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Decadal and seasonal dependence of North Pacific sea surface temperature persistence

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[1] Decadal and seasonal dependence of the persistence characteristics of area-averaged sea surface temperature (SST) anomalies in the North Pacific (150°E∼140°W, 20°N∼60°N) are investigated using two different SST data sets for the period 1948–2005. It is found that a persistence barrier exists around July–September (especially in September). This July–September persistence barrier is accompanied by a summer decline in the wind stress. The results confirm the existence of the July–September persistence barrier in the North Pacific SST discovered by Namias and Born (1970). Besides the seasonal change, North Pacific SST persistence also exhibits a pronounced decadal change. Taking all calendar months into account, North Pacific SST persistence is relatively strong from the mid-1950s to the mid-1960s but then weak from the mid-1960s to the mid-1980s, and becomes stronger again from the mid-1980s until the mid-1990s, after which it tends to become weak again. The recurrence of SST anomalies from one winter to the next is obvious from the mid-1950s to mid-1960s, but no obvious recurrence occurs after the mid-1960s. Decadal changes of the Pacific–North America (PNA) pattern, the SST-clouds feedback, and the Southern Oscillation Index (SOI) are found to be related to those of North Pacific SST persistence. The PNA index shows a significant upward trend after the 1980s. Besides, the PNA pattern also exhibits a high persistence in winter from the mid-1980s to the mid-1990s. These changes of PNA pattern are favorable to the occurrence of strong SST persistence in winter from the mid-1980s to the mid-1990s. In summer, the positive feedback between the marine boundary clouds and SST enhances the SST persistence in the North Pacific. It is found that the positive feedback between the SST and clouds in the North Pacific during summer becomes stronger from the mid-1980s to the mid-1990s, which would contribute to the longer SST persistence in summer from the mid-1980s to the mid-1990s. The SOI shows negative correlation with the North Pacific SST persistence and the PNA index, indicating the remote forcing of ENSO on the North Pacific climate change. In addition, the high north Pacific SST persistence from the mid-1980s to the mid-1990s coincides with the warm phase of the Pacific Decadal Oscillation (PDO). We concluded that the changes in the tropical SST or the PDO phase might explain the origin of decadal changes of North Pacific SST persistence.

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1. Introduction

[2] On account of the large thermal capacity of seawater and the slowly varying oceanic currents, the surface conditions of the world's oceans vary much more slowly than those of the atmosphere. Meteorologists have long agreed that the surface properties of the oceans (in particular, sea surface temperature, or SST) have great impacts on the low-frequency atmospheric changes. The influences of the ENSO-related SST anomalies on the global climate have been examined in numerous studies [e.g., *Rowntree*, 1972; *Pan and Oort*, 1983; *Ropelewski and Halpert*, 1987; *Andrade and Sellers*, 1988; *Alexander*, 1992; *Lau and Nath*, 2000; *Trenberth et al.*, 2002; *Hoerling and Kumar*, 2002]. Some studies have demonstrated the connection between SST anomalies in midlatitudes and the anomalous atmospheric circulation overlying and downstream [e.g., *Namias*, 1975; *Davis*, 1978; *Frankignoul*, 1985; *Czaja and Frankignoul*, 2002; *Liu and Wu*, 2004; *Frankignoul and Sennéchael*, 2007]. Given the importance of SST in the interaction with the atmosphere, it is of interest to investigate the temporal variations of the persistence of large-scale SST anomalies. In the present study, we will focus on studying the behavior of SST persistence in the North Pacific.

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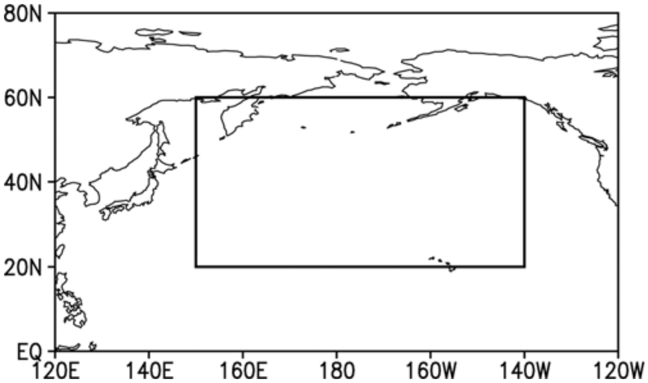

Figure 1. Rectangle shows the study area (150°E∼140°W, 20°N∼60°N).

