

Winter-to-Winter Recurrence of Sea Surface Temperature Anomalies in the Northern Hemisphere

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ABSTRACT

The spatiotemporal characteristics of the winter-to-winter recurrence (WWR) of sea surface temperature anomalies (SSTA) in the Northern Hemisphere (NH) are comprehensively studied through lag correlation analysis. On this basis the relationships between the SSTA WWR and the WWR of the atmospheric circulation anomalies, El Niño–Southern Oscillation (ENSO), and SSTA interdecadal variability are also investigated.

Results show that the SSTA WWR occurs over most parts of the North Pacific and Atlantic Oceans, but the spatiotemporal distributions of the SSTA WWR are distinctly different in these two oceans. Analyses indicate that the spatiotemporal distribution of the SSTA WWR in the North Atlantic Ocean is consistent with the spatial distribution of the seasonal cycle of its mixed layer depth (MLD), whereas that in the North Pacific Ocean, particularly the recurrence timing, cannot be fully explained by the change in the MLD between winter and summer in some regions. In addition, the atmospheric circulation anomalies also exhibit the WWR at the mid–high latitude of the NH, which is mainly located in eastern Asia, the central North Pacific, and the North Atlantic. The sea level pressure anomalies (SLPA) in the central North Pacific are essential for the occurrence of the SSTA WWR in this region. Moreover, the strongest positive correlation occurs when the SLPA lead SSTA in the central North Pacific by 1 month, which suggests that the atmospheric forcing on the ocean may play a dominant role in this region. Therefore, the “reemergence mechanism” is not the only process influencing the SSTA WWR, and the WWR of the atmospheric circulation anomalies may be one of the causes of the SSTA WWR in the central North Pacific. Finally, the occurrence of the SSTA WWR in the NH is closely related to SSTA interdecadal variability in the NH, but it is linearly independent of ENSO.

1. Introduction

The atmosphere has a very short memory, whereas the huge thermal capacity in the ocean enables the sea surface temperature (SST) variation to possess obvious lag and persistence characteristics. Such persistence of the ocean stores the information of the atmospheric

circulation changes through the air–sea interaction, which may influence the atmospheric circulation and the weather conditions in subsequent seasons. Clearly, the ocean plays a very important role in the climate system. Therefore, it is important for us to investigate the nature of temporal persistence of large-scale SST anomalies (SSTA).

The SSTA persistence has the characteristics of strong seasonal dependence. Namias and Born (1970, 1974) were the first to note a tendency for midlatitudinal 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 yr. In contrast, summer SSTA decay rapidly within a couple of

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months. Moreover, they speculated such seasonal dependence of the persistence is closely tied to seasonal variation of the oceanic mixed layer depth (MLD). They hypothesized that vigorous air–sea energy exchange during winter creates temperature perturbations that extend down to the base of the deep winter mixed layer. When the mixed layer shoals in late spring, the winter thermal anomalies become sequestered beneath the shallow summer mixed layer. As the mixed layer deepens again in late fall and early winter, a portion of the subsurface thermal anomalies may become reentrained into the mixed layer, thus influencing the SST in the following winter. 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, including Alexander and Penland (1996), Alexander et al. (1999, 2001), Bhatt et al. (1998), Watanabe and Kimoto (2000), Kushnir et al. (2002), Timlin et al. (2002), de Coëtlogon and Frankignoul (2003), and Deser et al. (2003), have confirmed the strong seasonal dependence of the persistence characteristics of large-scale SSTA patterns in both the North Atlantic and North Pacific and have shown that this reemergence mechanism occurs across much of the two basins. Hanawa and Sugimoto (2004) detected seven recurrence areas in the world’s oceans and pointed out that all of these areas correspond to the regions where mode waters are formed in winter.

These previous studies focused only on one type of winter-to-winter recurrence (WWR), a “collocated” recurrence, because the recurrence area is the same where the winter SSTA is set in previous winter. Sugimoto and Hanawa (2005a), on the other hand, discovered the existence of “remote” recurrence in the North Pacific, where the recurrence area is situated at a different location from where the winter SSTA are set in the previous winter as a result of water movement. For the Atlantic, de Coëtlogon and Frankignoul (2003) showed that the recurrence also occurs in the area along the Gulf Stream path, away from the area where water with SSTA in winter originates.

Although the atmosphere response to the extratropical oceanic variability remains a challenging problem in climate study, Cassou et al. (2007) and Liu et al. (2007) have pointed out that the WWR of the SSTA in the North Pacific and the North Atlantic probably has a non-negligible influence on the atmospheric circulation in the extratropics using their numerical models. Therefore, a better understanding of the WWR should help to improve the seasonal and interannual predictability in the extratropics, as well as for studying the air–sea interaction in the extratropics. In addition, previous studies

(e.g., Watanabe and Kimoto 2000) regarded the reemergence mechanism as one of the physical mechanisms that SSTA can maintain on the time scales from interannual to interdecadal in the Northern Hemisphere (NH); thus, a better understanding of this mechanism should help to understand the climate change on the interannual time scale and longer.

Because previous work mainly focused on the spatial extent of the SSTA WWR, there is little research on the characteristics of the timing of recurrence. Are there spatial differences in the timing? Alexander et al. (1999) indicated that the timing of the recurrence is different in the eastern, central, and western Pacific and that geographic variability in the MLD influences the timing of the recurrence signal. However, their analysis is based on several specific locations. What are the spatiotemporal characteristics of the SSTA WWR for the whole Pacific basin? Is the North Pacific Ocean similar to the North Atlantic Ocean in this regard or not? The analyses on the recurrence timing and the spatial extent will give us more comprehensive knowledge of the spatiotemporal distribution of the SSTA WWR in the NH. Furthermore, it is necessary to revisit the relationship between the spatial difference in the recurrence timing and the seasonal cycle of the MLD for a better understanding of the reemergence mechanism and the WWR phenomenon. It is known that a better understanding of the SSTA WWR may aid in our ability to make seasonal climate predictions at the midlatitude, because the SSTA WWR in the North Pacific and North Atlantic extends the memory of winter SSTA to longer than 1 yr. Thus, improved knowledge of the geographic differences in the recurrence timing should help seasonal climate prediction for different regions in the NH.

Because all the previous studies focused on the oceanic reemergence mechanism alone, research on the relationship between the SSTA WWR in the NH and other possible factors is needed. Among the factors worthy being studied, air–sea interaction in the extratropics, especially in winter, comes first, which mainly exhibits the atmosphere tends to drive the ocean (Davis 1976, 1978; Wallace and Jiang 1987; Frankignoul et al. 1998; Zorita et al. 1992). Does the WWR also exist in the atmosphere circulation anomalies in the NH? If so, does it have a close correlation with the SSTA WWR in the NH? Second, is El Niño–Southern Oscillation (ENSO) essential for the occurrence of the SSTA WWR in the NH, because ENSO, especially the air–sea heat exchange and the atmospheric circulation response in the winter during ENSO, has a large impact? Third, what is the relationship between the SSTA WWR and the SST variability on different time scales in the NH, considering that remarkable interannual and interdecadal changes in the

NH exist (e.g., Deser and Blackmon 1993, 1995; Nakamura et al. 1997; Zhang et al. 1997)?

In summary, this study will further examine the SSTA WWR in the NH, with a focus on these questions: What are the spatiotemporal characteristics of the SSTA WWR in the NH? What is the relationship between the spatial distribution of the recurrence timing and that of the seasonal cycle of the MLD? What are the relationships between the SSTA WWR and the WWR of atmospheric circulation anomalies in the NH, ENSO, and SSTA interdecadal variability, respectively? We will only focus on the collocated recurrence in this paper, whereas the remote recurrence is our on-going research will be presented separately. We will address these questions by applying several statistical methods to a combination of ocean and atmosphere datasets. The datasets and methods used here are described in section 2, and the results are presented in section 3 and summarized and discussed in section 4.

2. Data and methodology

a. Data

The two SST datasets used are the Improved Extended Reconstruction Sea Surface Temperature (IERSST; Smith and Reynolds 2004) on $2^\circ \times 2^\circ$ grid and the Hadley Centre Sea Ice and SST (HADISST; Rayner et al. 2003) on $1^\circ \times 1^\circ$ grid during 1950–2004. Monthly subsurface temperature data are obtained from the Joint Environmental Data Analysis Center 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 $2^\circ \times 5^\circ$ latitude–longitude grid. The climatological monthly mean MLD is obtained from the *World Ocean Atlas 1994* (Monterey and Levitus 1997) on $1^\circ \times 1^\circ$ grid, where the MLD is defined as the shallowest depth where the density exceeds the surface density by 0.0125 kg m^{-3} . The atmospheric data are obtained from the National Center for the Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) for the period 1950–2004 on $2.5^\circ \times 2.5^\circ$ grid, including the heat flux data. Monthly surface wind stress is obtained from the European Center for Medium range Weather Forecasting (ECMWF) reanalysis for the period 1958–2001 (Uppala et al. 2005). The annual cycle of each variable is removed by subtracting the mean monthly value at each grid point.

b. Methodology

When studying the SSTA WWR, previous studies primarily focused on analyzing dominant patterns of SSTA based on the leading empirical orthogonal function (EOF)

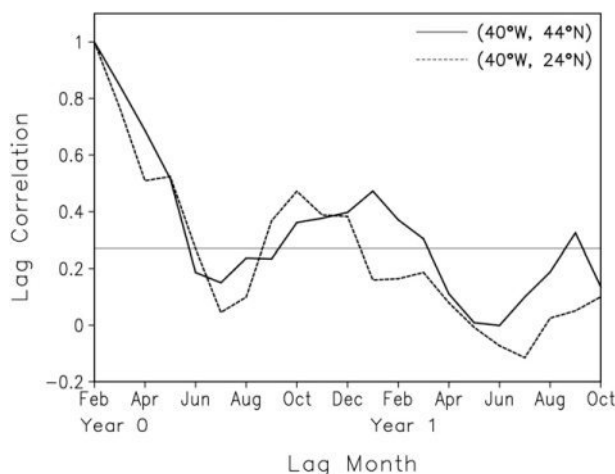


FIG. 1. Lag correlations between the SSTA in February and the SSTA from February of the current year (year 0) through October of the following year (year 1) for two locations in the North Atlantic along 40°W . The thick solid and dashed lines represent two kinds of recurrence timing, winter (January–March) and fall (October–December). The thin solid line indicates the 95% confidence level.

