Winter-to-winter recurrence and non-winter-to-winter recurrence of SST anomalies in the central North Pacific

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[1] All previous studies of the winter-to-winter recurrence (WWR) of sea surface temperature anomalies (SSTA) have focused on mean climatic characteristics. Here, interannual variability of the SSTA WWR in the central North Pacific (CNP) is studied. The SSTA WWR displays a strong interannual variability in the CNP. The relative roles of atmospheric forcing and the oceanic reemergence mechanism are investigated by comparing SSTA WWR years and non-WWR years. Oceanic reemergence mechanism operates every year, the SSTA in the following winter, however, depends not only on the oceanic entrainment but also the atmospheric forcing, which exhibits substantial interannual variability. During SSTA WWR years, atmospheric circulation anomalies also exhibit the WWR phenomenon. Atmospheric forcing as well as the oceanic reemergence mechanism can act synergistically to create SSTA in the following winter with the same sign. During SSTA non-WWR years, winter atmospheric circulation anomalies do not recur in the following winter, and the following winter has opposing atmospheric forcing on SSTA. Although the reemergence mechanism is likely still operating, the anomalous heating supplied by the oceanic reemergence mechanism is smaller than that coming through the atmospheric forcing. Overall, the WWR in the CNP is an evolutional characteristic of the whole air-sea system with the seasons, and the WWR of atmospheric circulation anomalies and its forcing play an important role in the SSTA WWR.

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1. Introduction

[2] The ocean plays an important role in climate variation because its huge thermal capacity enables sea surface temperature (SST) variation to possess obvious lag and persistence characteristics. The persistence of sea surface temperature anomalies (SSTA) has strong seasonal dependence in the midlatitude ocean. *Namias and Born* [1970, 1974] were the first to note a tendency for mid-latitudinal SSTA to recur from one winter to the next without persisting through the intervening summer, effectively extending the memory of winter SSTA to longer than 1 year. Subsequent studies have confirmed this strong seasonal dependence of the persistence characteristics of large-scale SSTA patterns in the North Pacific [*Alexander and Deser*, 1995; *Alexander et al.*, 1999; *Kushnir et al.*, 2002; *Deser et al.*, 2003]. A better understanding of physical processes contributing to this persistence should improve our understanding of climate change at interannual and longer time scales in the midlatitude [*Cassou et al.*, 2007; *Liu et al.*, 2007].

[3] *Namias and Born* [1970, 1974] speculated that the seasonal dependence of SSTA persistence is closely tied to the seasonal variation of oceanic mixed layer depth (MLD). They hypothesized that some thermal anomalies created in the deep winter mixed layer are sequestered in the statically stable seasonal thermocline in summer, and then reentrained into the surface layer during the following fall and winter when the mixed layer deepens again. In this way, SSTA would recur from one winter to the next without persisting through the intervening summer. *Alexander and Deser* [1995] examined this hypothesis in greater detail and termed it the reemergence mechanism. Subsequent studies have shown that this reemergence mechanism occurs across much of the North Pacific [*Alexander et al.*, 1999; *Kushnir et al.*, 2002; *Deser et al.*, 2003]. In addition, other dynamic oceanic processes, such as advection, may impact the persistence of the mixed layer temperature anomalies in the North Pacific [*Sugimoto and Hanawa*, 2005].

[4] The ocean dynamics is not the only physical process that influences the wintertime SSTA persistence in the North Pacific. In the extratropics, the atmosphere tends to drive the ocean, especially in winter [e.g., *Davis*, 1976, 1978; *Wallace*

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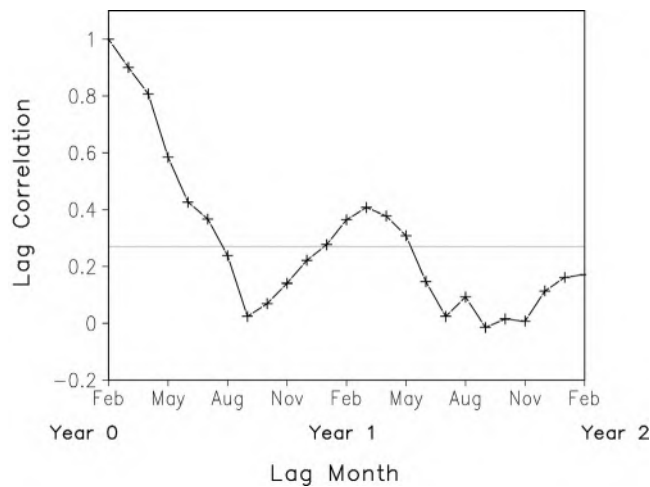
Figure 1. Lag correlation between monthly SSTA for February and monthly SSTA from February of the current year through February of the year after next year over the central North Pacific (CNP). The thin solid line indicates the 95% confidence level.

and Jiang, 1987; *Zhao and Li*, 2010]. However, WWR of atmospheric circulation anomalies and its role in the SSTA WWR in the North Pacific remains unclear. In our recent work [*Zhao and Li*, 2010], it was found that atmospheric circulation anomalies also show winter-to-winter recurrence (WWR) in the central North Pacific, which may be one of the causes of the SSTA WWR in this region. If anomalous atmospheric forcing were to occur repeatedly for several consecutive winters, but not in summer, this would tend to create recurring SSTA in winter.

[5] Previous studies have focused on the mean climatic characteristics of the SSTA WWR, and little attention has been given to its interannual variability. *Alexander et al.* [1999] described a possible occurrence of the oceanic reemergence mechanism over the North Pacific during 1972 (a link between SSTA in two winters via the summer thermocline during 1972). Whether the SSTA WWR occurs every year in the North Pacific remains unclear. The roles of the oceanic reemergence mechanism, and the atmospheric circulation, need to be further evaluated from the perspective of interannual variability. Quantitative investigation of the interannual variability of the WWR in the North Pacific should help to further understand the air-sea interaction in the midlatitudes on the interannual timescale and to improve interannual climate prediction in the extratropics.

[6] In the present study, we expand on previous studies and make extensive use of the concept of the SSTA WWR, by examining the interannual variability of the WWR in the North Pacific. Our results indicate that the SSTA WWR shows a strong interannual variability and does not occur every year in the central North Pacific (CNP). Furthermore, the relative roles of atmospheric forcing and the oceanic reemergence mechanism are investigated by comparing composite analysis results from SSTA WWR years and non-WWR years. The remainder of this manuscript is organized as follows. The data sets and methods used are described in Section 2, and the spatiotemporal characteristics of the

air-sea system in the North Pacific during WWR and non-WWR years are described in Section 3. In Section 4, we quantify the effects of oceanic entrainment and surface heat fluxes on the SSTA WWR in the CNP region. Finally, a summary is provided in Section 5.

2. Data and Methodology

2.1. Data

[7] The SST data set used is from the Improved Extended Reconstruction Sea Surface Temperature (IERSST) [*Smith and Reynolds*, 2004], which has a $2° \times 2°$ grid and extends from 1950 to 2004. Monthly subsurface temperature and mixed layer depth (MLD) are obtained from the Joint Environmental Data Analysis Center (JEDAC) at the Scripps Institution of Oceanography [*White*, 1995]. This archive contains temperatures at 11 levels (0, 20, 40, 60, 80, 120, 160, 200, 240, 300, and 400 m) during 1955–2003 on a $2° \times 5°$ latitude-longitude grid. MLD is defined as the depth at which temperature falls to SST − $1.0°C$. The atmospheric data are from the National Center for Environmental Prediction–National Centers for Atmospheric Research (NCEP–NCAR) reanalysis data [*Kalnay et al.*, 1996] for the period 1950–2004 on a $2.5° \times 2.5°$ grid. The annual cycle of each variable is removed by subtracting the climatological mean monthly value at each grid point.

2.2. Methodology

[8] *Alexander et al.* [1999] pointed out that the SSTA WWR and the reemergence mechanism are strong across much of the North Pacific at 40°N (see their Figures 1, 4, and 8). Seasonal variation of the oceanic mixed layer depth is also largest near 40°N. Especially, *Zhao and Li* [2010] indicated that atmospheric circulation anomalies display a significant WWR in the central North Pacific Ocean, closely related to the SSTA WWR near 40°N (165°E–160°W, 35°N–47°N). Therefore, the area-averaged SSTA over the central North Pacific (CNP: 165°E–160°W, 35°N–47°N) is used here to measure the interannual variability of the WWR in the North Pacific.