[3] Large-scale SST persistence in the North Pacific has been examined in previous studies, including *Namias and Born* [1970, 1974], *Reynolds* [1978], *Namias et al.* [1988], and *Deser et al.* [2003]. These studies indicated that North Pacific monthly SST anomalies often last more than 5 months. However, as recognized by *Namias and Born* [1970, 1974], the persistence of North Pacific SST anomalies is seasonally dependent, which is greatest in winter and lowest in summer. The SST anomalies in the North Pacific can recur from one winter to the next without persisting through the intervening summer, effectively extending the memory of winter SST anomalies to longer than 1 year. In contrast, the summer SST anomalies in the North Pacific decay rapidly, within a couple of months. Recently, the strong seasonal dependence of the persistence characteristics of SST anomalies in the North Pacific has been confirmed by *An and Wang* [2005], who found that North Pacific SST anomalies display a persistence barrier during August–September.

[4] Recent observational studies reveal that the North Pacific ocean-atmosphere system displays substantial variability from interannual to interdecadal timescales [*Trenberth*, 1990; *Latif and Barnett*, 1994; *Trenberth and Hurrell*, 1994]. Long period variations in the persistence of North Pacific SST patterns have also been examined and noticed by *Namias et al.* [1988], who found that North Pacific January SST persistence has undergone substantial multiyear variability and has increased significantly from 1950 to 1984. However, more than 20 years have passed since then and some changes of North Pacific SST persistence could happen during the past 20 years. In addition, decadal changes of North Pacific SST persistence in other calendar months except January might be different from those in January. Therefore, it is necessary to investigate again the decadal changes of North Pacific SST persistence for all calendar months using a longer time series of SST data. The objective of this study is to analyze observation and reanalysis data available from the past 58 years (1948–2005) to determine the decadal changes of North Pacific SST persistence. Different from pattern correlations adopted by *Namias et al.* [1988], the lagged correlation [*Ding et al.*, 2008] based on the area-averaged SST anomalies over the North Pacific basin (150°E∼140°W, 20°N∼60°N) (Figure 1) is used to measure the skill of North Pacific SST persistence. *Namias and Born* [1974] showed that temporal coherence between monthly mean area-averaged SST anomalies over the North Pacific is appreciably greater than pattern coherence. Therefore, it is more applicable to determine the changes of North Pacific SST persistence on the basis of the lagged correlation of area-averaged SST anomalies instead of pattern correlations.

[5] This paper is arranged as follow. Section 2 describes the data and analysis methods. Section 3 illustrates the seasonal dependence of North Pacific SST persistence. Section 4 presents the decadal variations in the North Pacific SST persistence. Section 5 links the decadal changes of the SST persistence to the changes in the atmospheric and oceanic states over the North Pacific and tropical Pacific. Finally, section 6 provides a summary and concluding remark.

2. Data and Methodology

[6] The basic SST data set used in this study is the version 2 of monthly NOAA Extended Reconstructed SST (ERSST) data at 2° × 2° spatial grid for the period 1854–2005. The Hadley Center Sea Ice and SST data set (HadISST) at 1° × 1° spatial grid for the period 1870–2005 is also used to verify results from ERSST. For the analysis of atmospheric circulation, the 2.5° × 2.5° NCEP/NCAR reanalysis data (1948–2005), the monthly Pacific–North America (PNA) index and Southern Oscillation Index (SOI) (1948–2005) from the Climate Prediction Center (CPC) are used. In addition, the monthly ocean mixed layer depth (1955–2003) from the National Oceanographic Data Center (NODC) and the monthly low cloud cover (1958–2001) from the ERA-40 reanalysis data set are also used to explore the causes for the decadal changes of North Pacific SST persistence.