or on the regions designated subjectively. Timlin et al. (2002) suggested that EOF analysis is very sensitive to regional boundary, which may result in different results when selecting different areas. de Coëtlogon and Frankignoul (2003) pointed out that the recurrence depends on the position and size of the selected regions. Therefore, we need to objectively and effectively detect the WWR and its spatiotemporal distribution. In this paper, lag correlation analysis for SSTA is made directly at each grid point, which avoids the dependence of the recurrence areas on specific spatial patterns or prior selection of regions. The lag correlation is defined as the correlation of values for one starting month m (all years) with a lag month k . For example, for a starting month $m = \text{February}$ and $k = 10$, the correlation is between the February time series and the December time series. Figure 1 shows the lag correlations between monthly SSTA in February and monthly SSTA from February of the current year through October of the following year for two locations in the North Atlantic along 40°W . To efficiently detect the recurrence areas and timing, we adopt the following criteria (see Fig. 1): 1) lag correlation coefficient drops to an insignificant level prior to reaching a maximum and 2) the WWR is considered as a tendency for SSTA to recur from late winter to the following fall/winter without persisting through the intervening summer. Thus, in this study the recurrence timing (the maximum of lag correlation coefficients exceed 95% confidence level) is divided into two kinds: fall (October–December) and winter (January–March).

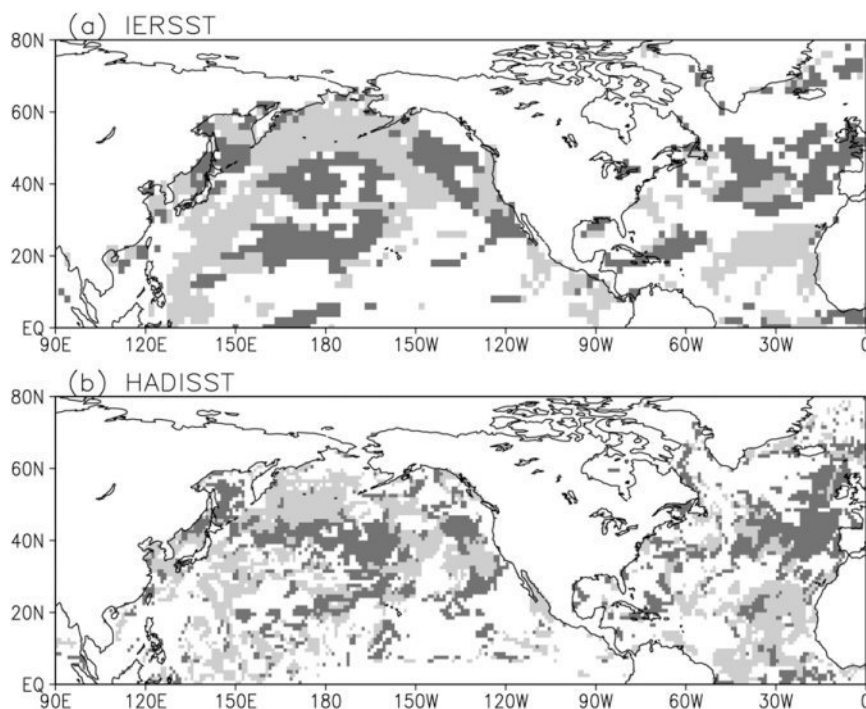


FIG. 2. Spatiotemporal distribution of the SSTA WWR in the NH for the starting month of February from (a) IERSST and (b) HADISST datasets. Dark (light) shading indicates the recurrence timing is in winter (fall).

The criteria we use here are similar to those used by Hanawa and Sugimoto (2004), but there are two differences. First, we study the SSTA WWR in the NH from a basin-wide perspective, whereas the severe criteria used by Hanawa and Sugimoto (2004) are not suitable to detect basin-wide recurrence areas. As Hanawa and Sugimoto (2004) mentioned, they set rather severe criteria; therefore, the areas detected in their study are very conservative. Second, to show the spatiotemporal characteristics of the SSTA WWR in the NH, the recurrence timing is also analyzed in our study, which is not considered by Hanawa and Sugimoto (2004).

3. Results

a. Spatiotemporal distribution of the SSTA WWR

Figure 2a shows the spatiotemporal distribution of the SSTA WWR in the NH for the starting month of February from the IERSST data. February is used as the reference month, because the spatial extents of the recurrence are the largest in February and March (figures for other starting months are not shown). Let us first see the spatial extent; the SSTA WWR in the North Pacific and the North Atlantic occurs in most parts of the basin but not in low latitude of the eastern Pacific. Second, the timing of the recurrence has obvious spatial differences.

In the North Pacific Ocean, the recurrence timing is in winter in the central, northwestern, and northeastern parts, whereas it is in fall in other regions. In the North Atlantic Ocean, the recurrence timing south of 30°N is earlier than that to the north; the south is in fall while the north is in winter. Clearly, the spatial distribution characteristics of the recurrence timing in the North Pacific are different from those in the North Atlantic.

To confirm this finding, it is necessary to use other independent data to verify the results. The results given in Fig. 2a are therefore reexamined by using the HADISST data (Fig. 2b). Comparisons of the results using the two different datasets show consistent features of the spatiotemporal distribution of the WWR. This agreement shows that these results are creditable.

Different from the method we use, some previous studies detected the SSTA WWR based on the leading EOF. Watanabe and Kimoto (2000) detected the SSTA WWR in the North Atlantic. They pointed out that the leading EOF shows a sandwich pattern, with a positive center near U.S. East Coast and two negative centers in the south of Greenland and subtropical eastern Atlantic. They found evidence for the recurrence at the two mid-latitude centers. Alexander et al. (1999) investigated the SSTA WWR in the North Pacific, also using the EOF analysis. They indicated that the leading SSTA pattern

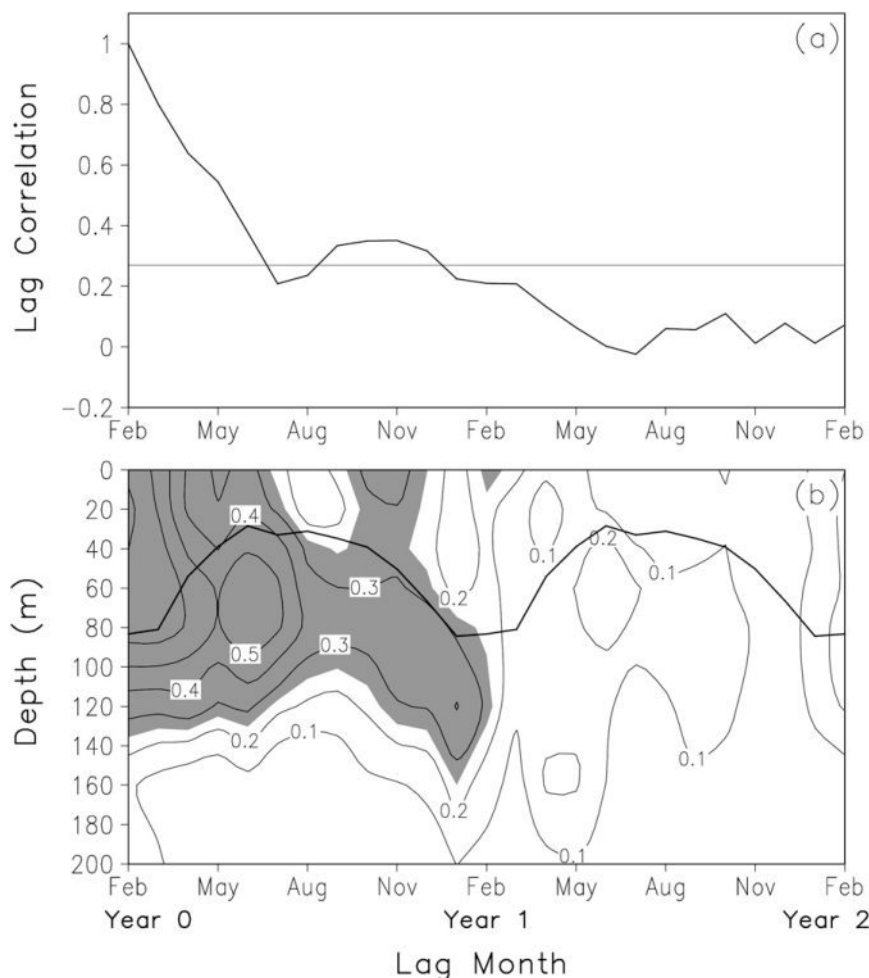


FIG. 3. (a) Lag correlation between the SSTA in February and the SSTA from February of the current year (year 0) through February of the year after next year (year 2) over the subtropics of the North Atlantic Ocean. The thin solid line indicates the 95% confidence level. (b) Lag correlation between the SSTA averaged over the subtropics of the North Atlantic Ocean in February and temperature anomalies between the surface and 200 m from the current February through February of the year after the next year. The contour interval is 0.1, and the shaded region indicates significant value at the 95% confidence level. The climatological MLD is shown by the thick solid line.

in the North Pacific during the winter, with anomalies of one sign in the central Pacific and anomalies of the opposite sign along the coast of North America, recurs in the following winter without persistence in summer. Compared with our results, it can be found that there is difference between the leading EOF pattern of SSTA and the spatiotemporal distributions of the SSTA WWR in the North Pacific and North Atlantic, which suggests that the WWR characteristics of a leading EOF pattern cannot fully represent those of SSTA at each grid point in the NH. Timlin et al. (2002) also made the same point when studying the SSTA WWR in the North Atlantic Ocean. They pointed out that the recurrence signal is not necessarily tied to a particular SSTA pattern, because it

appears in regions located in the centers of the leading EOFs and it is readily apparent in other regions. In addition, whether the SSTA WWR appears in the subtropics of the North Atlantic Ocean is still under debate. Watanabe and Kimoto (2000) found SSTA showed a sandwich pattern in the North Atlantic Ocean, and the recurrence was found at two centers but not at another center in the subtropics. Timlin et al. (2002) suggested that is because the annual cycle in MLD is small in the subtropics. However, our results show that there is a recurrence in the subtropics near 20°N and its timing is in fall. It can be clearly seen from the lag correlation of SSTA in this region (17°–30°N, 20°–50°W) that the peak of the recurrence is October–November (Fig. 3a). The

reemergence mechanism is examined here using subsurface temperature data. Figure 3b shows a depth–time diagram of lag correlation between the SSTA in February and the temperature anomalies from February to the following winter from the surface down to 300 m. It can be seen that temperature anomalies extending over the deep winter mixed layer are stored beneath the surface in summer and are reentrained into the mixed layer when it deepens again in the following winter. The maximum MLD is 80 m deep in winter, about 30–40 m deep in summer, and then again about 50 m deep in the following fall. Clearly, the reemergence mechanism also works in this region. Moreover, results are consistent with those reported by de Coëtlogon and Frankignoul (2003), although the methods of detecting the SSTA WWR are different. Just as they revealed, Watanabe and Kimoto (2000) found no recurrence at a southeastern center, because their data were mostly averaged over a region where the recurrence was not active, suggesting that the recurrence studies based on data averaged over large domains only provide a coarse picture of the geographical distribution of the recurrence phenomenon. To recap, compared with the previous results, our method used to detect the WWR has its advantage, which avoids the large influence of the EOF analysis and prior subjective selection of regions on the outcome.

