ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 23, NO. 1, 2006, 156–164

A Further Investigation of the Decadal Variation of ENSO Characteristics with Instability Analysis

MENG Xiangfeng* (孟祥凤), WU Dexing (吴德星), LIN Xiaopei (林霄沛), and LAN Jian (兰 健)

Physical Oceanography Laboratory, Ocean University of China, Qingdao 266003

(Received 1 February 2005; revised 4 November 2005)

ABSTRACT

Based on instability theory and some former studies, the Simple Ocean Data Assimilation (SODA) data are analyzed to further study the difference between the propagation of the ENSO-related oceanic anomaly in the off-equatorial North Pacific Ocean before and after 1976. The investigation shows that after 1976 in the off-equatorial North Pacific Ocean, there is a larger area where the necessary conditions for baroclinic and/or barotropic instability are satisfied, which may help oceanic anomaly signals propagating in the form of Rossby waves to absorb energy from the mean currents so that they can grow and intensify. The baroclinic energy conversion rate in the North Pacific after 1976 is much higher than before 1976, which indicates that the baroclinic instability has intensified since 1976. From another perspective, the instability analysis gives an explanation of the phenomena that the ENSO-related oceanic anomaly signal in the North Pacific has intensified since 1976.

Key words: ENSO, decadal variation, North Pacific Ocean, Rossby waves, baroclinic instability, barotropic instability

1. Introduction

Since the 1990s, following the intense research on ENSO, the study on the decadal variations of climate systems and their mechanisms has become one of the important research topics of climate change (Nitta and Yamada, 1989; Graham, 1994; etc.). Since the climate system in the Pacific Ocean functions as the major climate system to influence the global climate, its decadal variation can provide a background for climate systems with relatively shorter periods. The decadal variation of the Pacific climate system has attracted much attention. There are several viewpoints about the mechanism of decadal variation in the Pacific climate system. For example, the tropical ocean is the forcing origin of the decadal variation in the mid-latitude climate system (Trenberth and Hurrel, 1994; etc.); the decadal variation of Pacific Ocean can originate either from the tropical the Pacific or the extra-tropical Pacific (Liu et al., 2002; Wang et al., 2003a, b); and the interaction between the Tropics and the mid latitudes (Gu and Philander, 1997), the unstable air-sea interaction in the mid latitudes (Latif et al., 1994, 1996; etc.), and the interaction between the Tropics and the extratropical South Pacific (Wang and Liu, 2000; Luo and Yamagata, 2001; Giese et al., 2002; Chang et al., 2001) have been respectively proved by different researchers to force out the decadal variation .

As the most obvious interannual variation in the Pacific ocean-atmosphere system, ENSO influences the global climate most significantly. Former research works (Gu and Philander, 1995; Wang and Wang, 1996; An and Wang, 2000; Wang and An, 2002; Meng et al., 2004a; etc.) have shown that since the late 1970s, there has been significant decadal adjustment in the characteristics of ENSO: the dominant period of the ENSO cycle has changed from 2–3 yr to 4–6 yr and its intensity has increased. Wang and An (2001, 2002) fully studied the role of background wind in the decadal changes of ENSO characteristics. With the background thermocline unchanged, the decadal variation in the background wind and related variation of the upwelling in the upper ocean can lead to the observed decadal variations in the spatial structure and characteristics of ENSO. They argued that decadal changes of the background equatorial winds act as the fundamental factor to alter the properties of El Niño.

Based on the previous studies of El Niño events (White et al., 1989; Li and Mu, 1999; Chao et al., 2003, etc.), the propagation of the oceanic anomaly

*E-mail: mengxf@ouc.edu.cn

signal related to El Niño events has been found to usually propagate along the paths constituted by the equatorial wave guide, the east boundary, the zonal bands near 5°–15°N and the west boundary in the Pacific Ocean. In a minority of the El Niño events, such an oceanic anomaly propagates from the South Pacific to the equatorial region. One of the examples to illustrate this phenomenon is the propagation of the oceanic anomaly signal before the 1997/98 El Niño event (Chao et al., 2003). Therefore, the period of the ENSO cycle is related to the propagation of the El-Niño-related oceanic anomaly in the Pacific Ocean.

Capotondi and Alexander (2001) found the enhanced thermocline variability at 10°–15°N in the Pacific Ocean to be primarily associated with long baroclinic Rossby waves of periods more than 7 yr. The arrival of the thermocline variability to the equatorial regions in the form of waves will lead to the low frequency variation of the equatorial thermocline. Therefore, the decadal adjustment is also associated with the long baroclinic Rossby waves in the North Pacific. The numerical research of Meehl et al. (2001) shows that the ocean background vertical diffusivity may significantly influence the amplitude of El Niño. The physics is primarily related to a sharper equatorial thermocline. An intense and shallow equatorial thermocline helps to increase the Niño-3 SST interannual variability. The ENSO period is relatively longer in the case of a shallow equatorial thermocline. Based on an analysis of assimilated data, Gu et al. (2004) found an apparent abruptness of mean value in the tropical Pacific thermocline in the late 1970s. The EOF and wavelet analysis showed that there were both interannual and interdecadal cycles in the tropical Pacific thermocline. Meng et al. (2004a) showed that there was some difference between the mean depth of the main thermocline in the tropical Pacific before and after 1976. They argued that according to the classical theories, off-equatorial Rossby waves and equatorial Kelvin waves should be different corresponding to the adjusted thermocline. Their research also found that the propagation and intensity of the ENSO-related oceanic anomaly signal before 1976 are obviously different from that after 1976. Their further analysis showed that the decadal adjustment of the ENSO cycles is closely associated with the decadal adjustment of the tropical thermocline.