[9] In order to study the interannual variability of the SSTA WWR, we start from the original definition of the SSTA WWR (the mean climatic characteristic) to determine whether the SSTA WWR exists in the North Pacific each year. Previous studies used lag correlation analysis to define the SSTA WWR [e.g., *Alexander et al.*, 1999]. The lag correlation is calculated between the time series for the starting month m and that for the lag month k. For example, for starting month $m = Feb$ and $k = 10$, the correlation is calculated between February and December time series. Figure 1 shows the lag correlations between monthly SSTA for February and monthly SSTA for each subsequent month through February of the year after next year in the CNP region. February is used as the reference month because spatial extent of the recurrence is largest in February and March, as mentioned by *Zhao and Li* [2010]. As shown in Figure 1, the persistence of SSTA starting in winter (February) has two significant characteristics: a significant decline during the following summer (August to October) and an increase again during the following winter with a peak during February to April. Persistence of SSTA with

Table 1. Years Grouped According to Those With the WWR and Those Without the WWR (Non-WWR)

	Years
WWR	
Positive	1951, 1956, 1965, 1966, 1968, 1971, 1974
Negative	1959, 1960, 1977, 1978, 1983, 1985, 1986, 1994, 1996, 1998, 1999
Non-WWR	
Positive	1950, 1952, 1953, 1954, 1955, 1957, 1962, 1963, 1967, 1969, 1972, 1976, 1982, 1989, 1990, 1991, 1993, 2000, 2002
Negative	1958, 1961, 1964, 1970, 1973, 1975, 1979, 1980, 1981, 1984, 1987, 1988, 1992, 1995, 1997, 2001, 2003

these characteristics is called the WWR [e.g., *Alexander and Deser*, 1995]. To efficiently detect the interannual variability of the SSTA WWR, its two characteristics are quantitated for each year by using the following criteria: for positive (negative) SSTA during winter, (1) winter SSTA (January to March) is greater (less) than SSTA during the following summer (August to October) and (2) the following winter (February to April) SSTA is greater (less) than SSTA in the preceding summer and has the same sign as SSTA in the preceding winter. It is a positive (negative) WWR year

if a year meets the two criteria, and a positive (negative) non-WWR year if not. It will get same result if the winter in year 1 is the January–March seasonal average.

3. Spatiotemporal Characteristics of the Air-Sea System During WWR and Non-WWR Years

3.1. WWR Years and Non-WWR Years

[10] SSTA WWR years and non-WWR years in the CNP region were identified using the method presented in Section 2. As shown in Table 1, the SSTA WWR has notable interannual variability in this region. There are 18 WWR years and 36 non-WWR years during the period 1950–2003. Figures 2a and 2b show the seasonal evolution of SSTA in the CNP region during WWR years. In positive (negative) WWR years, the winter SSTA decreases (increases) significantly in summer, then increases (decreases) quickly during the following fall to winter. This evolution of SSTA with the season shows WWR characteristics during the WWR years. However, the seasonal evolution of SSTA shows markedly different characteristics during the non-WWR years. Overall, the SSTA shows continuous decreases (increases) in the positive (negative) non-WWR years without WWR (Figure 2c and 2d). Thus, the differences between
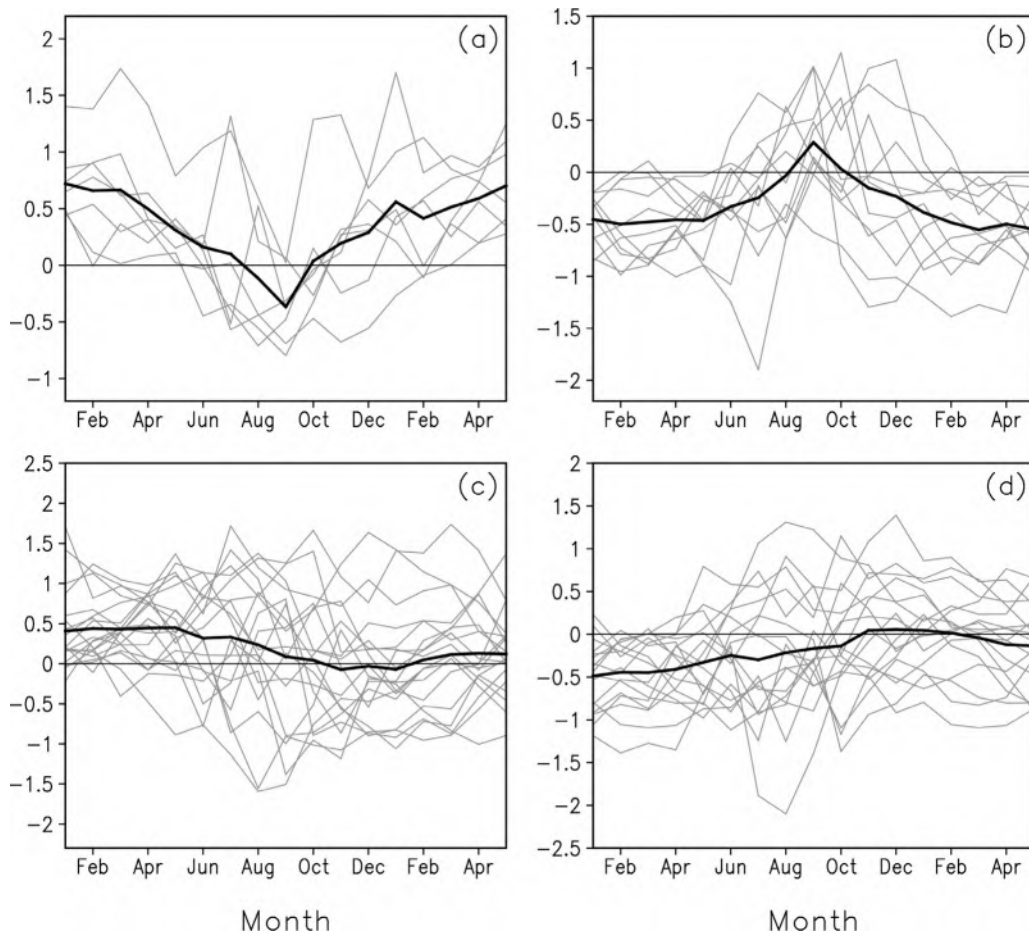

Figure 2. SSTA in the CNP region during (a) the positive WWR years, (b) the negative WWR years, (c) the positive non-WWR years, and (d) the negative non-WWR years. Gray lines denote SSTA during each year, and thick black lines denote the mean SSTA of the plotted group.
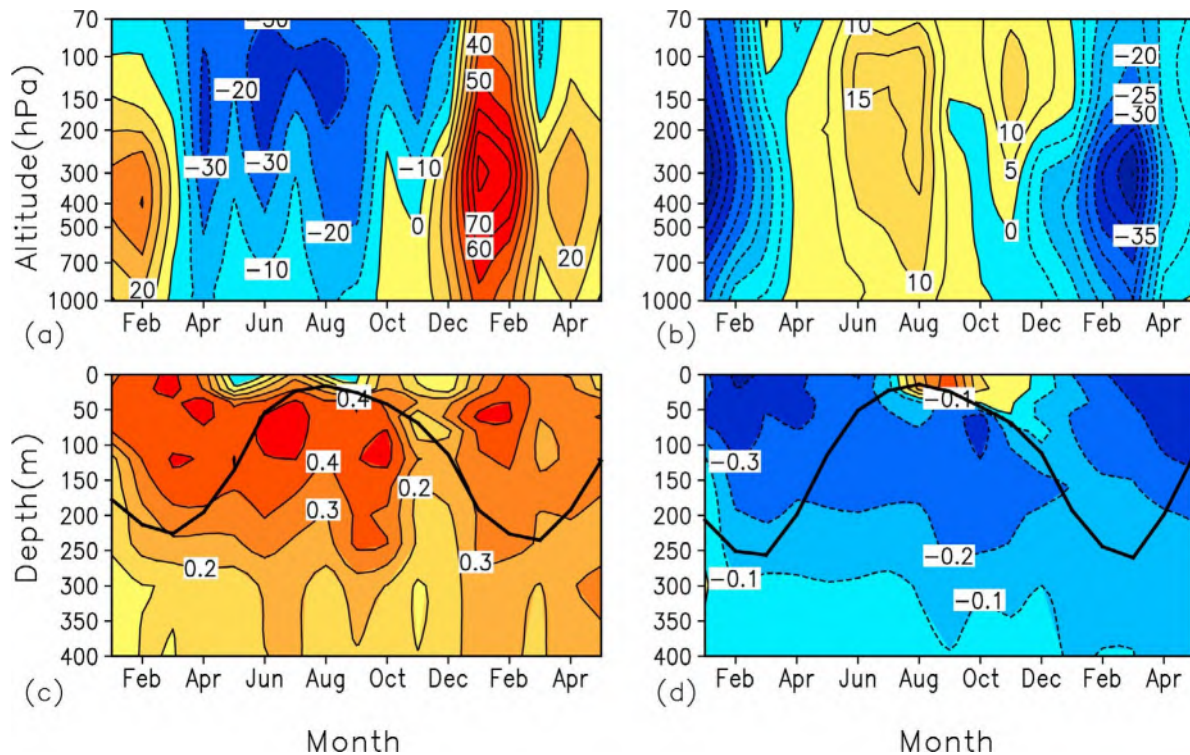
Figure 3. (a and b) Time-depth profiles of composite geopotential height anomalies from 1000 hPa to 70 hPa and (c and d) oceanic temperature anomalies between the surface and 400 m in the CNP region during the WWR years. Figures 3a and 3c are for the positive WWR years and Figures 3b and 3d are for the negative WWR years. The composite MLD is shown by the thick solid line.

the WWR and non-WWR years are mainly in the second winter, which are statistical significant from January to May. Among these, the significance is lost in February and March for the positive cases, which may be due to only seven positive WWR years were selected.