As mentioned in section 2, Hanawa and Sugimoto (2004) set severe criteria to detect the recurrence areas, so the extent of their results is much smaller than that of our results, which are basin wide. Obviously, the extent of the recurrence for February in Fig. 2a includes all areas in the NH detected by Hanawa and Sugimoto (2004), including regions n-NP, n-NA, s-NP, and s-NA (see the definitions of these regions in their Fig. 1). Moreover, the timing of the recurrence is also consistent. As shown by Hanawa and Sugimoto (2004), lag correlation coefficients reach their maxima about 1 yr later in n-NP and n-NA, around 7–8 months later in s-NP and s-NA. In Fig. 2a, the recurrence timing in n-NP and n-NA is in the winter (11–13 months later), and that in s-NP and s-NA is in the fall (8–10 months later). In addition, Sugimoto and Hanawa (2005b) indicated that the formation areas of the North Pacific Eastern Subtropical Mode Water (24°–30°N, 130°–145°W) and the North Atlantic Madeira Mode Water (30°–38°N, 15°–25°W) do not exhibit any WWR because of vigorous salt-finger-type convection throughout the water column. It can be seen from Fig. 2a that these two small formation areas of the mode waters are basically in the nonrecurrence areas. In fact, the largest area of nonrecurrence in Fig. 2 is the eastern Pacific (0°–20°N, 110°–160°W), which includes the ENSO region.

b. Seasonal cycle of the MLD

Alexander et al. (1999) showed that the timing of the recurrence can differ considerably from one region to the next in the North Pacific Ocean because of difference in the MLD. To advance their analysis that is only based on several specific regions in the North Pacific, we perform a basin-wide analysis for the NH. Figure 4a shows the differences in the climatological MLD between February and September. In the North Atlantic Ocean, the difference of the MLD north of 30°N is larger than that to the south; in the North Pacific Ocean, the difference of the MLD is larger in the central Pacific near 40°N and small in other regions. Figure 4b shows the distributions of the maximum MLD in winter (February). Obviously, the spatial distribution of the difference in the climatological MLD between February and September in the NH (Fig. 4a) are basically consistent with the distribution of the maximum MLD in February (Fig. 4b).

In the North Atlantic Ocean, the difference of the MLD north of 30°N is larger than that to the south, which accords with the spatiotemporal distribution of the SSTA WWR. In other words, the recurrence timing is late north of 30°N and early south of 30°N. In the North Pacific Ocean, the spatial differences in the recurrence timing over the western and central Pacific north of 30°N are basically consistent with those in the seasonal cycle of the MLD: namely, the larger the difference in the MLD between summer and winter, the later the recurrence appears and vice versa. They are, however, not consistent over the northeastern North Pacific (NENP; 40°–50°N, 130°–150°W) and the central North Pacific (CNP1; 20°–30°N, 160°E–160°W). The differences in the MLD between February and September in these two regions are small, but the timing of the SSTA recurrence is late. To show the results more clearly, the comparison is made among the NENP, CNP1, and their two adjacent regions (35°–43°N, 140°–152°W and 30°–40°N, 150°–165°E), through the averaged lag correlation of the SSTA and the seasonal cycle of the MLD. For the NENP, its difference in the MLD between winter and summer is the same as that of its adjacent region (Fig. 5a), whereas its recurrence timing is 3 months later than that of its adjacent region (Fig. 5b). For the CNP1, its MLD difference is much smaller than that of its adjacent region (Fig. 5d), whereas its recurrence timing is 1 month later than that of its adjacent region (Fig. 5e). The results suggest that in some regions the spatial differences of the recurrence timing cannot be completely explained by the spatial distribution of the difference in the MLD between winter and summer; thus, there must be other factors influencing this process. This does not mean that the reemergence mechanism

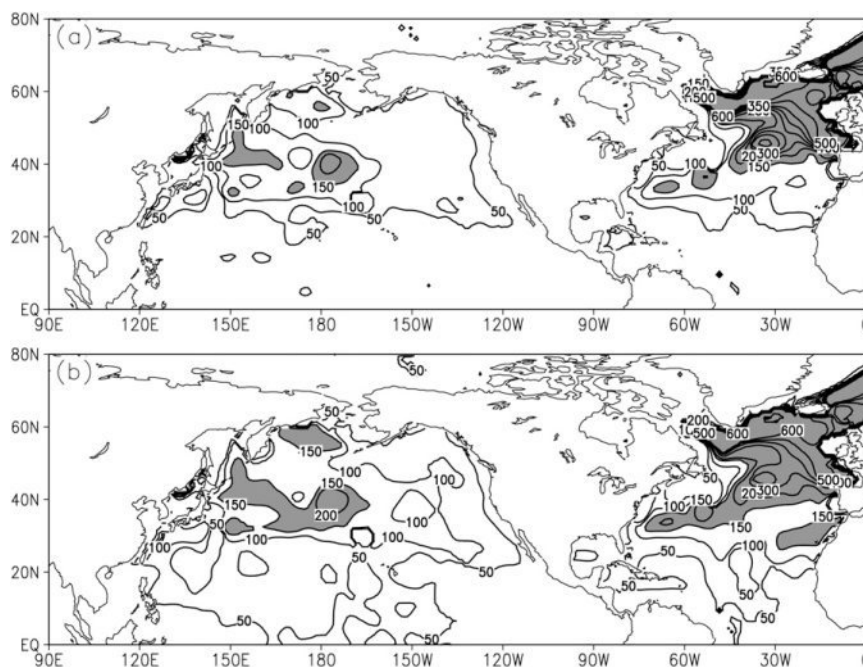


FIG. 4. (a) Climatological MLD differences in the NH between February and September. (b) Climatological MLD in February. The contour interval is 50 m with shading indicating MLD differences >150 m.

does not work in these regions. Figures 5c,f are depth–time diagrams of lag correlation between the SSTa in NENP and CNP1 in February with temperature anomalies from February to the following winter from the surface down to 300 m. They show that temperature anomalies extending over the deep winter mixed layer are stored beneath the surface in summer and are reentrained into the mixed layer when it deepens again in the following winter. The seasonal cycle of the MLD and the subsurface temperature anomalies in Figs. 5c,f suggest that the reemergence mechanism can contribute to the SSTA WWR. Therefore, these results indicate that in some regions the spatial differences of the recurrence timing cannot be completely explained by spatial distributions of difference in the MLD between winter and summer, although the reemergence mechanism does work there.

c. WWR in the atmospheric circulation anomalies

At midlatitude, departure in the SST from monthly and seasonal means strongly depends on local air–sea interaction. The lag correlation analyses indicate that in the extratropics the atmosphere tends to drive the ocean, especially in winter (Davis 1976, 1978; Wallace and Jiang 1987; Zorita et al. 1992; Frankignoul et al. 1998). Anomalous atmospheric forcing can induce SSTA through wind-driven vertical and horizontal motions, surface heat flux, diffusion, and vertical mixing. The SSTA may feed

back to the atmosphere, although there is strong evidence that at midlatitude the atmosphere forces the ocean. We have known that the SSTA WWR exist in the NH, but how about the atmosphere? Although observational and modeling studies (Namias 1986; Namias et al. 1988; Ting and Lau 1993; Graham et al. 1994; Lau 1997) have provided some evidence for the WWR of the atmospheric circulation anomalies, there is little research on the spatiotemporal characteristics of the WWR in the atmosphere. In this section, we therefore analyze the WWR of the atmospheric circulation anomalies in the NH and discuss its relationship with the SSTA WWR.