The research of An and Wang (2000) and Wang and An (2002) found that the decadal changes of the background wind in the Pacific Ocean play an important role in the decadal variation of ENSO characteristics. Meng et al. (2004a) pointed out that the decadal adjustment of the background ocean is also an important factor in causing the decadal variation in ENSO characteristics, which well supplements Wang and An's research on the decadal variations of ENSO characteristics.

Based on instability analysis, the research of Meng et al. (2004b) showed that the asymmetric propagation of the ENSO-related oceanic anomaly signal between the Northern Hemisphere and Southern Hemisphere results from the difference between their distributions of barotropic and/or baroclinic instability. These characteristics influence the intensification and propagation of off-equatorial Rossby waves in the South and North Pacific Oceans. Therefore, the ENSO-related oceanic anomaly can grow and propagate smoothly in the Northern Hemisphere while its growth and propagation in the Southern Hemisphere are not so effective.

It is known from Meng et al (2004a) that there is a large difference between the propagating speed, intensity, etc. of the ENSO-related oceanic anomaly signal before and after 1976. Based on an instability analysis, Meng et al. (2004b) gave an explanation for the asymmetric propagation of the ENSO-related oceanic anomaly in the Southern and Northern Hemispheres. From the above-mentioned two papers, it is not difficult for us to make such a deduction that the various decadal changes in the characteristics of the ENSO-related oceanic anomaly in the North Pacific since 1976 may be related to the changes in the baroclinic and/or baraotropic instability. The instability analysis may explain the phenomena to some extent. In this paper, some further study is to be made regarding the decadal variation of ENSO-related characteristics in the North Pacific. We will try to find the relation of the difference between the ENSO-related oceanic signal before 1976 and that after 1976 to the changes of the baroclinic and barotropic instability after 1976 in the North Pacific.

2. A brief introduction of the data and theory for the instability analysis

The beta7 version of SODA (Simple Ocean Data Assimilation) is used in this article. The data spans from January 1950 to December 2001. The model domain covers the zonal region between 62°S and 62°N. The horizontal resolution is 1° in the zonal direction but uneven in the longitudinal direction, with the highest resolution of about 0.45° at the Equator. The longitudinal resolution is 1° outside of the region between 10°S and 10°N. There is a total of 20 layers in the vertical direction, with an uneven vertical resolution. The depths of the layer center from bottom to top are 3622.5, 2885.6, 2201.3, 1598.79, 1099.46, 714.46, 443.79, 276.27, 190.61, 157.5, 142.5, 127.5, 112.5, 97.5, 82.5, 67.5, 52.5, 37.5, 22.5, 7.5 m respectively. The output of the model is monthly means and there are 624 records in all. The physical variables of

SODA include temperature, salinity, velocity, sea surface height, sea surface wind stress, the depth of the 20°C isotherm, the heat content in the upper 125 m and the heat content in the upper 500 m. The model setup of SODA, especially in the tropical regions, is fairly high among the global models. A great deal of observations are assimilated into the model, so SODA can reveal the variation in the real ocean better (Carton, 2000a, b). The long time series of 52 yr makes SODA applicable to studies on decadal timescales.

The theories used to analyze the baroclinic and barotropic instability of the North Pacific are based on Pedlosky (1987, 1996) and Lipps (1963). Some related studies such as Qiu (1999), Qiu and Chen (2004), Lin (2004), Lu and Luo (2004), Meng et al. (2004b) and Lin (2005, 2006) are also useful references.

3. The instability analysis of the climatological state of the North Pacific before and after 1976

According to the former studies, and following Meng et al. (2004b), the North Pacific is simplified to 2.5 layers to analyze the baroclinic instability. The seawater layer above the 25.0 kg m^{-3} isopycnal is approximated as the first active layer, the seawater layer between the 25.0 kg m^{-3} isopycnal and 27.1 kg m^{-3} isopycnal as the second active layer, and the seawater layer from the 27.1 kg m^{-3} isopycnal to the bottom as the inactive layer. To analyze the barotropic instability, the North Pacific is simplified to 1.5 layers. The active layer is the same as the first active layer of the 2.5-layer simplification. The inactive layer is the seawater layer from the 27.1 kg m^{-3} isopycnal to the bottom.

Around 1976, the North Pacific underwent a climate regime shift. Observations from the tropical Pacific Ocean have also identified an abrupt climate shift in 1976. Therefore, 1976 is selected as the dividing year for this study. Sometimes, the 1976 climate shift is also called the 1976–77 climate shift due to the shift period. To get rid of the shift's influence on the average state, the data of 1976 and 1977 are not used. Following Meng et al. (2004a), the comparison is made between the average from 1960 to 1975 and the average from 1978 to 1993. The average from 1960 to 1975 represents the climatological state before 1976, and the average from 1978 to 1993 represents the climatological state after 1976.

Potential vorticity (PV,ζ) and its meridional gradient are important variants to judge the existence of instability in the 1.5-layer simplification and the 2.5-layer simplification. For the related derivations, one may refer to Qiu (1999) and Qiu and Chen (2004). Here, we calculate the PV of the active layer in the 1.5-layer simplification and of the first layer in the 2.5-layer simplification as follows:

$$\zeta_1 = \frac{f}{h_1} \times \frac{\Delta\rho_{\sigma,1}}{1000+\rho_{\sigma,1}} , \quad (1)$$

where $\zeta_1, f, h_1, \Delta\rho_{\sigma,1}$ and $\rho_{\sigma,1}$ represent the potential vorticity, coriolis parameter, thickness, potential density difference between the surface seawater and the lower interface seawater, and the average potential density of the first layer, respectively.