[11] The seasonal evolution of SSTA in the CNP region has completely different characteristics in WWR years compared with non-WWR years. Previous studies, from the perspective of the climatic mean, have indicated that the SSTA WWR is not only closely tied to seasonal variation of the oceanic MLD [e.g., *Alexander and Deser*, 1995], but is also associated with the anomalous atmospheric circulation forcing in the CNP [*Zhao and Li*, 2010]. Therefore, It is necessary to evaluate further the roles of the oceanic reemergence mechanism and atmosphere forcing during both WWR and non-WWR years in the CNP region, from the perspective of interannual variability.

3.2. Vertical Structure of the Air-Sea System During WWR and Non-WWR Years

[12] Figures 3c and 3d show time-depth profiles of composite oceanic temperature anomalies between the surface and 400 m from January through May of the next year during the SSTA WWR years. For the positive WWR years (Figure 3c), vigorous air-sea energy exchange during winter creates temperature perturbations that extend down to the deep winter mixed layer (about 200 m); when the mixed layer shoals in late spring, the winter thermal anomalies become sequestered beneath the shallow summer mixed layer (about 20 m); as the mixed layer deepens again in the following late

fall and early winter, some of the subsurface thermal anomalies may become reentrained into the mixed layer, thus influencing the SSTA in the following winter. Similar evolution occurs during the negative WWR years. Subsurface ocean temperature anomalies in the second winter have the same sign as those of the preceding winter and have a sign opposite to that of the surface temperature anomalies in the intervening summer (Figure 3d). Therefore, it appears that the oceanic reemergence mechanism associated with seasonal variation of the MLD is at work during WWR years.

[13] Figures 3a and 3b show time-depth profiles of composite geopotential height anomalies between 1000 and 70 hPa during the SSTA WWR years. The result is consistent with that of the gradient in geopotential height (not shown). For the positive cases (Figure 3a), the seasonal evolution is characterized by two reversals in the sign of geopotential height anomalies in the CNP region. The geopotential height anomalies in the first winter are positive with a maximum in January–February; they change to negative in the following summer with a maximum in June–August; then they return to positive again in the second winter. Thus, the geopotential height field in the CNP region also displays WWR during the SSTA WWR years from the lower to upper layer. The geopotential height field shows an equivalent barotropic vertical structure, and the centers of anomalies are located in the high troposphere (500–300 hPa). In addition, when the air-sea system recurs during the second winter, the center of geopotential height anomalies occurs earlier than that of the subsurface temperature anomalies in the ocean. The strongest positive correlations
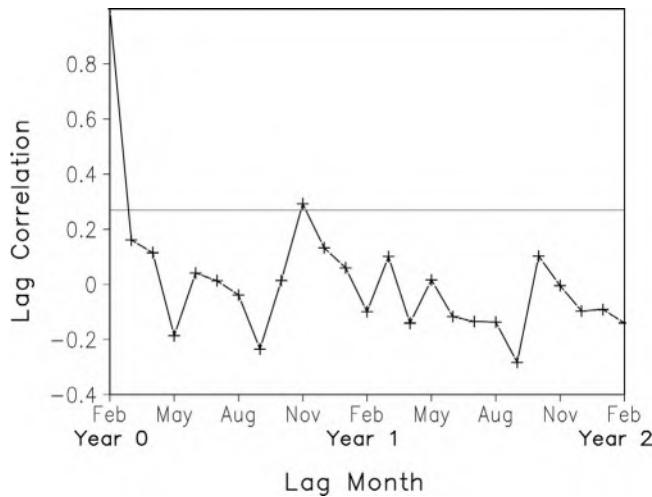
Figure 4. As in Figure 1, but for geopotential height anomalies at 300 hPa over the CNP.

occur when the sea level pressure anomalies (SLPA) lead the SSTA by 1–2 months, not only in winter [e.g., *Davis*, 1976, 1978; *Wallace and Jiang*, 1987; *Zhao and Li*, 2010], but also in summer (not shown), suggesting that atmospheric forcing on the ocean may play a dominant role in the CNP. Seasonal evolution of the geopotential height anomalies is similar during the negative cases (Figure 3b). The recurrence timing for the negative cases is later than that for the positive cases. The former is in January and the latter is in February–March. The atmospheric WWR could also be seen in the lag correlation map for the geopotential height anomalies at 300 hPa (Figure 4). The persistence of geopotential height

anomalies starting in winter has an increase again during the following winter with a peak in November. Therefore, in the SSTA WWR years, atmospheric circulation anomalies also display the WWR in the CNP region and it may be one of the causes of the SSTA WWR in this region, which further validates our earlier conclusions [*Zhao and Li*, 2010] from the perspective of the interannual variability of the WWR.

[14] The evolution of the air-sea system in the CNP region during SSTA non-WWR years (Figure 5) differs markedly from that during WWR years. Atmospheric circulation anomalies in winter do not recur in the following winter (Figures 5a and 5b). Similarly, subsurface temperature anomalies above 150 m show a reversal in sign from the first to second winter (Figures 5c and 5d) because of the atmospheric forcing. These results suggest that during non-WWR years, SSTA in the second winter do not primarily come from subsurface temperature anomalies in the preceding winter and summer, and the influence of atmospheric forcing on the SSTA may be more important. Our results do not preclude the impact of the reemergence mechanism upon the SSTA WWR in the North Pacific. It could be that the oceanic reemergence mechanism operates in both the WWR and non-WWR years, however, the SSTA in the following winter depends not only on the oceanic entrainment but also the atmospheric forcing. In non-WWR years the anomalous heating supplied by the oceanic reemergence mechanism during the second winter is smaller than that coming through the atmospheric forcing.

3.3. Horizontal Structure of the Air-Sea System During WWR and Non-WWR Years

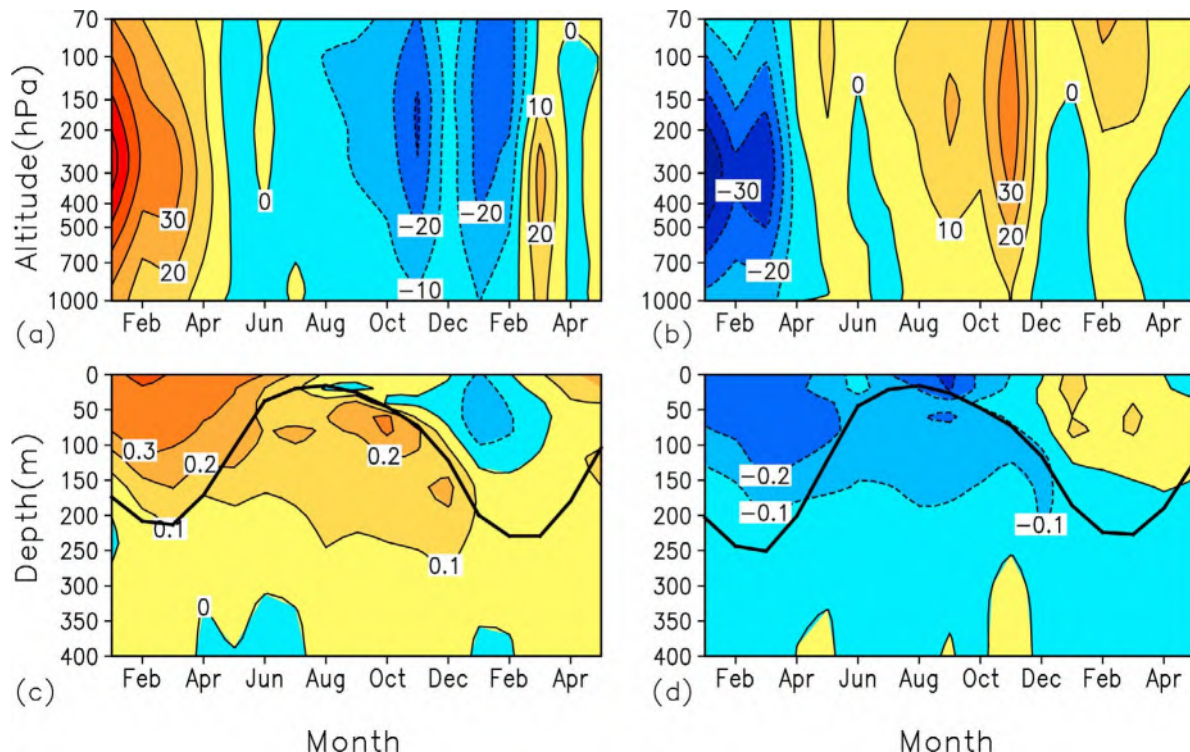[15] Figure 6a shows the evolution of the horizontal structure of SSTA (Figure 6a, middle), sea level pressure