Figure 6a shows the spatiotemporal distribution of the WWR of sea level pressure anomalies (SLPA) in February. Obviously, the WWR is mainly located in eastern Asia, the central North Pacific, and the North Atlantic in the mid–high latitude. Moreover, it also appears in geopotential height anomalies at 500 and 200 hPa (Figs. 6b,c). Then, what is the relationship between the distribution of the SLPA WWR and the dominant mode of the variability in the atmospheric circulation of the NH? An EOF analysis is performed for SLPA in February. Figure 7 shows the first EOF mode that accounts for 34.8% of the total variance and its time coefficient. The first SLPA EOF has a north–south dipole structure in the North Atlantic, which is well known as the North Atlantic Oscillation (NAO). The North Pacific features a large pressure anomaly in the

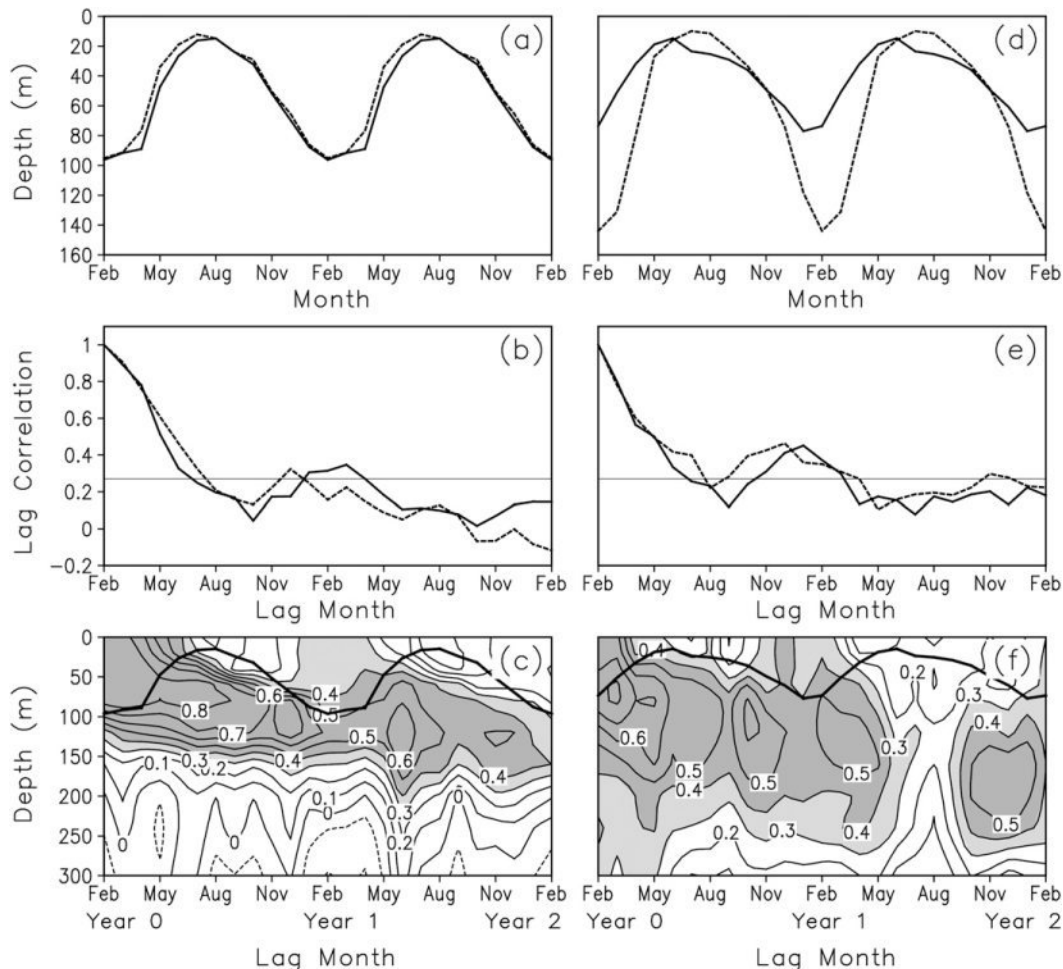


FIG. 5. (a) Seasonal variation of the MLD averaged in the NENP region (thick solid line) and its adjacent region (dashed line). (b) As in Fig. 3a, but for the SSTA averaged over the NENP region (thick solid line) and its adjacent region (dashed line). (c) As in Fig. 3b, but for the NENP region. (d),(e) As in (a),(b), but for the CNP1 region (thick solid line) and its adjacent region (dashed line). (f) As in (c), but for the CNP1 region.

central North Pacific. Compared with the distribution of the SLPA WWR in the NH, the recurrence regions are not at the action centers of the leading EOF pattern. This suggests that the spatial pattern of the SLPA WWR is different from the leading EOF of the SLPA over the NH, which is similar to SSTA result.

We have shown that the WWR of the atmosphere circulation anomalies is mainly located in eastern Asia, the central North Pacific, and the region near Newfoundland in the North Atlantic in the mid-high latitude. To examine their relationship to the SSTA, we set the three key areas in Fig. 6a as follows: EA (45° – 60° N, 110° – 135° E), the central North Pacific between 40° and 50° N (CNP2; 40° – 50° N, 170° E– 170° W) and the NA (45° – 55° N, 55° – 75° W). Figure 8 shows the correlations between the SLPA in the three recurrence areas and the SSTA in the NH in February. As shown in Figs. 8a,b, the

SLPA in the EA and CNP2 are both notably correlated with the North Pacific SSTA. The SLPA in the EA is significantly correlated with the SSTA in the western, central, and northeastern North Pacific. The SLPA in CNP2 is significantly correlated with the SSTA in the central and eastern North Pacific. Moreover, these significantly correlated regions in the ocean are where the SSTA display WWR (as shown in Fig. 2a). This also suggests, to a certain extent, that the air–sea WWR in these regions may be closely correlated. There is no remarkable correlation between the SLPA of the recurrence key area near Newfoundland and the North Atlantic SSTA (Fig. 8c), which indicates that the relationship between the WWR of the atmospheric circulation in this region and the SSTA of the North Atlantic may be not marked. Subsequently, we will mainly analyze the North Pacific.

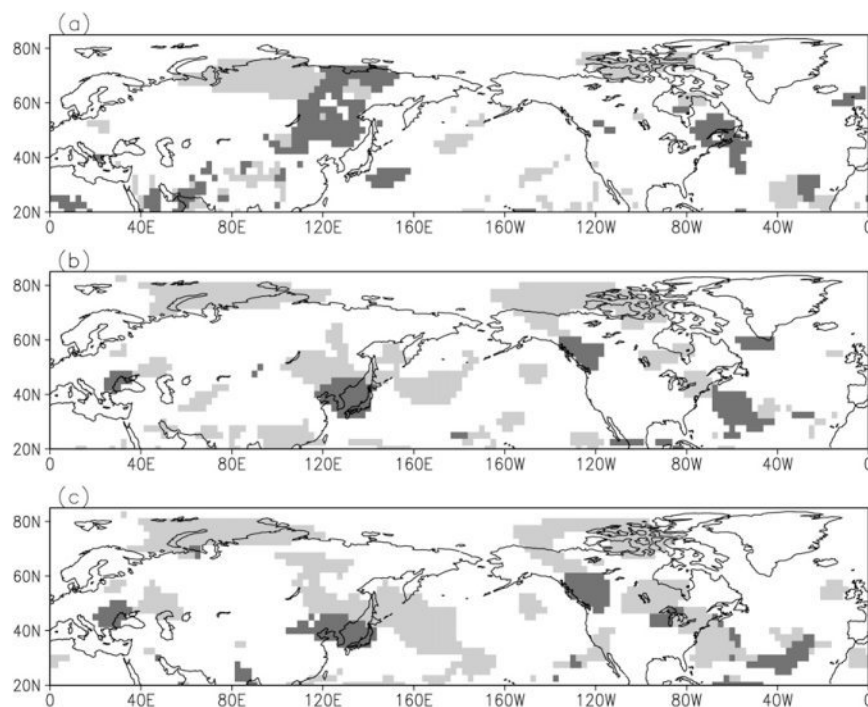


FIG. 6. Spatiotemporal distribution of the WWR of several atmospheric variables in the NH in February: (a) SLPA, (b) 500-hPa geopotential height anomalies, and (c) 200-hPa geopotential height anomalies. Dark (light) shading indicates the recurrence timing is winter (fall).

It has been shown that the SLPA in the EA and CNP2 regions are both significantly correlated with the SSTA in the North Pacific Ocean, and the SSTA in the significantly correlated regions also display the WWR. Then,

are the SLPA in the EA and CNP2 regions essential for the occurrence of the SSTA WWR in the NH? To answer this question, we perform a linear regression analysis.

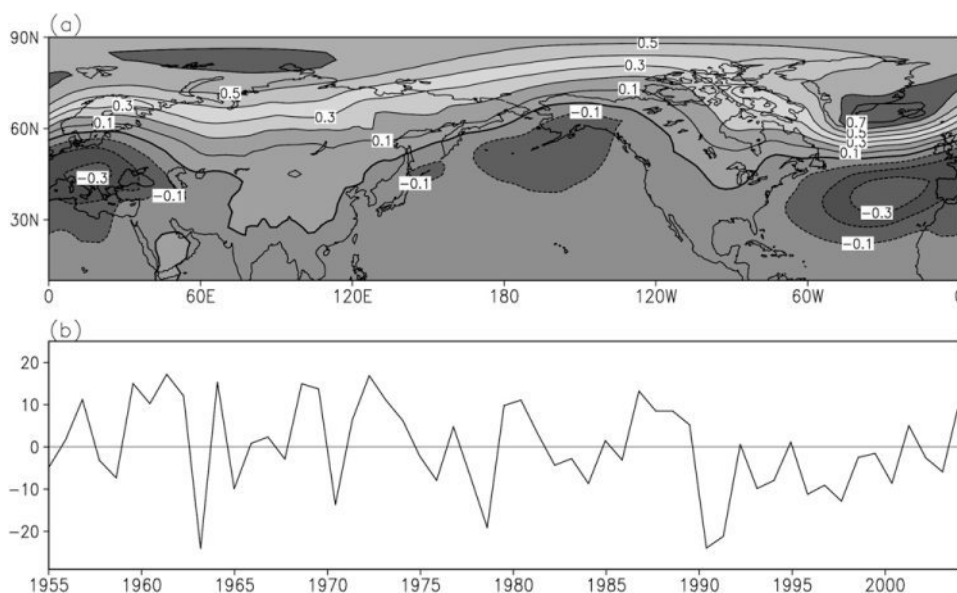


FIG. 7. (a) Leading EOF of the SLPA in February and (b) the associated time coefficient.