[7] Prior to the analysis, the area-averaged SST over the North Pacific basin (150°E∼140°W, 20°N∼60°N) is first obtained. Then the annual cycle and linear trend are removed from the area-averaged SST time series to obtain the monthly North Pacific SST anomalies. Lagged correlation analysis is used to measure the persistence of North Pacific SST anomalies, which is defined as the correlation between the time series of the starting calendar month (January–December) and the time series of a succeeding lag month in a given length of period. The persistence time (in unit of months) is determined as the number of months for which correlation coefficient drops to 0.6 for all calendar months. The value of 0.6 is subjectively chosen to characterize the persistence. The results are found not sensitive to the selection of particular value for this characterization. To examine the decadal variation of North Pacific SST persistence, we perform a moving lagged correlation analysis with time series of North Pacific SST anomalies. With this analysis, the persistence time of every calendar month are determined within a 13-year window that is shifted gradually (by 1 year) from 1948 to 2005. The time axis indicates the middle year of the 13-year moving window. As an example of moving lagged correlation analysis, the persistence of "January in year $(a + b)/2$" means the lagged correlation between Januaries and succeeding Februaries,

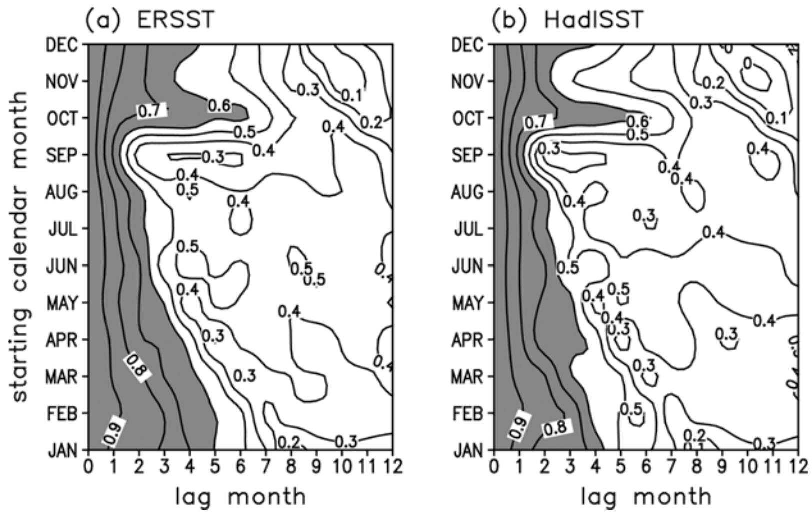

Figure 2. Lagged correlation coefficients of monthly North Pacific anomalies of (a) ERSST and (b) HadISST as a function of starting calendar month and lag time for the period 1948–2005. Shaded areas are correlations greater than 0.6.

Marches, etc until the correlation coefficient drops to 0.6 during a 13-year period from year *a* to year *b*.

3. Seasonal Dependence of North Pacific SST Persistence

[8] Figure 2a shows the lagged correlation coefficients of North Pacific SST anomalies from ERSST data set for the entire analysis period 1948–2005. It is indicated that North Pacific SST anomalies have most significant persistence in January–February (the coefficients falling below 0.6 after 5 months), while they have the low persistence in July–September with the least persistence in September (the coefficients falling below 0.6 only after 1 month). From February to September, the lagged correlation coefficients show a continuous drop with a sharp drop occurring from August to September. From September to October, the coefficients show a sharp rise. This figure shows clearly the July–September persistence barrier in the North Pacific SST anomalies, which is in agreement with the studies of *Namias and Born* [1970, 1974]. The pattern of lagged correlation coefficients calculated from HadISST data set (Figure 2b) is very similar to that shown in Figure 2a.

[9] What physical processes contribute to the seasonal differences in the persistence of North Pacific SST anomalies? *Namias and Born* [1970, 1974] speculated that the seasonal evolutions of wind speed and its variability were crucial factors. It is shown in Figure 3 that 700-hPa zonal wind speed and its standard deviation are great in the winter months (December, January, February), while they are small in July–September. With the greater wind stress, the greater vertical mixing in the ocean surface layers should be expected. The upper ocean mixed layer depth in the North Pacific is observed to be thickest in winter and thinnest in summer. The thermal anomalies in the deep winter mixed layer are therefore hard to change, while the thermal anomalies in the shallow summer mixed layer tend to undergo considerable change. However, the smallest zonal wind speed occurs in August cannot give an explanation of the September minimum in the lagged correlation coeffi-