Figure 5. As in Figure 3, but during the non-WWR years.
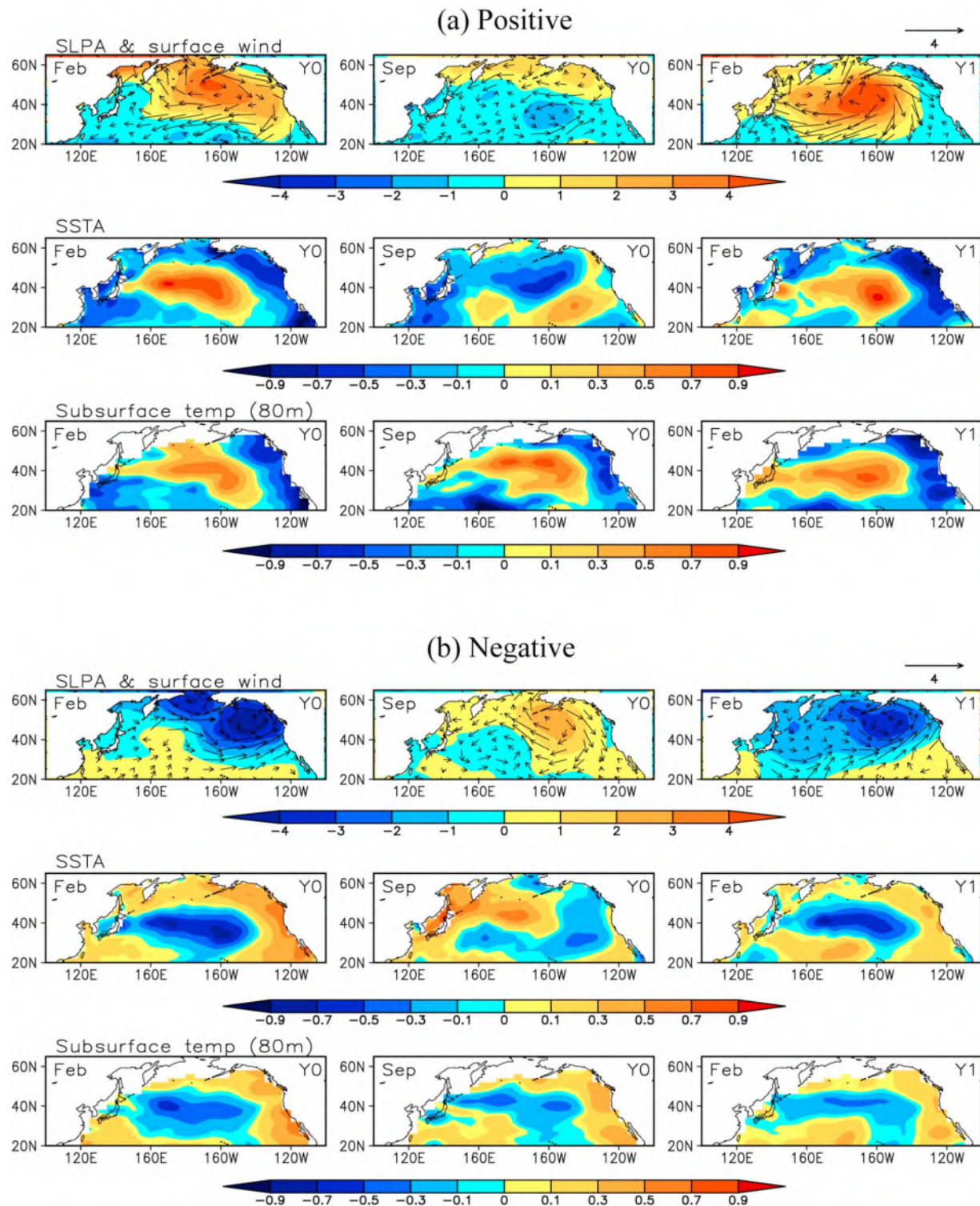
Figure 6. (a) Evolution of the composite air-sea system in the North Pacific during the positive WWR years: (top) SLPA and surface wind anomalies, (middle) SSTA, and (bottom) subsurface temperature anomalies at 80 m. Y0 indicates the current year and Y1 indicates the next year. (b) As in Figure 6a, but during the negative WWR years.

anomalies (SLPA) and the surface wind anomalies (Figure 6a, top), and subsurface temperature anomalies at 80 m (Figure 6a, bottom) in the North Pacific during the positive WWR years. SSTA is warm in the central North

Pacific and cool in other regions in winter (February) of the first year; the warm center begins to weaken in the following spring and reverses sign in summer (September); the warm center recurs in the next autumn and winter, and the

maximum is in winter (February) of the second year, with a spatial distribution and strength similar to those in the preceding winter. Thus, the SSTA WWR in the CNP region reflects the seasonal evolution of the large-scale SSTA pattern in the North Pacific. *Alexander et al.* [1999] also indicated that the dominant pattern of SSTA in the North Pacific in the winter is more strongly related to the pattern in the following winter than to the pattern in the intervening summer, through analyzing the evolution of SSTA using extended empirical orthogonal functions.

[16] In correspondence with the evolution of SSTA, the large-scale atmospheric circulation anomalies also display seasonal variation in the North Pacific. An anomalous high pressure center with a strong anomalous anticyclone extends across the whole North Pacific in the first winter (February); the SLPA and surface wind anomalies begins to weaken in the following spring and changes to a weak anomalous low pressure with a cyclone in summer (September); in the second winter (February), the anomalous high pressure center with an anomalous anticyclone recurs, and the spatial distribution and strength resembles those in the first winter. Thus, in the SSTA WWR years, atmospheric circulation in the North Pacific also has remarkable features of the WWR.

[17] Temperature anomalies in the subsurface ocean show a strong warm center over the central North Pacific throughout two winters and the intervening summer, resembling the spatial structure of SSTA in winter but not that in summer. This result is consistent with the reemergence mechanism, suggesting a link between SSTA in one winter and the next via the summer thermocline.

[18] Figure 6b shows an evolution of the air-sea system during the negative WWR years. The pattern of SSTA in the North Pacific is the reverse of that for the positive cases. The winter SSTA shows a strong cold center in the central North Pacific, which diminishes significantly in summer and recurs in the next winter, thus showing significant features of the WWR. A corresponding characteristic of the atmospheric circulation anomalies is the recurrence of an anomalous low pressure center with an anomalous cyclone from one winter to the next without persisting through the intervening summer. For the subsurface ocean, temperature anomalies in summer appear to be a link between SSTA in two winters in the North Pacific. Negative extratropical SSTA are associated with stronger than normal surface westerlies above, and straddled by a pair of SLPA, a cyclone poleward and an anticyclone equatorward. The opposite is true for positive SSTA. This is one of the salient features of observed extratropical SSTA and their associated atmospheric patterns, as described in *Frankignoul* [1985] and *Kushnir et al.* [2002].

[19] Figure 7 shows the characteristics of the air-sea system during the non-WWR years. In the first winter, the air-sea system in the North Pacific has a pattern similar to that during the WWR years. For the positive (negative) cases, SSTA and the subsurface temperature anomalies show a strong warm (cold) center in the North Pacific; the corresponding atmospheric state has an anomalous high (low) pressure center with an anomalous anticyclone (cyclone). Then, this air-sea system pattern gradually weakens. Compared with the WWR years, the marked differences are in the second winter. The anomalies weaken or even reverse sign in the second winter, so that the air-sea

system in the North Pacific has no recurrences in the second winter.

[20] Therefore, the seasonal variations of large-scale pattern of the air-sea system in the North Pacific have marked differences between the non-WWR and WWR years. During the WWR years, the Aleutian low weakens (strengthens) in the first winter, which induces the warming (cooling) of SSTA in the central North Pacific. Because atmospheric forcing is the same in the second winter, the SSTA signal recurs in those two winters. Moreover, the winter SSTA is preserved in the summer thermocline when the mixed layer is shallow, and some the subsurface thermal anomalies may become reentrained into the mixed layer when the mixed layer deepens again in the following winter. During the non-WWR years, the Aleutian low weakens (strengthens) in the first year, which induces warming (cooling) of SSTA in the central North Pacific. However, in the second winter, the Aleutian low strengthens (weakens), and SSTA and even temperature anomalies in the mixed layer are opposite to those in the first winter, due to the distinct atmospheric forcing on the ocean in two successive winters.