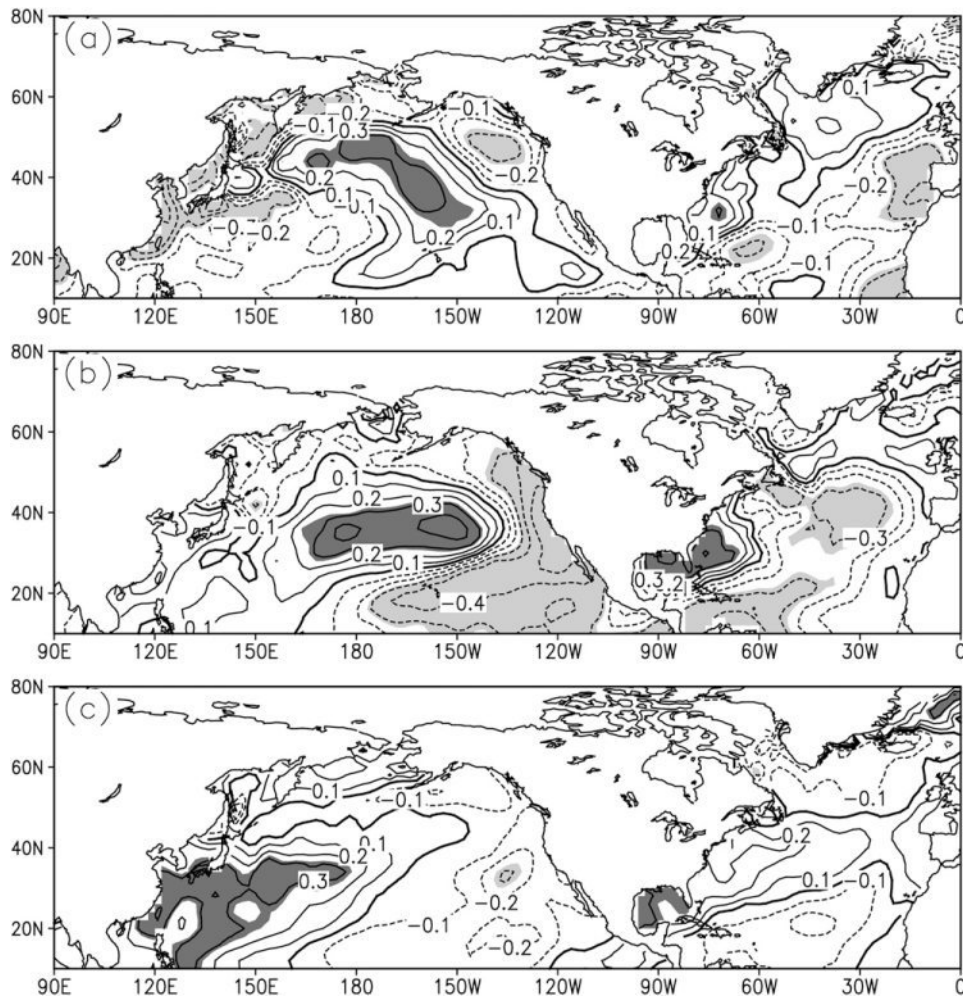


FIG. 8. (a) Correlation coefficient between the SLPA in EA and the SSTA in the NH in February. (b) Correlation coefficient between the SLPA in the CNP2 and the SSTA in the NH in February. (c) Correlation coefficient between the SLPA in NA and the SSTA in the NH in February. The counter interval is 0.1, and light (dark) shading indicates negative (positive) correlation coefficient values with a confidence level $>95\%$.

Let two time series be x_i and y_i , and $i = 1, \dots, n$. Remove the influence of the variable x_i from the variable y_i by

$$ry_i = y_i - r \times \left[\frac{\sigma(y)}{\sigma(x)} \right] \times x_i, \quad (1)$$

where $\sigma(x)$ and $\sigma(y)$ represent the standard deviation of x_i and y_i , respectively, and r is the correlation coefficient between x_i and y_i . The variability associated with x_i is obtained by regressing y_i upon x_i . The “residual value” ry_i , from which the variability associated with x_i has been removed, is obtained by subtracting the regression value from the original y_i .

Here, the influence of the SLPA in the CNP2 and EA are removed from the SSTA at each point in the North

Pacific Ocean using Eq. (1). Figure 9 shows the spatio-temporal characteristics of the SSTA WWR after removing the influence of the atmospheric signals in the CNP2 and EA. For the EA (Fig. 9a), the SSTA in the North Pacific exhibits the same features of the WWR as in Fig. 2a. For the CNP2 (Fig. 9b), the characteristics of SSTA WWR change significantly in the central North Pacific compared with the original results in Fig. 2a. The SSTA in the central North Pacific near 40°N does not show the WWR after removing the atmospheric signal in the CNP2. These results indicate that the SLPA in CNP2 are essential for the SSTA WWR in the central North Pacific to occur, whereas the SLPA in EA have no influence on the occurrence of the SSTA WWR in the North Pacific, although the SLPA in EA are significantly correlated with the SSTA in the North Pacific.

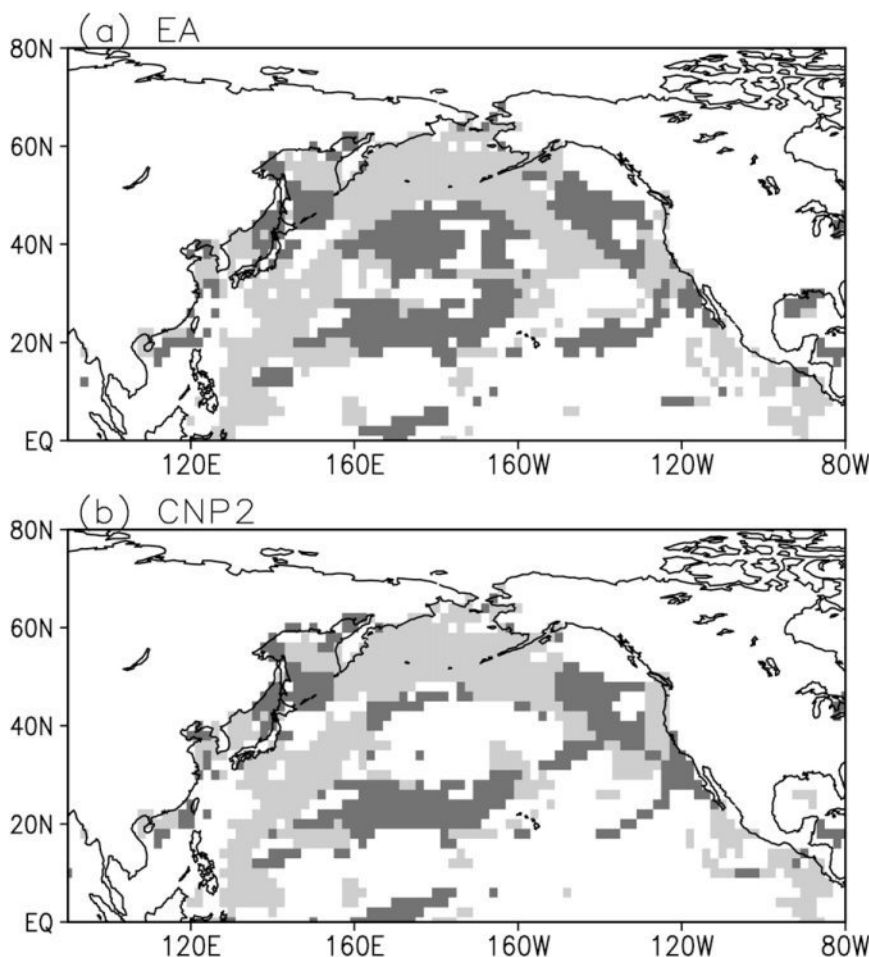


FIG. 9. Spatiotemporal distribution of the SSTA WWR in the North Pacific for February as the starting month for the residual field obtained by subtracting (a) “EA SLPA-related field” and (b) “CNP2 SLPA-related field” from the original data. Dark (light) shading indicates the recurrence timing is in winter (fall).

For the central North Pacific, the lead-lag correlation between the SLPA in CNP2 and the SSTA in the central North Pacific near 40°N (35°–47°N, 165°E–160°W) is given in Fig. 10. The results show that the strongest positive correlations occur when the SLPA in CNP2 lead the SSTA in the central North Pacific near 40°N by 1 month, which indicates that the atmospheric forcing on the ocean may play a dominant role in this region, consistent with the results of numerous previous studies (e.g., Frankignoul and Hasselmann 1977; Davis 1976; Cayan 1992; Deser and Timlin 1997). If the WWR exists in the atmosphere and tends to drive the ocean, the anomalies of the atmospheric circulation in winter/spring would create the SSTA, and in the following fall/winter the SSTA will recur when the anomalous atmospheric circulation recur. Therefore, the reemergence mechanism is not the only process influencing the SSTA WWR, and the WWR of the atmospheric circulation anomalies may

be one of the causes of the SSTA WWR in the central North Pacific.

Given that the WWR of the atmospheric circulation in the central North Pacific can influence the SSTA WWR in this region, what processes may be involved? The extratropical SSTA are generated mainly by the atmosphere, through turbulence fluxes of moist static energy at the air–sea interface or through wind stress anomalies that cause turbulence and shallow (Ekman) currents in the upper ocean (e.g., Frankignoul and Reynolds 1983; Cayan 1992; Deser and Timlin 1997; Frankignoul et al. 1998; Seager et al. 2000, 2001; Junge and Haine 2001). Next, the WWR of the wind stress and the net heat flux is investigated. Figures 11a,b show the spatiotemporal distribution of the WWR of the zonal and meridional wind stress components in the North Pacific, respectively. The recurrence of the zonal wind stress is mainly located in the central and northeastern North Pacific,

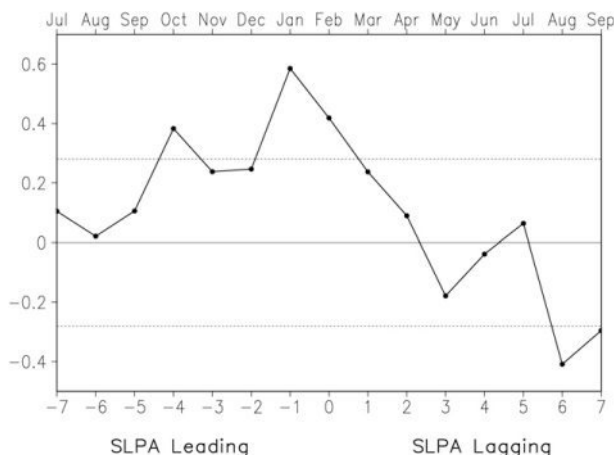


FIG. 10. Monthly lead-lag correlation between the SSTA averaged over the central North Pacific near 40°N in February and the SLPA averaged over the CNP2 from the previous June through the following September. Negative lags refer to SLPA leading SSTA. Dashed lines indicate the 95% confidence level.

