailand, Malaysia, Vietnam, Indonesia and Australia jointly proposed and undertook the APN cooperative research project 'Monitoring and prediction of ENSO events and SSTA over the warm pool in the western Pacific Ocean' (1999-2000) (Ding, 2002). Since all the participating institutions are from APN countries/regions, which are affected greatly by the Asian monsoon and the warm pool, they have great concern for ENSO events and the warm pool as well as their impact on the East Asian monsoon. This is the central issue of our project. Therefore, under the project's goals and objectives, a close regional cooperative relationship has been established and has worked jointly very well. Through the development and establishment of an international network, this project has greatly increased the APN's capability to disseminate and exchange monitoring and prediction information on ENSO events and the warm pool to APN countries. This kind of infrastructure building is especially useful to developing countries in this region for timely provision of information and warnings to help them prepare for potential disasters. Their development of national capability in this regard will be also enhanced. Therefore, this project contributes to the fundamental APN goal of building regional and national capacities for studying global environmental change issues. On the other hand, the provided information can assist policymakers in taking necessary action for prevention of potential disasters.

The present paper is a brief summary of scientific highlights derived from this project, which include the development of some new indices for monitoring ENSO events and sea temperatures and associated convective activity over the warm pool; use and verification of multiple model ensemble predictions by dynamic and statistical models for ENSO events; and a proposal for an air-sea conceptual model applicable to predicting the sea temperatures over the warm pool in the western Pacific Ocean. These scientific results provide a physically sound basis for supporting this regional APN network.

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