4. Quantifying the Effects of Oceanic Entrainment and Surface Heat Fluxes

[21] The evolution of the air-sea system in the CNP during the SSTA non-WWR years is very different from that during the WWR years. During the non-WWR years, winter atmospheric circulations anomalies do not recur in the following winter. Similarly, subsurface temperature anomalies above 150 m in the second winter have signs opposite to those in the first winter. It seems that the influence of the atmospheric forcing on the SSTA is more important than the reemergence mechanism. Note that our results do not preclude the impact of the reemergence mechanism upon the SSTA WWR, and the reemergence mechanism should operate in both WWR and non-WWR years via entrainment. Previous studies indicated that the oceanic reemergence mechanism is closely tied to the seasonal variation of the oceanic MLD. Figure 8 shows that the seasonal variation of the MLD is similar during the WWR and non-WWR years: deep in winter and shallow in summer. If the MLD is defined using the criterion of a 0.125 kg m^{-3} change in potential density from the ocean surface (potential density is a function of temperature, salty and pressure), the result is similar to that determined only from the temperature profile (not shown). Thus, it could be that oceanic reemergence process (a portion of the SSTA in the first winter may be carried into the next winter though the summer thermocline) should operate every year, the SSTA in the following winter, however, depends not only on the oceanic entrainment but also the atmospheric forcing, which exhibits substantial interannual variability.

[22] The dominant forcing mechanism of SSTA is the net surface heat fluxes anomalies [e.g., *Cayan*, 1992], thus their seasonal evolution determines to a large extent of the seasonal evolution of the SSTA. To quantify the effects of the reemergence mechanism and atmospheric forcing in the SSTA WWR and non–WWR, it is helpful to calculate the oceanic entrainment and surface heat fluxes anomalies from the equation for the anomalous heat budget of the ocean
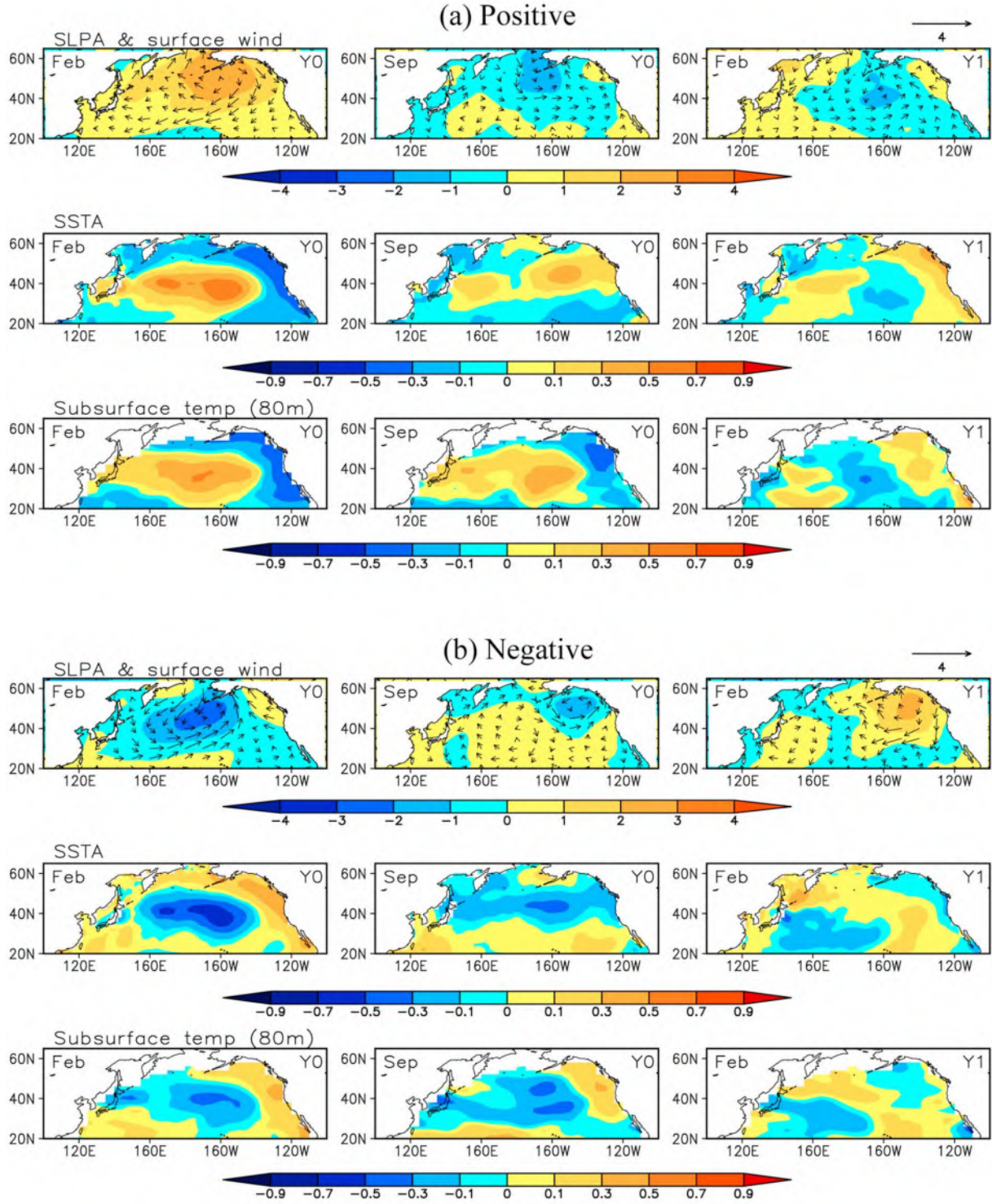
Figure 7. As in Figure 6, but for the non-WWR years.

mixed layer. This equation has been examined in greater detail in *Alexander and Deser* [1995], *Alexander et al.* [2000], *Kim et al.* [2004], and *Park et al.* [2006]

$$\rho C_p [MLD] \left(\frac{d}{dt} T' \right) \approx Q'_{net} + \rho C_p [W_e] \Delta T' + \rho C_p W'_e [\Delta T],$$

where T is the SST, $\Delta T = (T_b - T)$, T_b is the temperature below the mixed layer water, [ ] is the seasonally varying climatological mean, and prime is an anomaly from the mean. Q'_{net} is surface heat fluxes anomalies. ρ is the density of seawater (=1025 kg m^{-3}) and C_p is the specific heat of seawater at constant pressure (=4000 J kg^{-1} K^{-1}). W_e is the entrainment rate, and $W_e = dMLD/dt$ when the mixed
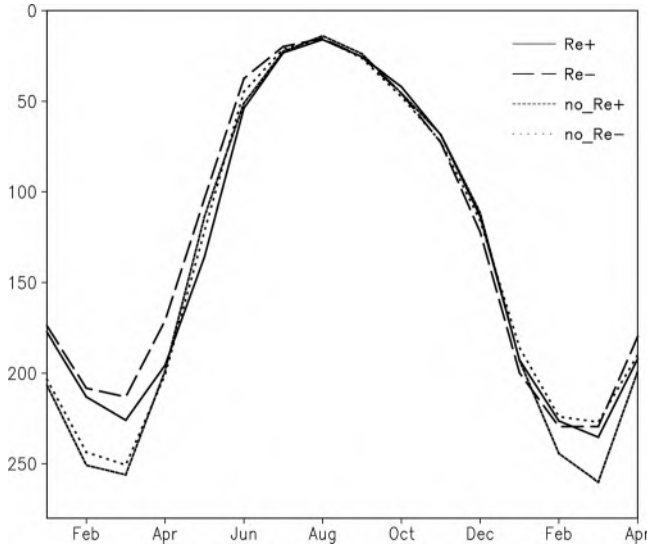
Figure 8. Evolution of the composite MLD in the CNP region during the positive WWR years (Re+), the negative WWR years (Re−), the positive non-WWR years (no_Re+), and the negative non-WWR years (no_Re−).

layer deepens and $W_e = 0$ when it shoals. We calculate the surface heat flux anomalies Q'_{net} (Figure 9), the oceanic entrainment $\rho C_p [W_e] \Delta T'$ (Figure 10) and the $\rho C_p W'_e [\Delta T]$ (Figure 11) in the CNP region during the WWR and non-WWR years.