whereas that of the meridional wind stress is mainly located in the central and western North Pacific. The results indicate that the atmospheric circulation in the CNP2 may influence the SSTA in the central North Pacific through both the zonal and meridional wind stress components. In addition, the dominant forcing mechanism of the winter SSTA is the net surface heat flux (Frankignoul 1985; Cayan 1992). Thus, the character of the seasonal correlation of net heat flux determines to a large extent the seasonal evolution of the SSTA. If the net heat flux is out of phase between winter/spring and the following fall/winter, the SSTA will also tend to be out of phase. To examine this possibility, we show the spatiotemporal distribution of the net surface heat flux in Figs. 11c–f. The WWR is mainly located in the western North Pacific, and there is basically no recurrence in the central North Pacific, except for the longwave radiation, which indicates that in the central North Pacific the effects of the net heat flux may be insignificant.

d. ENSO

It is well known that ENSO is the leading mode of interannual variability of the climate system, and it has a significant impact on global climate variability (e.g., Alexander et al. 2002). Thus, we need to explore the relationship between the occurrence of the SSTA WWR in the NH and the ENSO variability in the tropics. It is known that the ENSO index is significantly correlated with the SSTA outside the equatorial Pacific (not shown). Does it mean that ENSO is essential for the occurrence of the SSTA WWR in the NH? The SSTA in the North Pacific and North Atlantic oceans associated with the ENSO cycle, formed by regressing the SSTA

upon the Niño-3 SSTA time series, do not exhibit any WWR phenomena (not shown). Whereas the residual SSTA field, obtained by subtracting the regression value from the original data, exhibits the recurrence in most parts of the basin (not shown), the spatiotemporal distribution of the SSTA WWR is similar to that in the original data (Fig. 2a). This indicates that ENSO is not essential for the SSTA WWR to occur in the NH, because the SSTA WWR without any ENSO signal exists. In fact, this result is due to the persistence characteristics of the ENSO itself. As mentioned in section 3a, the eastern Pacific is the largest area of nonrecurrence of the SSTA in the Pacific Ocean (Fig. 2a). Figure 12 gives the lag correlation of the Niño-3 SST as functions of the 12 calendar months and lag months. Obviously, there is a spring persistence barrier but not any recurrence, regardless of the starting month. Why the SSTA in the ENSO region does not exhibit any WWR is not the question we investigated in this paper, whereas from Fig. 4a it can be seen that the MLD cycle in this region is much smaller than that in the mid-high latitude in the NH. Similarly, ENSO is also not essential for the WWR of the atmospheric circulation anomalies in the NH. Therefore, the WWR of the air–sea system in the NH should be inherent persistence characteristics in the extratropics and its occurrence is linearly independent of ENSO in the tropics. In the North Pacific, our result is consistent with that of Alexander et al. (2001), which also indicated that the SSTA in the tropical Pacific associated with El Niño are not essential for the WWR to occur in their numerical experiments.

e. Interannual to interdecadal variability at each grid point

A number of studies have already documented that, in the North Pacific and North Atlantic, there exists not only interannual variability but also significant interdecadal variability (Deser and Blackmon 1993, 1995; Nakamura et al. 1997; Zhang et al. 1997). Then, what is the relationship between the SSTA WWR in the NH and the interannual–interdecadal variability of the SSTA at each grid point in the NH?

The 10-yr low-pass filtered time series of the SSTA at each grid point in the NH are generated by Gaussian-type filter. Then, the low-frequency variability is subtracted from the original time series of the SSTA at each grid point. For the SSTA with periods shorter than 10 yr (Fig. 13a), the spatial extent of the NH WWR becomes smaller compared with the result of the original data (Fig. 2a), which only exists in the central North Pacific Ocean and at high latitudes of the North Pacific and North Atlantic. This indicates the SSTA WWR does not exist in some regions, after removing low-frequency variability

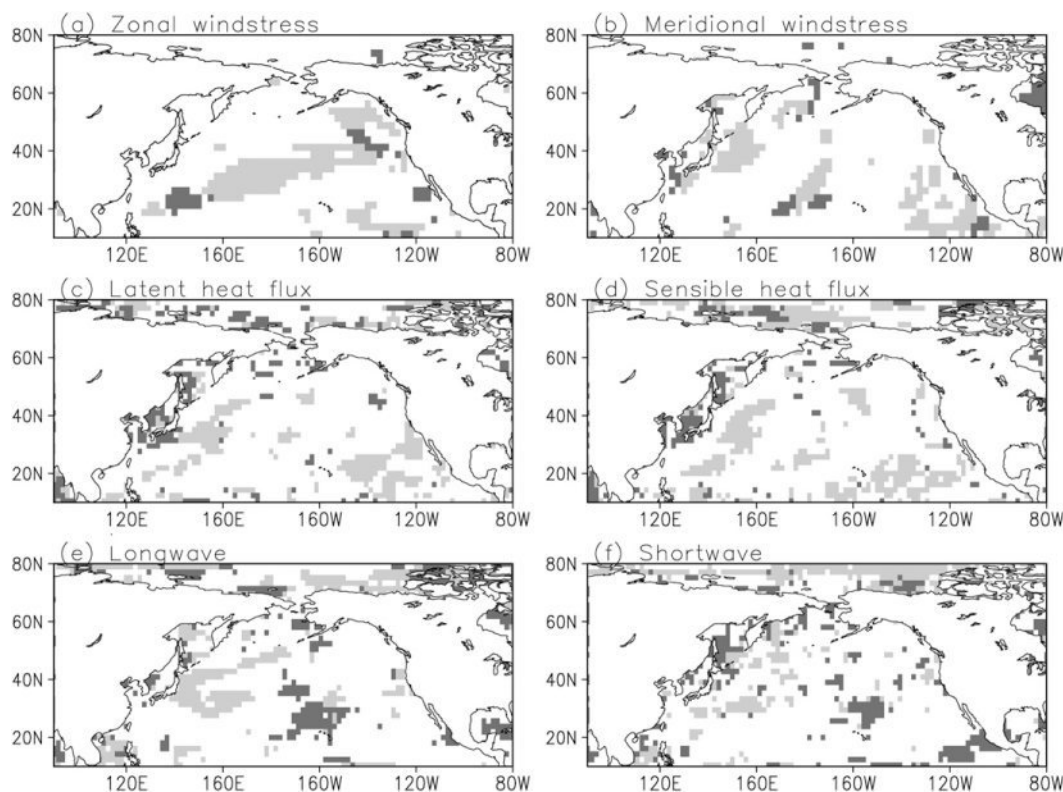


FIG. 11. Spatiotemporal distribution of the WWR of atmospheric variables for February as the starting month: (a) zonal wind stress, (b) meridional wind stress, (c) latent heat flux, (d) sensible heat flux, (e) longwave radiation, and (f) shortwave radiation. Dark (light) shading indicates the recurrence timing is winter (fall).

(10 yr and longer) of the SSTA at each grid point. However, the spatial extent of the SSTA WWR obviously increases in both the North Pacific and North Atlantic when adding the SSTA variability of 10–20 yr (Fig. 13b). When adding longer variability of the SSTA (Fig. 13c), the spatiotemporal structure of the WWR does not show obvious differences when compared with that in Fig. 13b. These results suggest that, in addition to the interannual variability of the SSTA, the SSTA WWR is also closely associated with interdecadal variability of SSTA at each grid point in the NH, especially with the period of 10–20 yr. Many studies also revealed that the interdecadal variability of the North Pacific Ocean is active over two periods of ~ 20 and ~ 50 yr (e.g., Minobe 1997, 1999). We reexamined the result using a Lanczos filter (not shown), and the spatiotemporal distribution of the SSTA WWR in the NH is consistent with that using the Gaussian filter, confirming that this result does not depend on the filter type.

In addition, it is well known that a significant interdecadal climatic regime shift occurred in the North Pacific in 1976/77 (e.g., Miller et al. 1994; Xiao and Li 2007). Figure 14 gives the spatiotemporal distribution of the WWR over the periods before and after the 1976/77

regime shift. In the North Pacific Ocean, the spatial extent of the recurrence after 1976 is larger than that before 1976, and their main difference exists in the central and eastern North Pacific. This indicates that, with the interdecadal abrupt change of the SST around 1976/77, there was a notable transition in the characteristics of the SSTA WWR in the North Pacific during the mid-1970s. Xiao and Li (2007) pointed out that the interdecadal abrupt change of the SST around 1976/77 mainly existed in the central North Pacific and along the west coast of North America. The winter SST in the central North Pacific dropped distinctly and the opposite trend occurred along the west coast of North America (e.g., Zhang et al. 1997). It means that, with the persistent cooling (warming) condition over the central (eastern) North Pacific after 1976, the spatial extent of the SSTA WWR in these regions becomes larger, opposite to that before the mid-1970s.

f. The PDO

In the previous section, the influence of the interdecadal variability of the SSTA at each grid point in the NH on the SSTA WWR in the NH has been analyzed.

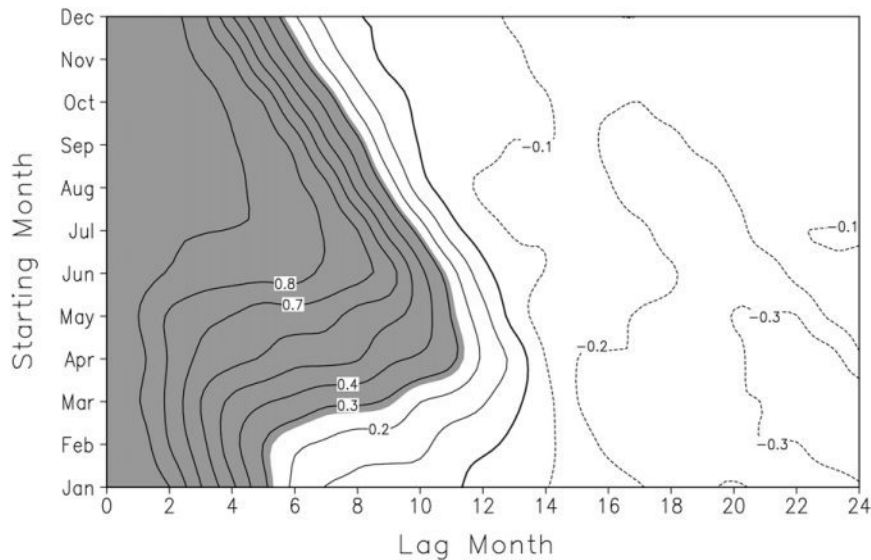


FIG. 12. Lag correlation of the Niño-3 SST time series as a function of the starting month (ordinate) and lag month (abscissa). The shaded region indicates significance at the 95% confidence level.