And we calculate the PV of the second layer in the 2.5-layer simplification as follows:

$$\zeta_2 = \frac{f}{h_2} \times \frac{\Delta\rho_{\sigma,2}}{1000+\rho_{\sigma,2}} , \quad (2)$$

where $\zeta_2, f, h_2, \Delta\rho_{\sigma,2}$, and $\rho_{\sigma,2}$ represent the potential vorticity, coriolis parameter, thickness, potential density difference between the upper interface seawater and the lower interface seawater, and the average potential density of the second layer, respectively.

The distributions of the meridional gradient of potential vorticity (PV) of the active layer in the 1.5-layer simplification before and after 1976 are shown in Fig. 1. According to Lipps (1963) and Qiu and Chen (2004), the necessary condition for barotropic instability is satisfied in the region where the meridional PV gradient changes signs. The monthly perimeters of such regions before and after 1976 are shown in Fig. 2. The figures indicate the following facts: such a region before 1976 is in slightly higher latitudes than after 1976; the perimeters of the zonal strip region where the meridional gradients of PV change sign before 1976 are shorter than after 1976. Therefore, the situation after 1976 may help the off-equatorial Rossby waves absorb more energy to grow and intensify through the mechanism of barotropic instability. As shown in Figs. 1 and 2, there is a significant seasonal variation in the zonal strip region where the necessary condition for barotropic instability is satisfied. Such a phenomenon is related to the seasonal variation of horizontal velocity shear between the North Equatorial Countercurrent (NECC) and North Equatorial Current (NEC) and the horizontal velocity gradient in the NEC itself.

The distribution of the area where the meridional PV gradient of the first active layer has an opposite sign compared to that of the second active layer in the 2.5-layer simplification before and after 1976 is shown in Fig. 3. According to Qiu (1999), Qin and Chen (2004), the necessary condition of baroclinic instability is satisfied in such regions. The monthly areas of such regions before and after 1976 are shown in Fig. 4. The figures indicate some similar information as found in Fig. 1 and Fig. 2: such regions before 1976 are in slightly higher latitudes; and the area of the zonal strip region where there may be baroclinic instability is smaller than that after 1976. Therefore, the situation after 1976 helps the off-equatorial Rossby

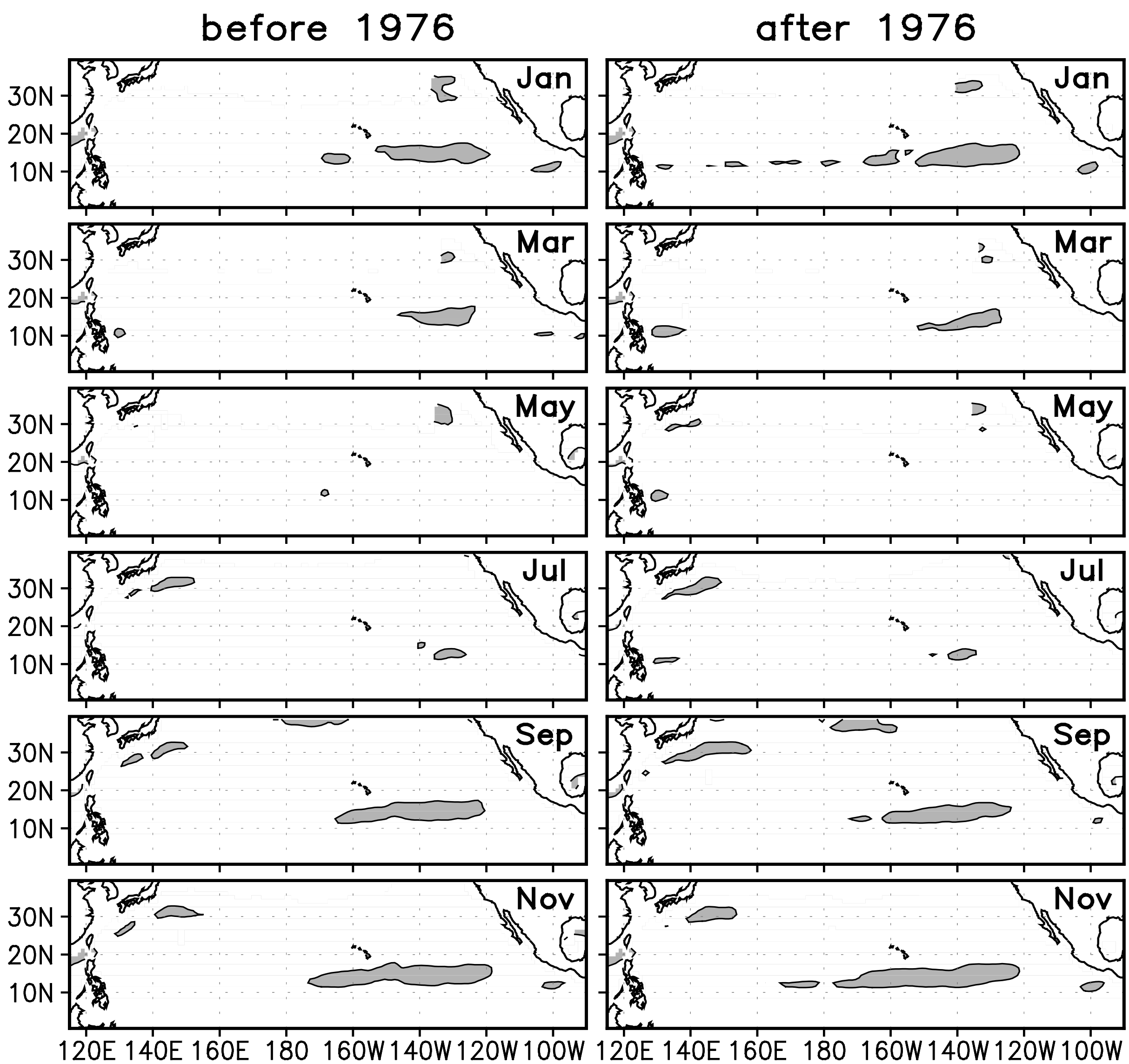

Fig. 1. The climatological distribution of areas where the meridional PV gradient changes sign in the active layer of the 1.5-layer ocean in January, March, May, July, September, and November before 1976 (left) and after 1976 (right). (The shaded region is negative.)