[23] Similar to evolution of SSTA, surface heat fluxes anomalies Q'_{net} exhibit the WWR phenomenon during WWR years and do not recur during non-WWR years (Figure 9). The oceanic entrainment terms $\rho C_p [W_e] \Delta T'$ and $\rho C_p W'_e [\Delta T]$ show notable differences. For the oceanic entrainment term $\rho C_p [W_e] \Delta T'$ (Figure 10), its evolution has no significant differences during the WWR and non-WWR years, which means oceanic reemergence process should operate every year. For the oceanic entrainment $\rho C_p W'_e [\Delta T]$ (Figure 11), its evolution is basically similar to that of the surface heat fluxes. During the WWR years, the oceanic entrainment $\rho C_p W'_e [\Delta T]$ and $\rho C_p [W_e] \Delta T'$ (Figures 10a, 10b, 11a, and 11b) have the same sign as the surface heat fluxes anomalies Q'_{net} in the fall/winter. Thus, the oceanic entrainment could enhance the anomalous heating supplied by atmospheric forcing. During the non-WWR years, the oceanic entrainment $\rho C_p [W_e] \Delta T'$ in the fall/winter has the same sign as that during the WWR years, but the oceanic entrainment $\rho C_p W'_e [\Delta T]$ in winter has a sign opposite to the $\rho C_p [W_e] \Delta T'$ (Figure 10c, 10d, 11c, 11d), suggesting the oceanic reemergence mechanism is weakened. Thus, during the non-WWR years, consecutive winters have the opposing atmospheric forcing, and the anomalous heating supplied by
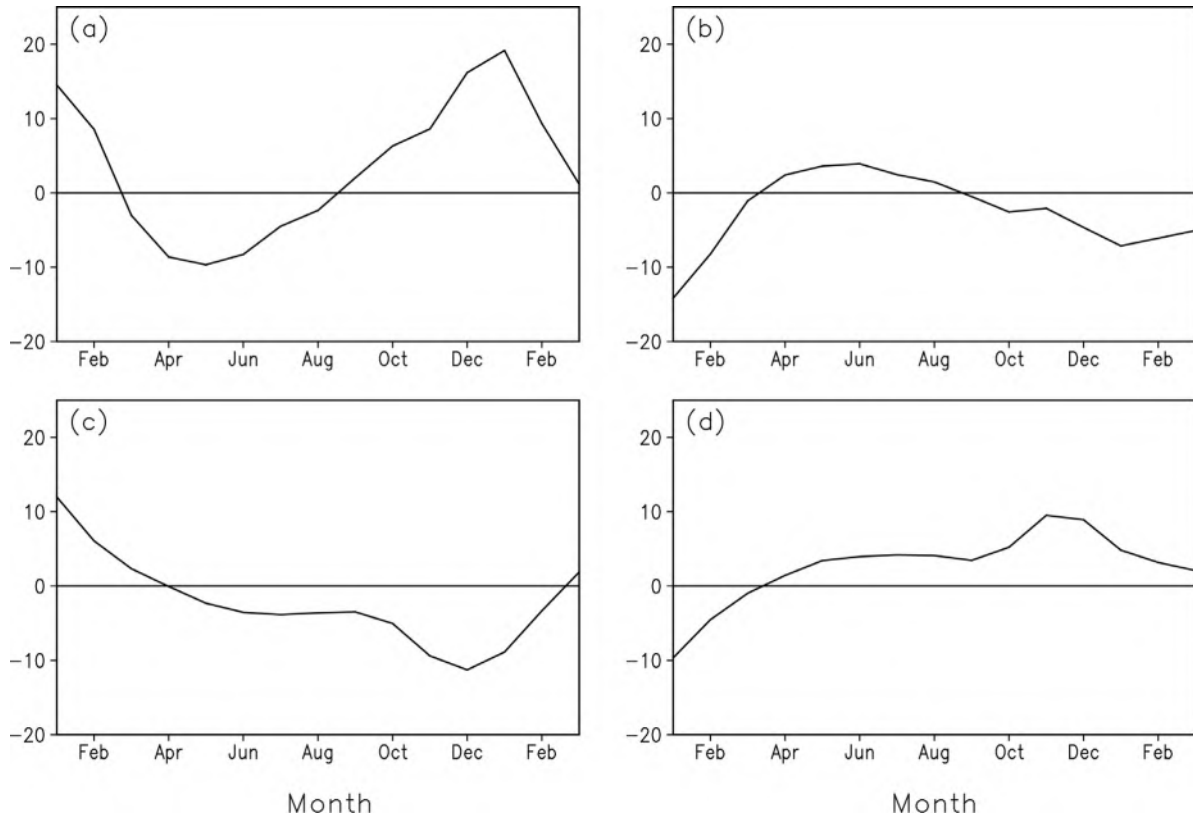

Figure 9. Evolution of the composite surface heat flux anomalies (Q'_{net}, latent heat flux, sensible heat, shortwave, and longwave radiation and positive values indicate that the atmosphere vents heat to the ocean) in the CNP region during (a) the positive WWR years, (b) the negative WWR years, (c) the positive non-WWR years, and (d) the negative non-WWR years.
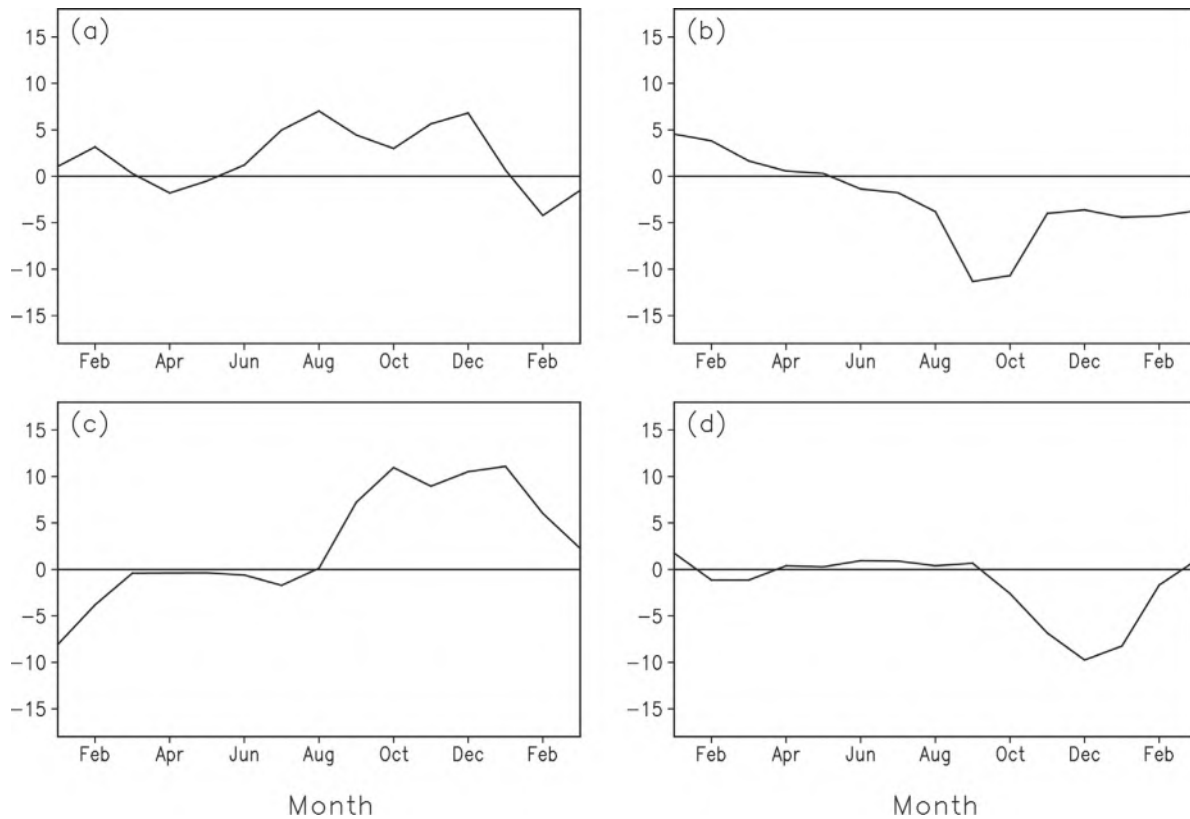
Figure 10. Evolution of the composite oceanic entrainment $\rho C_p[W_e]\Delta T'$ in the CNP region during (a) the positive WWR years, (b) the negative WWR years, (c) the positive non-WWR years, and (d) the negative non-WWR years.

the oceanic reemergence mechanism via entrainment is smaller than that coming through atmospheric forcing via surface heat fluxes during the second winter.

[24] The contribution of the heat advection of anomalous temperatures associated with the mean currents to the SSTA is opposite to that of the surface heat fluxes anomalies, but the heat advection is much smaller than the oceanic entrainment and surface heat fluxes anomalies (not shown). For the curl of wind stress anomalies, its contribution is in phase with that of the surface heat fluxes anomalies (not shown), but Ekman pumping has negligible effects on the large-scale SSTA [e.g., *Frankignoul*, 1985].