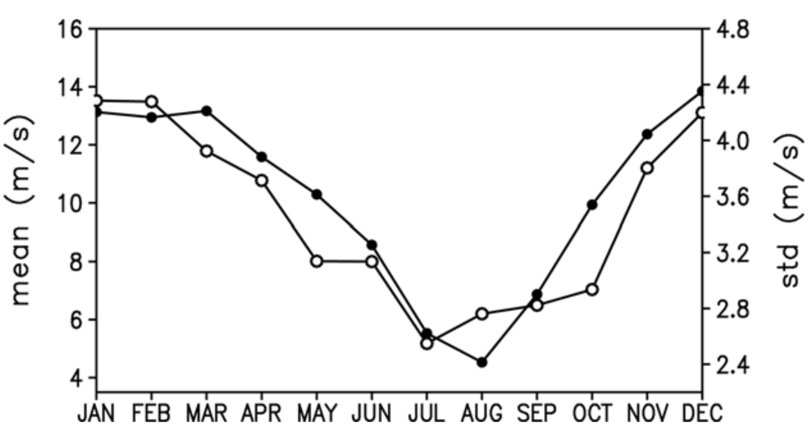

Figure 3. Annual variations of the 700-hPa zonal wind (solid circle; left *y* axis) and the standard deviation of zonal wind (open circle; right *y* axis) averaged over the North Pacific (150°E∼140°W, 30°N∼50°N).

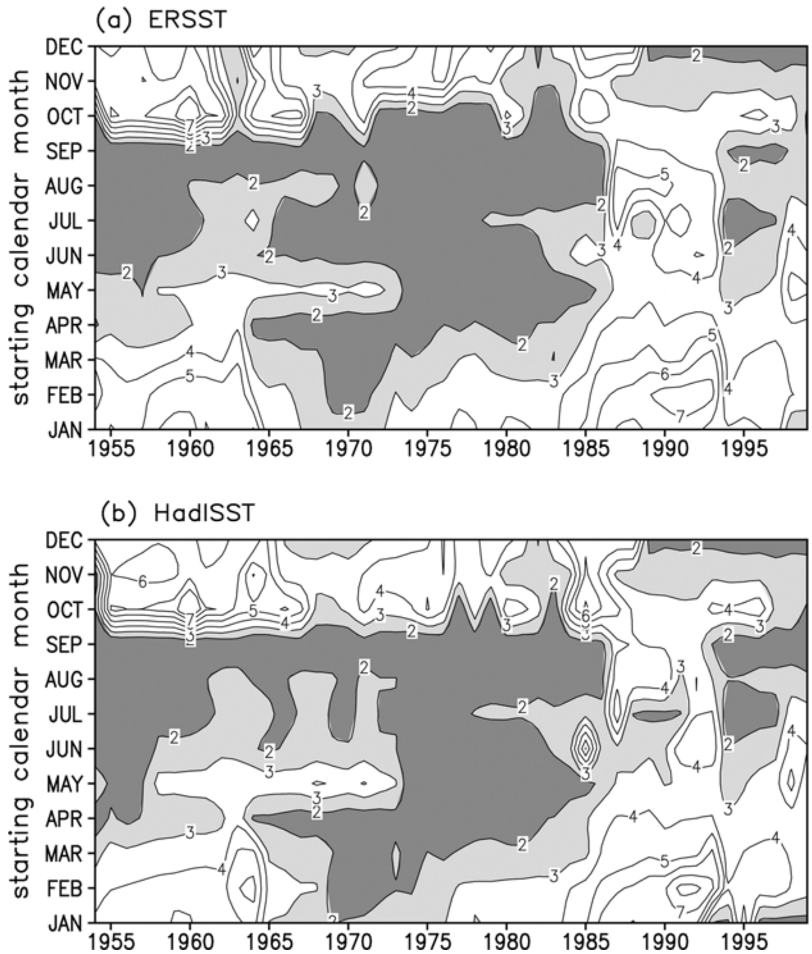

Figure 4. Persistence time (in months) that the lagged correlation coefficient calculated from (a) ERSST and (b) HadISST within a 13-year moving window drops to 0.6 as a function of starting calendar month and year. The 13-year moving window is shifted year by year from 1948 to 2005. The dark, white, and light regions indicate the persistence time shorter than 2 months, longer than 3 months, and between 2 and 3 months, respectively. The contour interval is 1 month.

cients. Actually, owing to the large thermal inertia and long adjustment timescale, the response of SST anomalies in the North Pacific to atmospheric forcing is delayed. North Pacific SST anomalies have a maximum correlation with the 700-hPa zonal wind across the North Pacific at a lag of 1 month (not shown). Therefore, it is possible that the minimum surface wind speed in August leads to the minimum SST persistence in September. In addition, although the 700-hPa zonal wind exhibits an obvious rise after August, this change does not seem to fully explain the sharp recovery of SST persistence from September to October mentioned in Figure 2. Further work may be needed to examine whether the sharp recovery of SST persistence is related to a sudden strengthening of ocean-air coupling in the North Pacific from September to October.