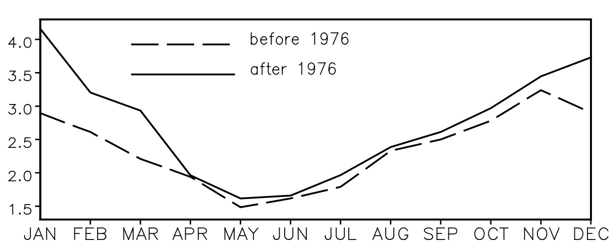

Fig. 2. The climatological monthly perimeters of regions where the meridional PV gradient changes sign in the active layer of the 1.5-layer ocean in the tropical North Pacific Ocean (5°–20°N, 130°E–100°W) before and after 1976 (units: 10^7 km).

waves absorb more energy to grow and intensify through the mechanism of baroclinic instability. As shown in Fig. 3 and Fig. 4, there is also a significant seasonal variation in the zonal strip region where the necessary condition for baroclinic instability is satisfied. Such a phenomenon is related to the seasonal variation of the vertical velocity gradient in the NEC itself and the vertical velocity shear between the NEC and subtropical countercurrent (STCC).

According to the classic wave theory, the depth of the main thermocline and the latitude act as the dominant factors that influence the first-mode baroclinc Rossby wave speed. The higher the latitude, the slower the Rossby wave speed. However, from Meng et al. (2004a), we know the fact that the ENSO-related

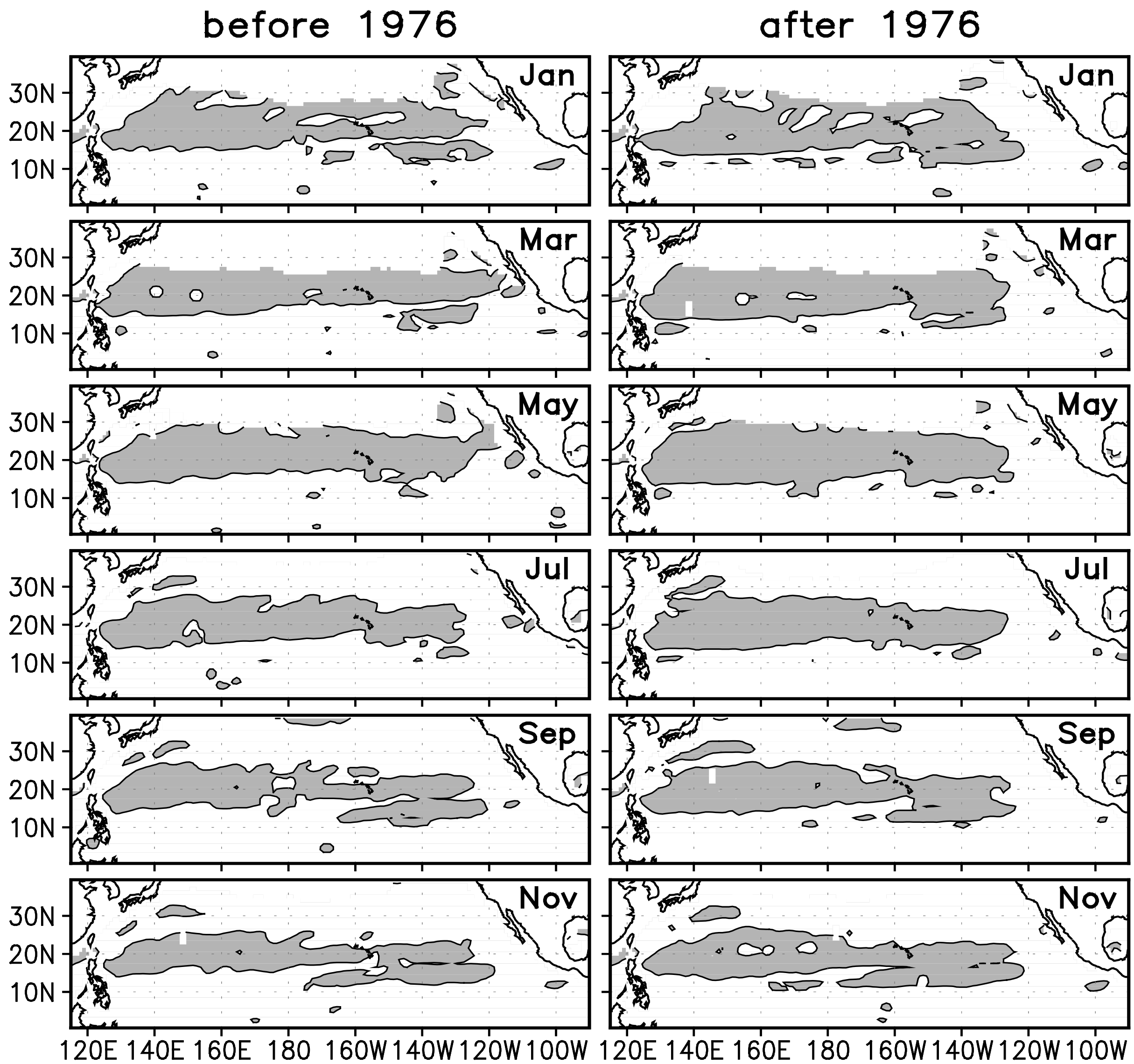

Fig. 3. The climatological distribution of areas (the shaded regions) where the meridional PV gradient of the first active layer has an opposite sign of that of the second active layer in the 2.5-layer ocean in January, March, May, July, September, and November before 1976 (left) and after 1976 (right).