5. Summary and Discussion

[25] Previous studies on the SSTA WWR only focused on the mean climatic characteristics, whereas the present study investigated interannual variability of the SSTA WWR in the CNP region. The results indicate that the SSTA WWR shows a strong interannual variability and does not occur every year in the CNP. In fact, WWR in the CNP is an evolutional characteristic of the whole air-sea system with the seasons. In the WWR years, the atmospheric circulation anomalies also exhibit the WWR phenomenon, recurring from one winter to the next without persisting through the intervening summer. In the non-WWR years, winter atmospheric circulation anomalies do not recur in the following winter. Similarly, subsurface temperature anomalies above 150 m in second winter have signs opposite to those in the

first winter, because of the atmospheric forcing through heat flux. From the perspective of the interannual variability of the SSTA WWR, it is further identified that the WWR in the atmosphere and ocean are closely correlated in the CNP region, and the WWR of the atmospheric circulation anomalies is one of the causes of the SSTA WWR in the CNP. The present study focuses on the atmospheric WWR and its forcing on the SSTA WWR in the CNP region. Note that the atmospheric WWR and its forcing on the SSTA WWR do not exist in the whole North Pacific. The results may differ for other regions, such as the northeastern North Pacific, where the atmospheric forcing does not have a clear relationship with the SSTA (not shown).

[26] The present results do not preclude the impact of the oceanic reemergence mechanism upon the SSTA WWR in the North Pacific. From the perspective of the climatic mean, *Alexander and Deser* [1995] indicated that WWR of SSTA is caused by the reemergence mechanism closely tied to seasonal variation of the oceanic MLD. Because the seasonal variation of the MLD is similar during the WWR and non-WWR years (i.e., deep in winter and shallow in summer), it could be that the reemergence mechanism operates in both the WWR and non-WWR years via entrainment. However, the oceanic reemergence mechanism cannot explain the marked difference of SSTA in the second winter between the WWR and non-WWR years. The SSTA in the following winter depends not only on the oceanic entrainment but also the atmospheric forcing, which should exhibit substantial interannual variability. The relative roles of
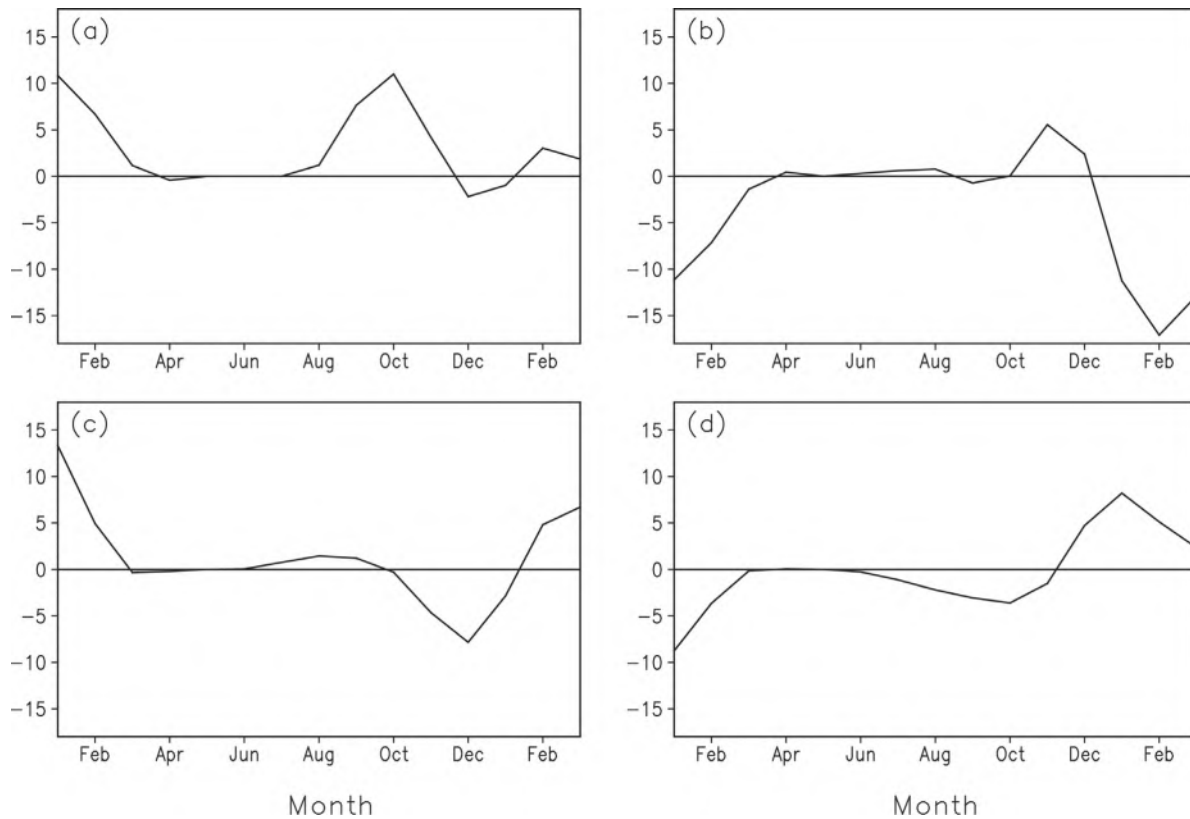
Figure 11. Evolution of the composite oceanic entrainment $\rho C_p W_e'[\Delta T]$ in the CNP region during (a) the positive WWR years, (b) the negative WWR years, (c) the positive non-WWR years, and (d) the negative non-WWR years.

atmospheric forcing and the reemergence mechanism are different for the SSTA WWR and non-WWR years. During the SSTA WWR years, the atmospheric circulation anomalies also recur from one winter to the next. Thus, both the atmospheric forcing and the oceanic reemergence mechanism can act synergistically to create winter SSTA with the same sign, resulting in the SSTA WWR. During the non-WWR years, consecutive winters have opposite atmospheric forcing, and the influence of the oceanic reemergence mechanism is smaller than that coming through the atmospheric forcing, resulting in no SSTA WWR in the CNP.

[27] A number of studies have already documented that there exists not only interannual variability but also significant interdecadal variability in the North Pacific [e.g., *Deser and Blackmon*, 1995; *Mantua et al.*, 1997; *Nakamura et al.*, 1997]. Moreover, the Aleutian Low in the central North Pacific has a dominant low-frequency time scale, and low-frequency SST variations result from the atmospheric forcing of the Aleutian Low [e.g., *Nakamura et al.*, 1997; *Minobe*, 1999]. In our results, the SSTA WWR in the North Pacific also has interdecadal variability, possibly associated with the climatic regime shift that occurred in the North Pacific in 1976/1977 [e.g., *Miller et al.*, 1994]. All the positive WWR years appear before 1977, and most of the negative WWR years exist after 1977 (Table 1). It is worthwhile to discuss the influence of the interdecadal variability on the WWR and non-WWR of the air-sea system in the CNP region. Figure 12 (Figure 13) shows the evolution of the air-sea system in the CNP region during the WWR (non-WWR)

years, after low-frequency variability at time scales longer than 10 years is subtracted from the original subsurface temperature anomalies and geopotential height anomalies. The 10-yr low-pass filtered time series are generated by Gaussian-type filter. Removing low-frequency variability (10 yr and longer) does not result in strong changes to the spatiotemporal evolutions of the air-sea system during the WWR and non-WWR years, as can be seen by comparing Figures 3 (Figure 5) and 12 (Figure 13). The result is similar when 8-yr low-pass filtered used, or after removing the linear trend in the subsurface temperature anomalies and geopotential height anomalies. In addition to the climatic regime shift in 1976, there is a similar shift occurred in the North Pacific in 1998 [e.g., *Chavez et al.*, 2003], but it is not shown in the SSTA WWR (Table 1).