4. Decadal Changes in the North Pacific SST Persistence

[10] Figure 4 shows the results from applying the moving lagged correlation analysis to both the ERSST and HadISST. In Figure 4a, it is found that the low persistence (the dark shading) mainly occurs around August–September before the mid-1960s, extends to around April–October from the mid-1960s to the mid-1980s, vanishes in summer from the mid-1980s to the mid-1990s, and appears again around July–September after the mid-1990s. It should be noted that the low persistence occurs in December after the late 1980s. Taking all calendar months into account, North Pacific SST persistence is relatively strong from the mid-1950s to the mid-1960s but then weak from the mid-1960s to the mid-1980s, and becomes stronger again from the mid-1980s till the mid-1990s, after which it tends to become weak again. We perform similar analyses with an 11-year and 15-year running window (not shown) and found little sensitivity of the results to the window length. The changes of January persistence in Figure 4a are consistent with *Namias et al.* [1988], who found that North Pacific January SST persistence is relatively strong from the mid-1950s to the mid-1960s but then weak from the mid-1960s until the mid-1970s, and becomes strong again from the mid-1970s to the mid-1980s. The decadal changes of North Pacific SST persistence calculated from the HadISST data set (Figure 4b) are very similar to those from the ERSST data

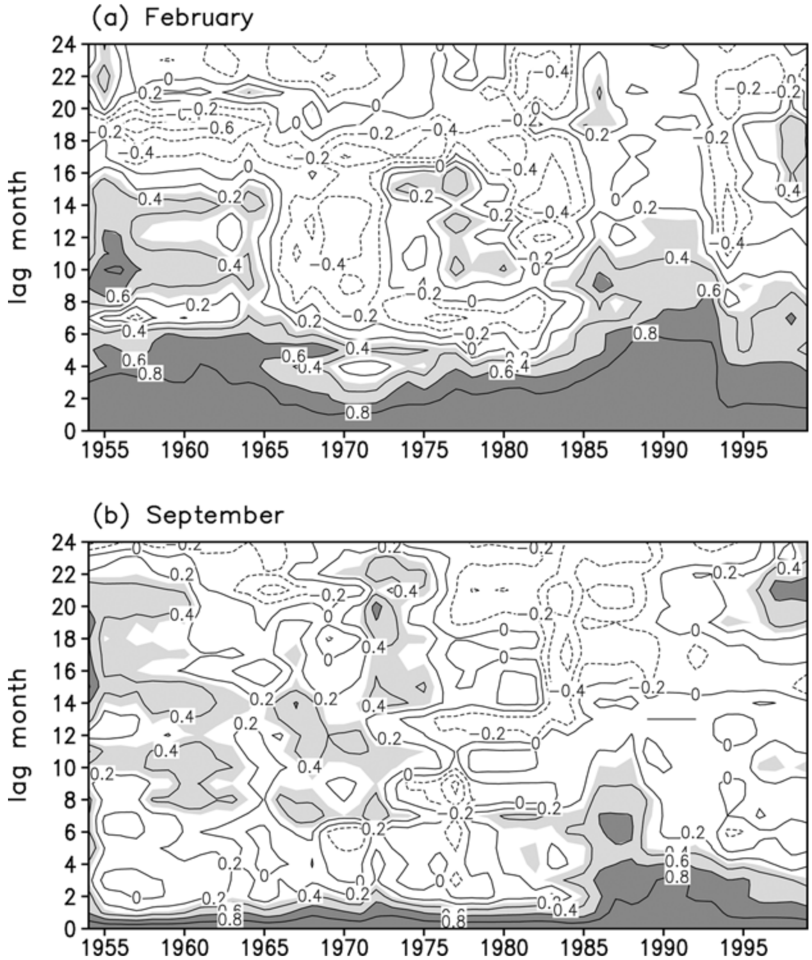

Figure 5. Lagged correlation coefficients for the starting calendar month (a) February and (b) September within a 13-year moving window from the ERSST data set. The dark and light regions indicate the correlation coefficient greater than 0.6 and between 0.3 and 0.6, respectively. The contour interval is 0.2.