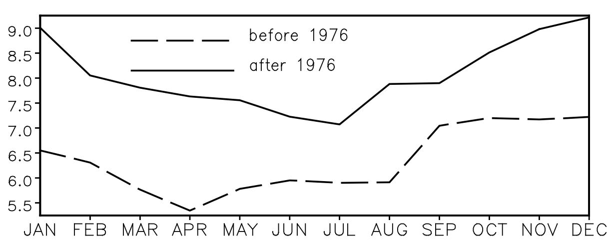

Fig. 4. The climatological monthly area of regions where the meridional PV gradient of the first active layer has an opposite sign of that of the second active layer of the 2.5-layer ocean in the tropical North Pacific Ocean (5°–20°N, 130°–100°W) before and after 1976 (units: 10^{12} km^2).

oceanic anomaly signal propagates more slowly after 1976. Their further analysis showed that the phenomenon is related to the changes in the main thermocline since 1976; the shallowness of the main thermocline in the related regions in the North Pacific makes the Rossby wave slower after 1976. Therefore we can deduce that although the region where there is the possibility of baroclinic and/or barotropic instability is in slightly lower latitudes after 1976, the Rossby wave propagates at a slower speed. The interdecadal changes of the main thermocline depth dominate the speed of the ENSO-related oceanic signal in the off-equatorial North Pacific Ocean. The conclusion is still consistent with that of Meng et al. (2004a).

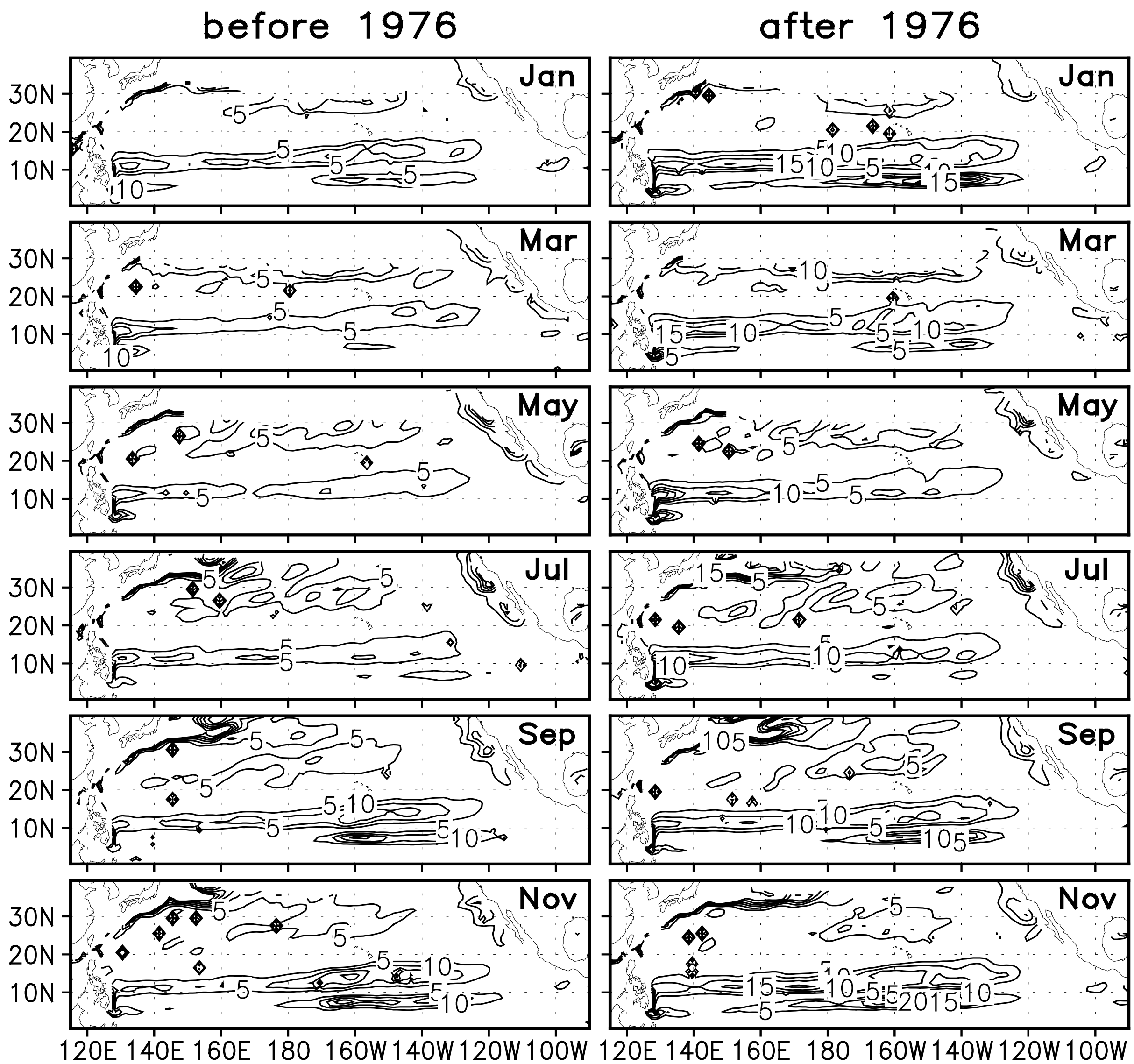

Fig. 5. The climatological distribution of the baroclinic energy conversion rate in the second active layer of the 2.5-layer ocean in January, March, May, July, September, and November before 1976 (left) and after 1976 (right). The contour interval is 500 W m^{-2}.