The leading mode with decadal time scale in the North Pacific is usually called the Pacific decadal oscillation (PDO; Mantua et al. 1997; Schneider et al. 2002; Tanimoto et al. 2003; Mochizuki and Kida 2006). We want to further investigate whether the influence of the interdecadal variability of the SSTA at each grid point on the SSTA WWR in the NH is closely associated with the PDO. The PDO index (1950–2004) we used is from the Joint Institute for the Study of Atmosphere and Ocean (JISAO) at University of Washington, which is defined as the leading principal component of North Pacific monthly SST variability (poleward of 20°N for the 1900–93 period). It can be seen from Fig. 15a that the PDO index in February also shows the WWR. However, the PDO-related SSTA field does not appear any the WWR (not shown). The residual SSTA field (Fig. 15b), which is linearly independent of the PDO cycle, does not show the basin-wide differences when compared with that of the original data (Fig. 2a). The regional differences mainly exist in the central and northeastern North Pacific. In other regions, the influence of the interdecadal variability of the SSTA on the SSTA WWR seems not to be mainly from the PDO. Is that really so?

We suspect that these results indicate two kinds of possibilities. On the one hand, the monthly PDO index includes the shorter time-scale fluctuations, which may contaminate the representation of the decadal variation (and the associated WWR) of interest. To confirm this point, we repeat the analysis after removing the shorter time-scale fluctuations (<10 yr) of the PDO index. As shown in Fig. 15c, the influence of the PDO index on the

SSTA WWR still mainly exists in the central and northeastern North Pacific, whereas compared with that of Fig. 15b the spatial extent of the no recurrence becomes larger in these two regions after removing the shorter time-scale fluctuations of the PDO index. On the other hand, as we pointed out in section 3a, there is a difference between the leading EOF pattern of the SSTA and the spatiotemporal distribution of the SSTA WWR in the North Pacific and North Atlantic, which suggests that the WWR characteristics of a leading EOF pattern cannot fully represent the SSTA WWR at each grid point in the NH. Moreover, the interdecadal variability of the SSTA in some regions may not be synchronized with that of the PDO index. Thus, the influence of the interdecadal variability of the SSTA on the SSTA WWR in some regions in the NH maybe result from the influence of other factors of interdecadal variability but not that of the PDO; for example, another dominant decadal-time-scale SST pattern is in the Kuroshio–Oyashio Extension region (Nakamura et al. 1997; Miller and Schneider 2000), or the interdecadal variability influences the SSTA WWR mainly through the forcing of the ocean subsurface temperature variability (Möller et al. 2008). It remains an open question and needs further investigation.

4. Summary and discussion

The spatiotemporal characteristics of the SSTA WWR in the NH are comprehensively studied through the lag correlation analysis, including the relationships between the SSTA WWR and the WWR of the atmospheric

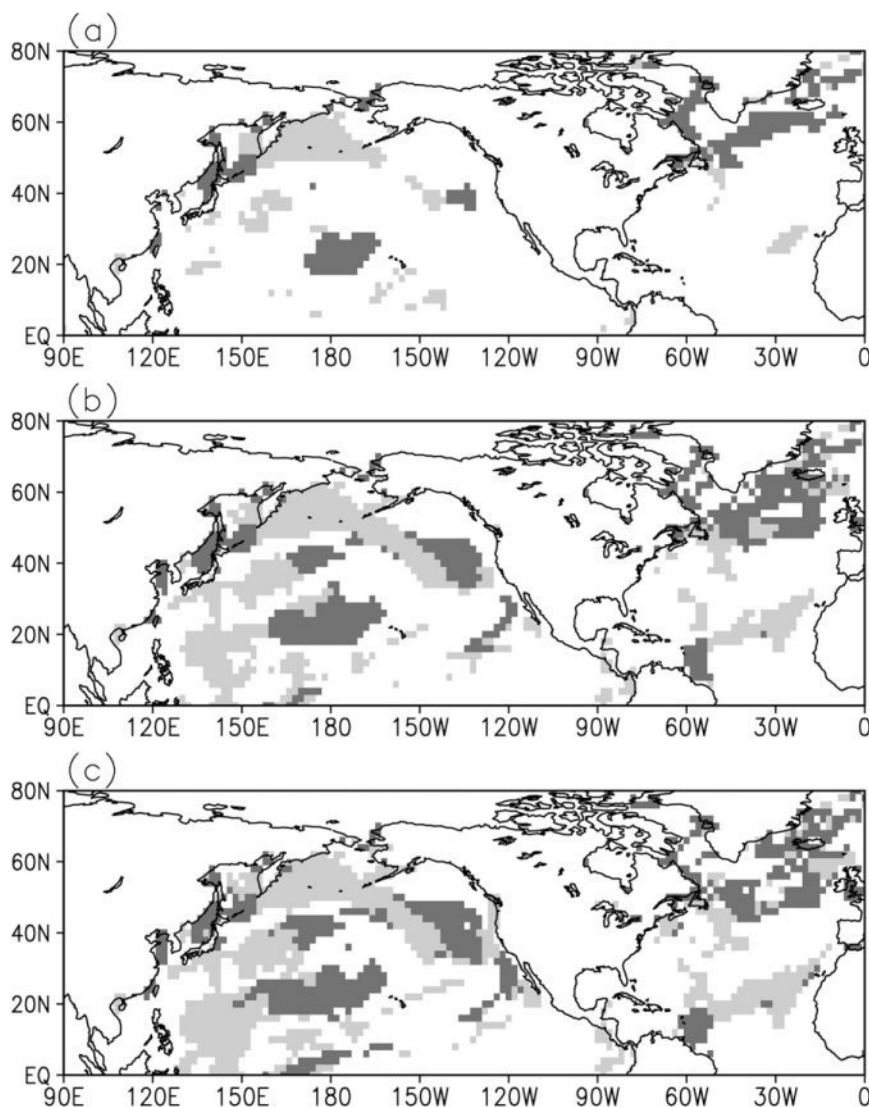


FIG. 13. Spatiotemporal distribution of the SSTA WWR for February as the starting month from (a) 10-, (b) 20-, and (c) 30-yr high-pass filtered data. Dark (light) shading indicates the recurrence timing is in winter (fall).

circulation anomalies, ENSO, and SSTA interdecadal variability in the NH. The SSTA WWR in the North Pacific and North Atlantic both occur in most parts of the basin, but they have completely different spatiotemporal distributions. In the North Pacific Ocean, the recurrence timing in the central, northwestern, and northeastern parts is in winter (late), and that in other regions is in fall (early). In contrast, the recurrence timing north of 30°N in the North Atlantic Ocean is in winter, which is later than that to the south. Further analyses show that in the North Atlantic Ocean the spatiotemporal distribution of the WWR is consistent with the spatial distribution of the seasonal cycle of the MLD: namely, deep in the north and shallow in the

south. In contrast, the spatial difference of the seasonal cycle of the MLD in the North Pacific Ocean is not completely coincident with that of the recurrence timing. In some regions, the difference in the climatological MLD between winter and summer is smaller but the timing of the WWR is later compared with their adjacent regions, although the reemergence mechanism still works there. This indicates the spatial difference of the recurrence timing cannot be completely explained by the spatial distribution of the difference in the MLD between winter and summer in these regions.

We also analyze the WWR of the atmospheric circulation anomalies in the NH. The results indicate that the main recurrence areas of the atmospheric circulation

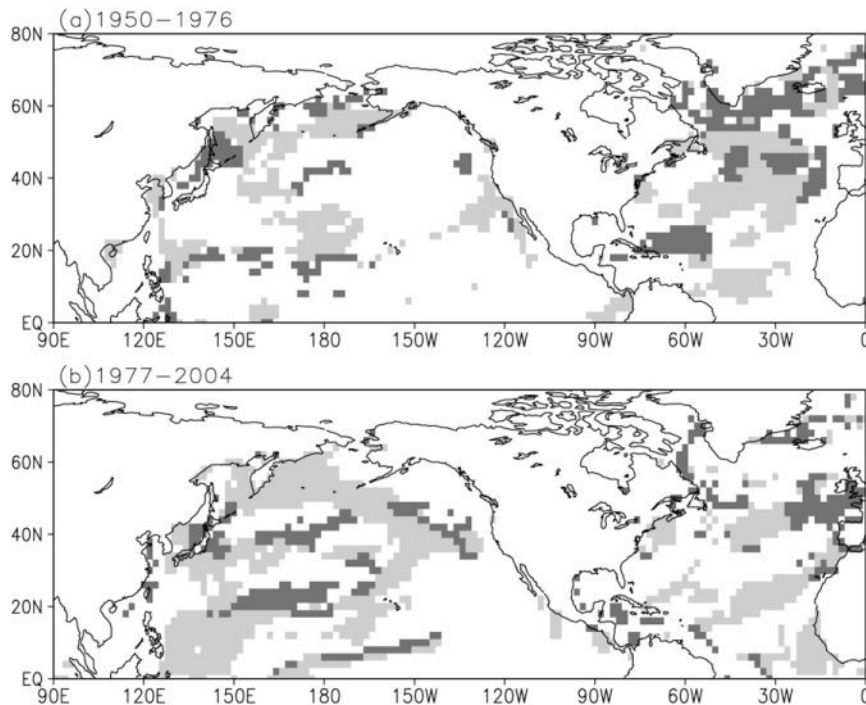


FIG. 14. Spatiotemporal distribution of the SSTA WWR for February as the starting month for (a) 1950–76 and (b) 1977–2004. Dark (light) shading indicates the recurrence timing is in winter (fall).

anomalies are in eastern Asia, the central North Pacific, and the North Atlantic at mid–high latitude. Further analyses show that the SLPA in the central North Pacific, which is one of the key areas of the WWR of the atmospheric circulation anomalies, is significantly correlated with the SSTA in the North Pacific Ocean in February. The strongest positive correlations occur when the SLPA lead the SSTA in the central North Pacific by 1 month, suggesting that the atmospheric forcing on the ocean may play a dominant role in this area. Moreover, the linear regression analysis also indicates that the SLPA in the central North Pacific is essential for the occurrence of the SSTA WWR in the central North Pacific. Therefore, the reemergence mechanism is not the only process influencing the SSTA WWR, whereas the WWR of the atmospheric circulation anomalies may be one of the causes of the SSTA WWR in the central North Pacific. This relationship of the air–sea system is, however, not notable between the SLPA in the eastern Asia (the region in the North Atlantic near Newfoundland) and the SSTA in the North Pacific (the North Atlantic). In addition, it can be seen from Fig. 6a that there is a region in the subtropical Atlantic where the SLPA also show the WWR, and our analyses indicate that the atmospheric WWR might have a local influence on the occurrence of the SSTA WWR in this region (figures not shown here).