set, but there are small differences between these two data sets due to the use of different historical bias corrections as well as different data and analysis procedures [*Smith and Reynolds*, 2003]. *Smith and Reynolds* [2004] showed that the temporal correlation of monthly HadISST and ERSST. v2 anomalies between 20°N and 60°N is much higher after 1950 than in earlier periods when only sparse data is available. The similar variations in the HadISST and ERSST give us confidence in the results. The changes of North Pacific SST persistence in the most recent decades is remarkable, suggesting that the decadal change of SST persistence is a real phenomenon.

[11] To further examine in detail the differences of the die-away process of North Pacific SST persistence in different decades, Figure 5 shows respectively the lagged correlation coefficients from February and September as a function of lag time and the year of moving window. In Figure 5a, it is shown that the correlation coefficients from February remain positive for the lag time up to 16 months before the mid-1960s. A longer persistent time of positive correlation coefficients occurs from the mid-1980s through the mid-1990s. However, during the mid-1960s to mid-1980s, the positive correlation coefficients only last about 6 months, after which negative correlation coefficients begin to occur. In addition, the correlation coefficients show strong recurrence from February to around February next year from the mid-1950s to mid-1960s. Consistent with the weak persistence, no obvious recurrence of correlations is found from the mid-1960s to mid-1980s. Only in the late 1970s, the correlation coefficients show weak recurrence. During the mid-1980s to the mid-1990s, the correlation coefficients also show no obvious recurrence due to high persistence in summer. In Figure 5b, it is shown that the lagged correlation coefficients from September drop quickly to small values for most periods with the exception of the period from the mid-1980s to the mid-1990s, during which the correlation coefficients remain large for the lag time up to 3–4 months. In addition, we note that when the initial month is in September, the lagged correlation coefficients also show recurrence from September to around September next year before the 1970s. This recurrence is different from the recurrence process of SST anomalies from one winter month to subsequent winter months pointed out by *Namias and Born* [1970, 1974]. The reason for this phenomenon

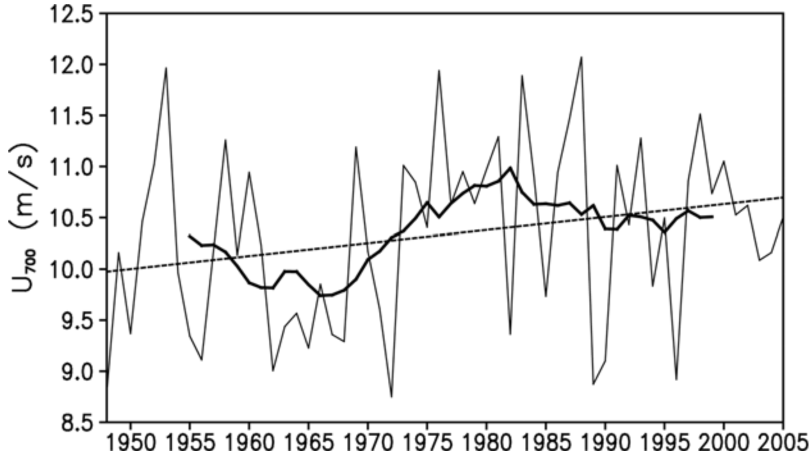

Figure 6. Time series of annual mean 700-hPa zonal wind averaged over the North Pacific (150°E∼140°W, 30°N∼50°N). The thick solid line indicates the 13-year running mean, and the dashed line indicates the linear trend.

remains unexplained. We will try to investigate some processes in the ocean and find the reason. This question is left for further study.