[28] It is well known that the lack of long-term observation (longer than 50 years), especially from the subsurface and deep ocean, makes it difficult to describe the long-term variability of subsurface temperature using observations. Before the 1980s, the subsurface temperature was observed mainly by using the mechanical bathythermograph (MBT). The maximum observation depth of MBTs is about 200–300 m, and there are a few observations over the North Pacific in a given month or season, while *White* [1995] statistical interpolation scheme fills in these voids the values may be somewhat fictitious. Other assimilation systems, such as Simple Ocean Data Assimilation (SODA), provide data that come from a reanalysis of ocean climate variability that begins with a state forecast produced by the Parallel
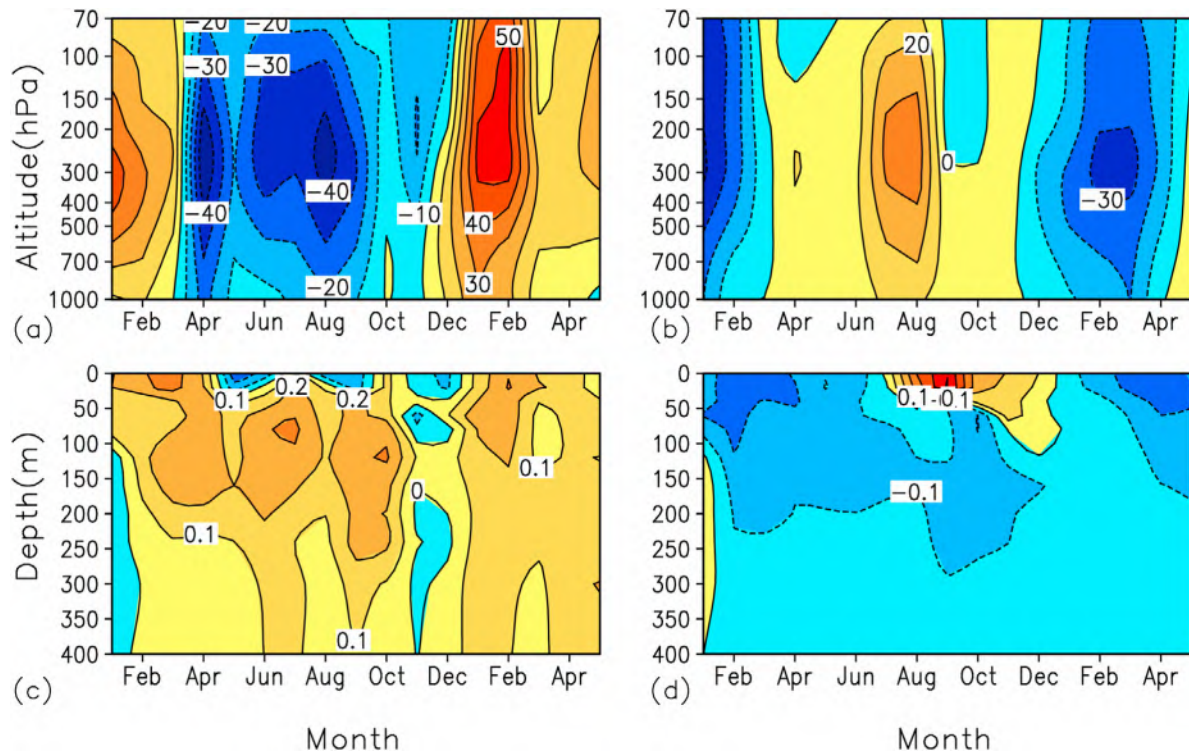
Figure 12. As in Figure 3, but in which low-frequency variability at time scales longer than 10 years is subtracted from the original data of the subsurface temperature anomalies (geopotential height anomalies) in the CNP.
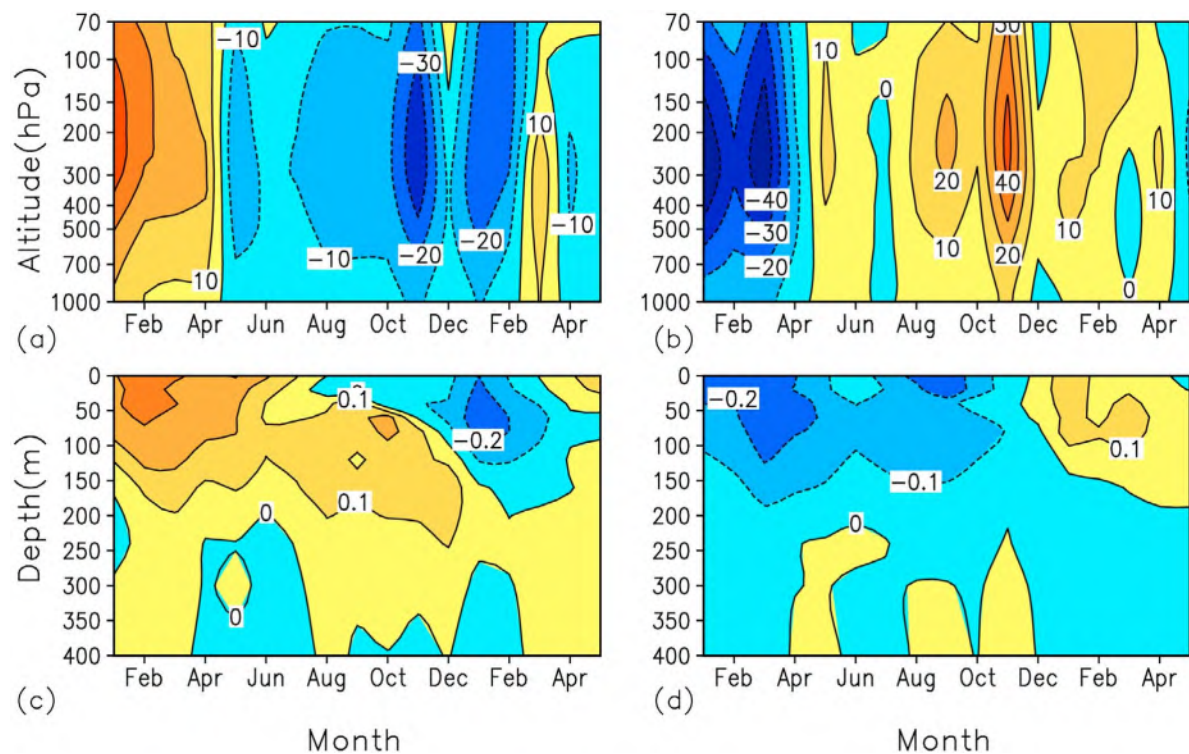

Figure 13. As in Figure 5, but in which low-frequency variability at time scales longer than 10 years is subtracted from the original data of the subsurface temperature anomalies (geopotential height anomalies) in the CNP.

Ocean Program (POP) general circulation model [*Carton et al.*, 2000]. SODA also has a lot of issues and uncertainty, although it provides a long-term data with records approximately 50 years long. Our analysis shows that even the sea surface temperature data cannot capture the characteristic of the SSTA WWR in the CNP region (not shown), suggesting the SODA data might be not suitable for use in studying the WWR in this region. A new ocean reanalysis, based on NEMOVAR, has been developed at the European Center for Medium range Weather Forecast (ECMWF) [*Balmaseda et al.*, 2010]. This new reanalysis is a deliverable for the Comprehensive Modeling of the Earth System for Better Climate Prediction and Projection (COMBINE) project. A selection of data from NEMOVAR-COMBINE is publicly available at http://icdc.zmaw.de/easy_init_ocean. html?&L=1, spanning the period 1958–2008. Our analysis indicated that the result of the NEMOVAR-COMBINE is consistent with that of the JEDAC. During WWR years, subsurface ocean temperature anomalies in the second winter have the same sign as those of the preceding winter and have a sign opposite to that of the surface temperature anomalies in the intervening summer. During non-WWR years, subsurface temperature anomalies above 100 m show a reversal in sign from the first to second winter because of the atmospheric forcing (not shown).

[29] Here we evaluate the influence of the oceanic process associated with the seasonal variation of the MLD on the SSTA WWR in the North Pacific. Other dynamic oceanic processes (e.g., advection, the slow propagation of oceanic Rossby waves, subduction, diffusion, and eddy mixing) may also influence the persistence of mixed-layer temperature anomalies [*Qiu*, 2000; *Xie et al.*, 2000; *Sugimoto and Hanawa*, 2005; *Wu and Kinter*, 2010]. The contribution of the heat advection of anomalous temperatures associated with the mean currents to the SSTA is opposite to that of the surface heat fluxes anomalies, but the heat advection is much smaller than the oceanic entrainment and surface heat fluxes anomalies. For the curl of wind stress anomalies, its contribution is in phase with that of the surface heat fluxes anomalies, but Ekman pumping has negligible effects on the large-scale SSTA [e.g., *Frankignoul*, 1985].

[30] Causes of the atmospheric WWR are still an open question. It seems like that the SSTA WWR would not be the origin of the WWR of the atmospheric circulation, because there is strong evidence that at midlatitude the atmosphere forces the ocean, especially in winter [e.g., *Davis*, 1976]. Tropical ENSO is not essential for the WWR to occur in the North Pacific, because the persistence characteristics of the ENSO itself do not show any recurrence regardless of the starting month. Effect of other external forcings, e.g., sea ice, is also not significant. Is the dominant source of the atmospheric WWR internal atmospheric dynamics? The Arctic Oscillation (AO) is the dominant pattern of non-seasonal sea level pressure (SLP) variations north of 20°N, and it is characterized by SLP anomalies of one sign in the Arctic and anomalies of opposite sign across the subtropical and midlatitudes [e.g., *Thompson and Wallace*, 1998; *Li and Wang*, 2003]. The AO is at the negative phase in the positive WWR years, and at the positive phase in the negative WWR years, but it seems not to be the cause of atmospheric WWR (not shown). In the North Pacific, the systematic changes in the storm tracks and associated synoptic transient eddy allow the possibility that the heat and momentum or vorticity fluxes may have helped maintain the anomalous mean circulation [e.g., *Hoskins et al.*, 1983]. The CNP region is in the location of the storm track in the North Pacific. Change in storm track and associated synoptic eddy may be one of the causes for the WWR of atmospheric circulation in the North Pacific, which lead to quick transition of height anomalies around March and the maintenance of the opposite sign height anomalies for 2–3 seasons. Further research is required.

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