As is well known, the extratropical interaction between ocean and atmosphere is not one way. Cassou

et al. (2007) and Liu et al. (2007) investigated the atmospheric responses to the recurrence of the SSTA in the North Atlantic and North Pacific, respectively. It seems that interaction of the WWR between the ocean and the atmosphere may exist. Does it mean that the ocean–atmosphere coupling would be the origin of the WWR in the atmospheric circulation (Fig. 6a)? Although a feedback between the midlatitude SSTA and the atmosphere aloft may be important, the issue whether the atmosphere significantly responds to the midlatitude SSTA remains controversial (Saravanan 1998; Peng and Whitaker 1999, and references therein). There is strong evidence that at midlatitude the atmosphere forces the ocean, especially in winter. As claimed by Cassou et al. (2007), while addressing the question as to what extent the reemergence mechanism affects the overlying atmosphere, we have to keep in mind that the dominant source of the NAO variability is internal atmospheric dynamics. Therefore, it seems that at this stage we could not draw the conclusion that the ocean–atmosphere coupling would be at the origin of the WWR of the atmospheric circulation. This question needs more in-depth investigation. In fact, the cause of the atmosphere recurrence is an interesting question, because atmosphere has a very short memory compared with the huge thermal capacity of the ocean. Then, the atmosphere recurrence might come from the atmospheric response to the winter anomalies in other physical variables (e.g., snow cover,

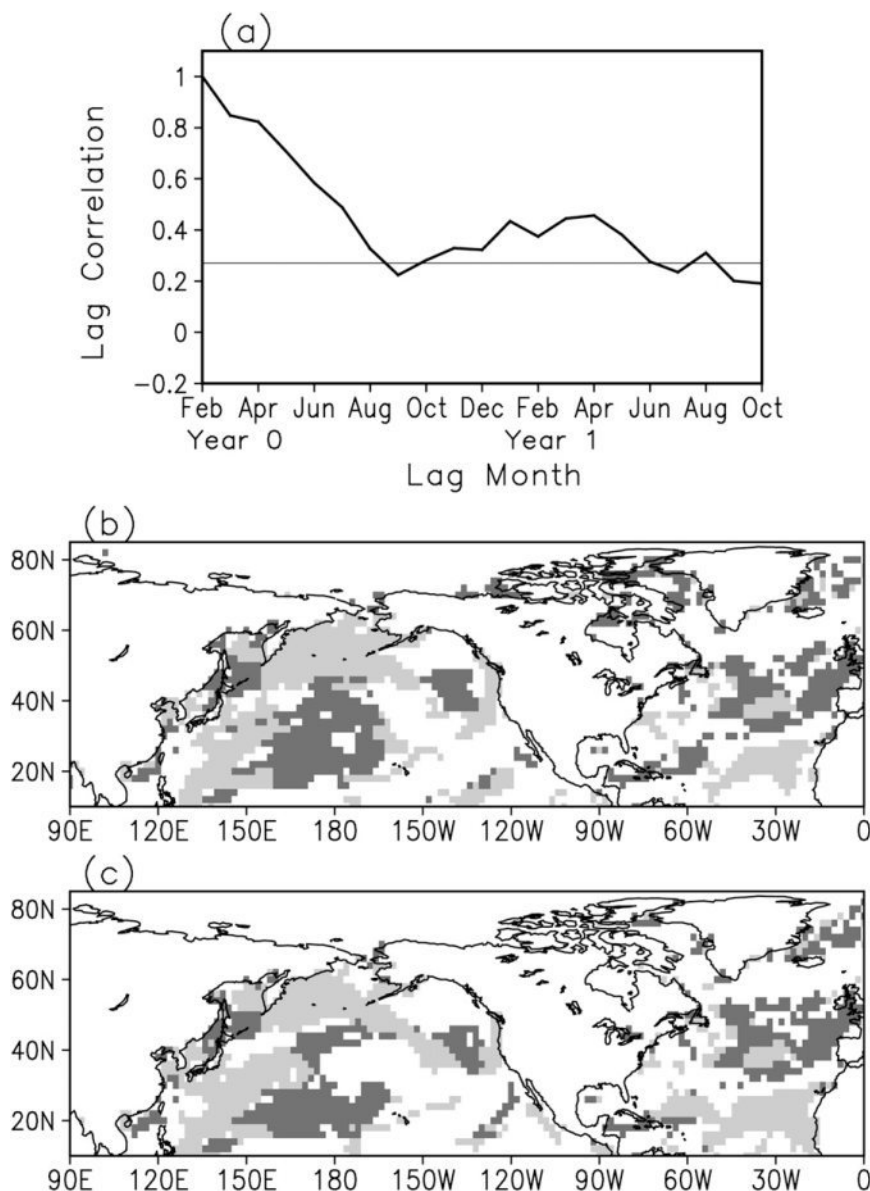


FIG. 15. (a) As in Fig. 1, but for the PDO index. The thin line indicates the 95% confidence levels. (b) The spatiotemporal distributions of the WWR of the SSTA in the NH for February as the starting month for the residual field obtained by subtracting “PDO-related field” from the original data. (c) As in (b), but the short-time-scale fluctuations (<10 yr) of the PDO index have been removed. Dark (light) shading indicates the recurrence timing is in winter (fall).

sea ice, land surface conditions, etc.). To examine these possibilities, we carry out some analyses. The preliminary results (not shown) indicate that the influences of the snow cover and the sea ice on the atmosphere recurrence are not significant. Thus, the cause of the atmosphere recurrence remains an open question and needs further study.

Similar to the SSTA WWR, the occurrence of the WWR of the atmosphere circulation in the NH is linearly independent of ENSO because of no recurrence in the ENSO index. This implies that the WWR of the air–sea

system in the NH could be an inherent persistence characteristic in the NH.

Although previous studies focus on using the winter reemergence mechanism to explain the interdecadal variability of the SSTA, it is also necessary to investigate the effect of the interdecadal variability of the SSTA on the WWR. Through filtering analysis, we find that the SSTA WWR in the NH is also closely associated with the interdecadal variability of the SSTA in addition to the interannual variability, although it is not yet clear what

physical processes may contribute to this relationship. Because the SSTA WWR is closely associated with the seasonal cycle of the MLD and the WWR of the atmospheric circulation, we ask whether the interdecadal variability of the SSTA on the SSTA WWR is through atmospheric forcing or subsurface thermal and MLD anomalies. In fact, about this point, Möller et al. (2008) is likely to provide some evidence that the interdecadal variability influences the WWR mainly through the forcing of the ocean subsurface temperature variability but not the atmospheric forcing. They illustrated that SSTA “show enhanced variance at the annual period in the extratropics ... by observations and model simulations” and that “a mechanism, related to the reemergence of winter SST anomalies, is proposed to explain the annual peak in SST spectrum.” Moreover, the results of their model experiments suggest that “the annual peak is either weak or absent if decadal SST variability is forced by local air–sea interaction. However, if ocean subsurface temperature variability forces decadal SST variability, the annual peak is much stronger.” However, to confirm this point, further investigations are needed.

Note that the results of our study do not preclude the impact of the reemergence mechanism upon the SSTA WWR in the NH. What we want to express is that there may be different ways for the SSTA to recur from one winter to the next in addition to the reemergence mechanism. Our results show that, if the anomalous atmospheric forcing is to repeat several winters in a row but remains independent in summer, this would tend to create recurring SSTA in winter. In places where there is winter-to-winter forcing of the SSTA by the atmosphere, the SSTA WWR resulting from the reemergence mechanism is likely to be amplified. In addition, dynamic oceanic processes, such as advection, slow propagation of ocean Rossby waves, subduction, diffusion, and eddy mixing, may also impact the persistence of the mixed layer temperature anomalies. Advection could shift the recurrence pattern, and subduction could weaken it. de Coëtlogon and Frankignoul (2003) and Sugimoto and Hanawa (2005a) have examined the impact of advection on the recurrence in the North Atlantic and North Pacific, respectively. In addition, the dynamical effect of ocean Rossby waves on SST has been documented extensively over the northwest Pacific along the Kuroshio Extension. Earlier work includes Qiu (2000) from observations and Xie et al. (2000) using an ocean GCM, followed up by Tomita et al. (2002) and Nonaka et al. (2006). These studies showed that ocean subsurface anomalies persist from one winter to another, not only through the one-dimensional deepening of the mixed layer during winter but also because of ocean Rossby waves. Westward propagation of these waves and the atmospheric forcing

were documented in Schneider and Miller (2001) and Taguchi et al. (2007). Hence, several factors may contribute to the SSTA WWR in the NH, and the relative influence of these factors may be different in different regions. The SSTA WWR in the NH is complex, so further quantitative assessment of the effect of each process is needed, and model simulations are very helpful for such future work.

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