5. Possible Explanations of Decadal Changes of North Pacific SST Persistence

[12] As mentioned in section 3, the surface wind intensity over the North Pacific is expected to impact the SST persistence by influencing the ocean mixed layer depth. Figures 6 and 7 present the time series of 700-hPa zonal wind and its standard deviation, respectively. Figure 6 shows that the 700-hPa zonal wind over the North Pacific exhibits a distinct increase after the late 1970s, which corresponds well with the drastic climate transition of the North Pacific atmosphere-ocean system occurring in the late 1970s (Figure 8). The 700-hPa zonal wind with high values in the late 1970s and the 1980s and low values in the 1960s, does not fluctuate in phase with the SST persistence but leads the SST persistence by a few years. Figure 8 shows that the standard deviation of 700-hPa zonal wind is largest during the mid-1980s to the mid-1990s, which is consistent with high SST persistence in this period. However, the relatively high standard deviation in the 1970s and the relatively low standard deviation in the 1960s do not match the fluctuations of SST persistence. On the whole, the changes of surface wind intensity are not totally responsible for the decadal changes of North Pacific SST persistence.

[13] Previous studies suggested that the reemergence process of North Pacific SST persistence is associated with the seasonal changes of the mixed layer depth [*Namias and Born*, 1974; *Deser et al.*, 2003]. To examine if it is the change of ocean mixed layer that is responsible for the decadal change of North Pacific SST persistence, we compare in Figure 9 the seasonal variations of mixed layer depth in four different periods. The mixed layer depth all shows similar seasonal variations in different periods, with the maximum value in February–March and the minimum value in July–September. The winter mixed layer depth shows relatively great differences among all four periods. There are only little differences in summer mixed layer depth. The winter mixed layer in 1975–1984 is deepest among all four periods. The winter mixed layer in 1965–1974 comes second. The winter mixed layer in 1955–1964 is shallowest. *Deser et al.* [2003] showed that the shallower winter mixed layer would favor a stronger attenuation of the SST lagged correlation. However, the deeper winter mixed layer in 1975–1984 does not correspond with the stronger SST persistence in this period shown in Figure 4, while the shallower winter mixed layer in 1985–1994 also does not correspond with the weaker SST persistence. Actually, the maximum difference of winter mixed layer depth among all four periods is only 18 m, which is far below the maximum difference of 240 m in the experiment performed by *Deser et al.* [2003]. It is possible that the little change of mixed layer depth is not enough to cause an obvious change in the North Pacific SST persistence. The results suggest that the change of mixed layer depth over the North Pacific is not one of main causes responsible for the decadal changes of North Pacific SST persistence.

[14] *Namias et al.* [1988] suggested that strong cases of North Pacific SST persistence are associated with the high-

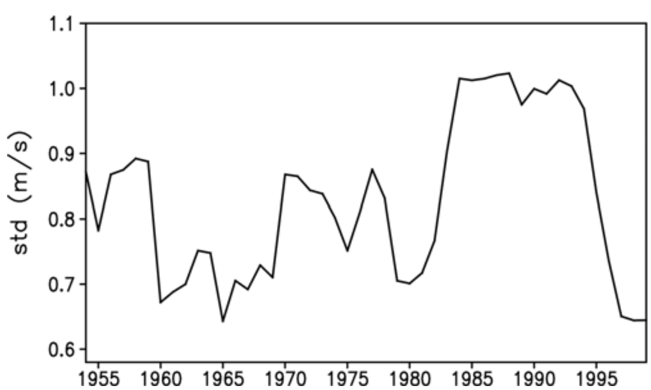

Figure 7. Time series of running standard deviation of annual mean 700-hPa zonal wind averaged over the North Pacific (150°E∼140°W, 30°N∼50°N) calculated within a 13-year window that moves year by year from 1948 to 2005.