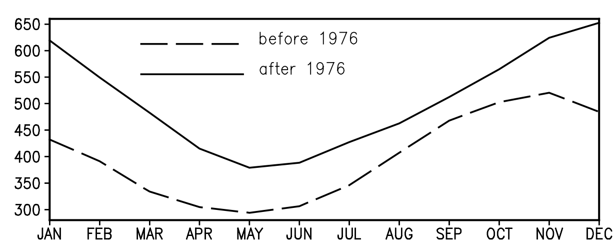

Fig. 6. The climatological monthly baroclinic energy conversion rate averaged in the second active layer of the 2.5-layer ocean in the tropical North Pacific Ocean (5°–20°N, 130°E–100°W) before and after 1976. (units: W m^{-2}).

Kirtman (1997) found with coupled models that the participation of off-equatorial Rossby waves is an important factor to determine the timescales of the ENSO cycles. The meridional structure of the off-equatorial Rossby waves may lead to different ENSO periods: the broader the meridional width of the off-equatorial Rossby waves, the longer the ENSO periods. Figure 3 of Meng et al. (2004a) shows that the Rossby waves after 1976 have a broader meridional width. The spatial structure of the Rossby waves after 1976 helps to make longer ENSO periods.

Figure 1–4 provide us with some qualitative information about the reason why there are some changes in the North Pacific Rossby waves since 1976. It is possible for us to quantify the intensity of baroclinic or barotropic instability to compute the energy conversion rate. Using the method provided by Qiu and Chen (2004), it is possible to compute the energy conversion rate from mean currents to eddy kinetic energy (EKE) through the mechanism of barotropic instability. However, the monthly means of SODA cannot provide information on the perturbation velocity, which is necessary to compute the barotropic energy conversion rate. Fortunately, the baroclinic energy conversion rate can be computed by the following formula according to Gent et al. (1995):

$$\dot{p}_{e,bt} = -g k_{th} \frac{\nabla\rho \cdot \nabla\rho}{\rho_z} , \qquad (3)$$

where k_{th}=1000 m^2 s^{-1} as suggested by Gent et al. (1995), ∇ is the horizontal operator, and $\rho_z = \partial\rho/\partial z$.

The formula indicates that the spatial structure of the seawater's density determines the baroclinic energy conversion rate. The spatial structure of the seawater's density includes information on the thermocline, e.g., its tilting and intensity, etc. Therefore, the thermocline and its adjustment are closely associated with the baroclinic energy conversion and its changes. A larger horizontal density variation or a smaller vertical density variation (flatter and weaker thermocline) makes a larger baroclinic energy conversion rate.

The spatial distribution of seawater density can be obtained with the temperature and salinity data of SODA, thus it is possible for us to compute the baroclinic energy conversion rate. The baroclinic energy conversion rates averaged in the climatological thermocline before and after 1976 are shown in Fig. 5. The baroclinic conversion rates after 1976 are higher than before 1976. Such a phenomenon indicates that the baroclinic instability has intensified after 1976 and that there is more energy transferred from the mean kinetic energy to the Rossby-wave-related oceanic perturbation. The above analysis supports the idea that after 1976, the intensified baroclinic instability has enabled the Rossby wave to absorb more energy to grow, intensify and propagate.

From Fig. 4 of Meng et al. (2004a), we can find that the thermocline is flatter in the zonal direction, although there is a sharper ridge in the longitudinal direction after 1976 in the tropical North Pacific. There is a larger horizontal density variation and a flatter thermoline after 1976 in the tropical North Pacific. Therefore, the baroclinic energy conversion rate here is larger after 1976. Such a situation helps the Rossby wave to absorb more energy to grow and intensify.

Some information about the unstable baroclinic Rossby waves such as their wavenumber, wavelength, etc., can be obtained from the 2.5-layer reduced-gravity model. Following Qiu (1999) and Qiu and Chen (2004), the ocean is simplified into two active layers and one inactive layer. The thickness, density and zonal velocity of the first active layer are H_1, ρ_1 and U_1 respectively. The thickness, density and zonal velocity of the second active layer are H_2, ρ_2 and U_2 respectively. The density of the inactive layer is ρ_3. The parameters can be obtained from the average state before and after 1976. Substituting the parameters into the quasi-geostrophic PV equations of the 2.5-layer ocean in Qiu (1999) and Qiu and Chen (2004), we can acquire the growth rate and phase speed with wavenumber. The largest growth rate corresponds to the most unstable wave. We made a detailed comparison and found that there is little difference between the wavenumber of the most unstable wave before 1976 and that after 1976 (not shown here). The wavenumber of the most unstable wave changes with latitude, longitude and time. Its variation with latitude is the most significant. Its variations with longitude and time are relatively insignificant. The most unstable wavenumbers are roughly in the range of 1×10^{-5}–3×10^{-5} m^{-1} from west to east in the tropical North Pacific Ocean. The latitude of the most unstable wave at the same longitude and the same time becomes higher from west to east. The horizontal distribution of the most unstable wave inclines from northeast to southwest. The inclined distribution of the most unstable waves is consistent with the characteristics of the propagating oceanic anomaly related to El Niño events in the North Pacific in Meng et al. (2004a). It is also consistent with the Rossby waves amplified in baroclinically unstable regions of the North Pacific subtropical gyre in Galanti and Tziperman (2003). Corresponding to the wavenumbers, the wavelengths of the most unstable wave are roughly in the range of 628–209 km. Although there is little difference between the wavenumbers of the most unstable Rossby wave before and after 1976, the intensity of the El-Niño-related oceanic anomaly in the tropical North Pacific Ocean after 1976 is much greater. The reason should be attributed to the intensified baroclinic instability after 1976, which makes the unstable Rossby wave absorb more energy from the mean currents so that it can grow and intensify.

Based on the above analysis, an explanation is given to the fact that after 1976, the ENSO-related oceanic anomaly signal intensifies in the off-equatorial North Pacific Ocean: there is a larger area where baroclinic and/or barotropic instability is possible. Therefore, it may help the ENSO-related oceanic anomaly to absorb more energy so that it can grow, intensify and propagate. The quantitative information on the baroclinc energy conversion rate confirms that the baroclinic instability in the North Pacific intensifies after 1976, and therefore, the ENSO-related oceanic signal propagating in the form of Rossby waves in the North

Pacific is much stronger than that before 1976.

4. Summary and discussion

Based on instability theory a further investigation has been made regarding the phenomenon found in Meng et al. (2004a) that the ENSO-related oceanic anomaly signal before 1976 is different from that after 1976. The instability analysis about the climatological state before and after 1976 shows that after 1976, there is a larger area where baroclinic and/or barotropic instability is possible. The quantitative computation of the baroclinic conversion rate shows an intensified baroclinic instability after 1976, which helps the ENSO-related anomaly to absorb more energy from the mean currents so that it can intensify and propagate. Instabilities acts as an important mechanism for the oceanic perturbation signal such as eddies and waves etc., to absorb energy from the mean currents. The change in the propagating speed of the ENSO-related anomaly in the North Pacific since 1976 is attributed to the decadal adjustments of the main thermocline. The thermocline and its adjustment are also closely associated with the baroclinic conversion rate and its changes. The decadal adjustment of the thermocline not only influences the propagating speed of the Rossby wave but also the energy it absorbs from the mean currents. The depth of the main thermocline dominates the propagating speed of the Rossby wave, and its spatial structure influences the energy it can absorb from the mean currents.

In this paper, a simple instability analysis has been performed to explain the phenomenon that the ENSO-related oceanic anomaly intensifies in the North Pacific after 1976. Due to limitations in the data, the barotropic instability before and after 1976 has not been quantified. The analysis we have made provides us enough information to confirm that the changes in the propagating speed of the ENSO-related oceanic anomaly in the North Pacific since 1976 are attributed to the decadal adjustment of the thermocline; the changes in the intensity of the baroclinic instability since 1976 can influence the intensity of the off-equatorial Rossby waves. The changes in the baroclinc instability are also closely related to the adjustment of the thermocline. The possible role of the barotropic instability can be further investigated with data that contain oceanic variations with a shorter period. The influence of instability on the intensity of the off-equatorial Rossby wave acts as one of the mechanisms in the decadal variation in ENSO characteristics.

Acknowledgments. Thanks go to Prof. J. A. Carton and Ms. X. Cao of the University of Maryland who kindly provided SODA. This work was supported by the NSFC (Grant Nos. 40506007, 40136010, 40306004, and 90411010) and the Doctorate Foundation of China (Grant No. 20030423004).

REFERENCES

An, S., and B. Wang, 2000: Interdecadal change in the structure of the ENSO mode and its impact on the ENSO frequency. *J. Climate*, **13**, 2044–2055.

Capotondi, A. I., and M. A. Alexander, 2001: Rossby waves in the tropical North Pacific and their role in decadal thermocline variability. *J. Phys. Oceanogr.*, **31**, 3496–3515.

Carton, J. A., G. Chepurin, and X. Cao, 2000a: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950–95. Part I: Methodology. *J. Phys. Oceanogr.*, **30**, 294–309.

Carton, J. A., G. Chepurin, and X. Cao, 2000b: A Simple Ocean Data Assimilation analysis of the global upper ocean 1950–95. Part II: Results. *J. Phys. Oceanogr.*, **30**, 311–326.

Chang, P., B. S. Giese, L. Ji, H. F. Seidel, and Wang Fan, 2001: Decadal change in the south tropical Pacific in a global assimilation analysis. *Geophys. Res. Lett.*, **26**, 615–618.

Chao Jiping, Yuan Shaoyu, Chao Qingchen, and Tian Jiwei, 2003: The origin of warm water mass in "warm pool" subsurface of the western tropical Pacific—The analysis of the 1997–1998 El Niño. *Chinese J. Atmos. Sci.*, **27**(2), 145–151.

Galanti, E., and E. Tziperman, 2003: A midlatitude-ENSO teleconnection mechanism via baroclinically unstable long Rossby waves. *J. Phys. Oceanogr.*, **33**, 1877–1888.

Gent, P. R., J. Willebrand, T. J. McDougall, and J. McWilliams, 1995: Parameterizing eddy-induced tracer transports in ocean circulation models. *J. Phys. Oceanogr.*, **25**, 463–474.

Giese, B. S., S. C. Urizar, and N. S. Fuckar, 2002: Southern Hemisphere origins of the 1976 climate shift. *Geophys. Res. Lett.*, **29**(2), 1-1–1-4.

Graham, N. E., T. P. Barnett, R. Wilde, M. Ponater, and S. Schubert, 1994: On the roles of tropical and midlatitude SSTs in forcing interannual to interdecadal variability in the winter Northern Hemisphere circulation. *J. Climate*, **7**, 1416–1441.

Gu, D., and S. G. H. Philander, 1997: Interdecadal climate fluctuations that depend on exchanges between the Tropics and extratropics. *Science*, **275**, 805–807.

Gu, D., and S. G. H. Philander, 1995: Secular changes of annual and interannual variability in the Tropics during the past century. *J. Climate*, **8**, 864–876.

Gu Dejun., Wang Dongxiao, Li Chunhui, and L. Wu, 2004: Analysis of interdecadal variation of tropical Pacific thermocline based on assimilated data. *Acta Oceanologica Sinica*, **23**(1), 61–67.

Kirtman, B. P., 1997: Oceanic Rossby wave dynamics and the ENSO period in a coupled model. *J. Climate*, **10**(7), 1690–1704.

Latif, M., and T. P. Barnett, 1994: Causes of decadal climate variability over the North Pacific and North America. *Science*, **266**, 634–637.

Latif, M., and T. P. Barnett, 1996: Decadal climate variability over the North Pacific and North America: dynamics and predictability. *J. Climate*, **9**, 2407–2423.

Li Chongyin, and Mu Mingquan, 1999: El Niño occurrence and sub-structure ocean temperature anomalies in the Pacific warm pool. *Chinese J. Atmos. Sci.*, **23**(5), 513–521.

Lin Xiaopei, 2004: The intraseasonal long Rossby waves in the subtropical ocean and its effect to the Kuroshio in the East China Sea. Ph. D. dissertation, Ocean University of China, 88pp. (in Chinese)

Lin Xiaopei, Wu Dexing, Li Qiang, and Lan Jian, 2005: An amplification mechanism of intraseasonal long Rossby wave in subtropical ocean. *Journal of Oceanography*, **61**(2), 369–378.

Lin Xiaopei, Wu Dexing, Lan Jian, and Li Qiang, 2006: The analysis of intraseasonal long Rossby wave speed in the subtropical Pacific Ocean. *Journal of Hydrodynamics* (Ser. B). (in press)

Lipps, F. B., 1963: Stability of jets in a divergent barotropic fluid. *J. Atmos. Sci.*, **20**, 120–129.

Liu, Z., L. Wu, R. Gallimore, and R. Jacob, 2002: Search for the origins of Pacific decadal climate variability. *Geophys. Res. Lett.*, **29**(10), 42-1–42-4.

Luo, J. J., and T. Yamagata, 2001: Long term El Niño-Southern Oscillation ENSO-like variation with special emphasis on the South Pacific. *J. Geophys. Res.*, **106**, 22211–22227.

Lu Yan, and Luo Dehai, 2004: Non-zonal baroclinic instability in the North Pacific subtropical countercurrent. *J. Hydrodynamics* (Ser. B), **16**(5), 564–570.

Meehl, G. A., P. R. Gent, J. M. Arblaster, B. L. Otto-Bliesner, E. C. Brady, and A. Craig, 2001: Factors that affect the amplitude of El Niño in global coupled models. *Climate Dyn.*, **17**, 515–527.

Meng Xiangfeng, Wu Dexing, and Hu Ruijin, 2004a: Preliminary study on decadal variations of El Niño-associated adjustment in the tropical Pacific thermocline. *Acta Oceanologica Sinica*, **23**, 415–426.

Meng Xiangfeng, Wu Dexing, and Lin Xiaopei, 2004b: Characteristics and mechanisms of transmission of oceanic anomaly signal related to ENSO cycles. *Journal of Tropical Oceanography*, **6**, 22–29. (in Chinese)

Nitta, T., and S. Yamada, 1989: Recent warming of the tropical surface temperature and its relationship to the Northern Hemisphere circulation. *J. Meteor. Soc Japan*, **67**, 375–383.

Pedlosky, J., 1987: *Geophysical Fluid Dynamics*. Springer-Verlag, Germany, 710pp.

Pedlosky, J., 1996: *Ocean Circulation Theory*. Springer-Verlag, Germany, 453pp.

Qiu, B., 1999: Seasonal eddy field modulations of the North Pacific subtropical countercurrent: TOPEX/POSEIDON observations and theory. *J. Phys. Oceanogr.*, **29**, 2471–2486.

Qiu, B., and S. Chen, 2004: Seasonal modulations in the eddy field of the South Pacific Ocean. *J. Phys. Oceanogr.*, **34**, 1515–1527.

Trenberth, K. E., and J. W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Climate Dyn.*, **9**, 303–319.

Wang, B., and S. I. An，2001: Why the properties of El Niño changed during the late 1970s. *Geophys. Res. Lett.*, **28**, 3709–3712.

Wang, B., and S. I. An，2002: A mechanism for decadal changes of ENSO behavior: Roles of background wind changes. *Climate Dyn.*, **18**, 475–486.

Wang, B., and Y. Wang, 1996: Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. *J. Climate*, **9**, 1586–1598.

Wang Dongxiao, and Z. Liu, 2000: The pathway of the interdecadal variability in the Pacific Ocean. *Chinese Science Bulletin*, **45**(17), 1555–1561.

Wang Dongxiao, J. Wang, L. Wu, and Z. Liu, 2003a: Relative importance of wind and buoyancy forcing for interdecadal regime shifts in the Pacific Ocean. *Science in China* (Ser. D), **46**(5), 417–427.

Wang Dongxiao, J. Wang, L. Wu, and Z. Liu, 2003b: Regime shifts in the North Pacific simulated by a COADS-driven isopycnal model. *Adv. Atmos. Sci.*, **20**(5), 743–754.

White, W. B., S. E. Pazan, and He Youhai, 1989: Off-equatorial westward propagating Rossby waves in the tropical Pacific during the 1982–83 and 1986–87 ENSO events. *J. Phys. Oceanogr.*, **19**, 1397–1406.