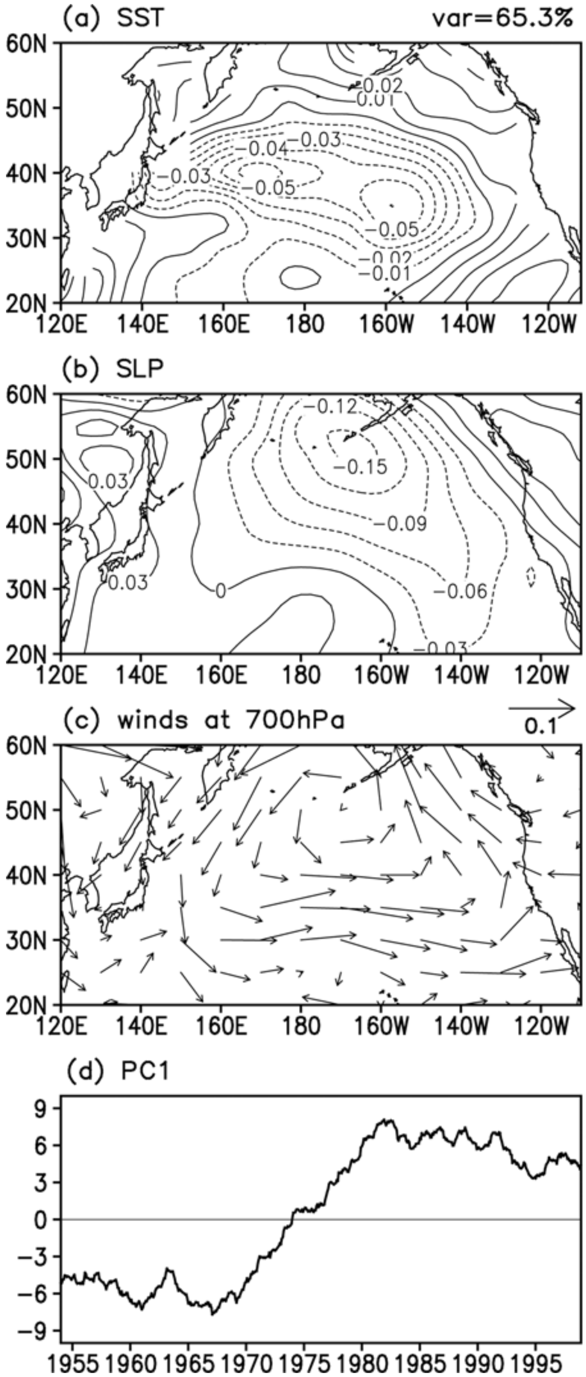

Figure 8. First combined empirical orthogonal function (EOF) of 13-year running mean fields obtained from monthly mean fields. (a) SST, (b) sea level pressure (SLP), (c) wind vector at 700 hPa, and (d) time evolution of the first principal component (PC1).

persistence atmospheric anomaly pattern, which is similar to the PNA pattern. It is of interest to further examine the linkages of the decadal changes of the PNA pattern to those of North Pacific SST persistence. The variations of annual mean PNA index are shown in Figure 10 for comparison with those of the SST persistence. The PNA index shows the high values before the mid-1960s, the low values in the late 1960s and the 1970s, and a significant upward trend after the 1980s. Compared with the SST persistence, the PNA index shows similar decadal changes that match those of SST persistence before the mid-1990s, after which the SST persistence tends to become weak and is not consistent with higher and higher values of the PNA index. Besides the strength of the PNA pattern, it is possible that the persistence of the PNA pattern also has an important influence on the North Pacific SST persistence. Figure 11 shows the persistence variations of PNA index for each calendar month. It is interesting to notice from Figure 11 that the persistence of the PNA pattern is high near January–April from the mid-1980s till the mid-1990s, which relates well with the high SST persistence in the North Pacific. The high persistence of the PNA pattern around October from the mid-1960s to the late 1970s also corresponds well with the high SST persistence in the North Pacific. During the 1970s to the mid-1980s, the low persistence of the PNA pattern near April–October is also consistent with the low SST persistence in the North Pacific. However, the low persistence of the PNA pattern in summer from the mid-1980s to the mid-1990s does not match the high SST persistence. This is because the PNA pattern is strong in winter and weak in summer [*Wallace and Gutzler*, 1981]. The weak PNA pattern in summer will exert relatively little effect on the North Pacific SST persistence. Different from SST persistence in winter, there are other mechanisms responsible for the decadal changes of SST persistence in summer.

[15] With diminished winds and the weak PNA pattern, the coupling between atmospheric circulation and the North Pacific SST during the summer season is not strong as in winter. Other processes (i.e., clouds and radiative phenomena) could regulate the North Pacific SST and thus affect the North Pacific SST persistence [*Namias and Born*, 1974; *Norris et al.*, 1998]. The marine boundary cloud amount in the North Pacific is found to be negatively correlated with local SST, suggestive of a positive cloud feedback on SST [*Norris et al.*, 1998]. The decrease of SST due to increased cloud cover reduces the boundary layer temperature, which promotes condensation and increases the stability of the capping inversion [*de Szoeke et al.*, 2006]. The stronger inversion discourages entrainment of dry air into the plan-

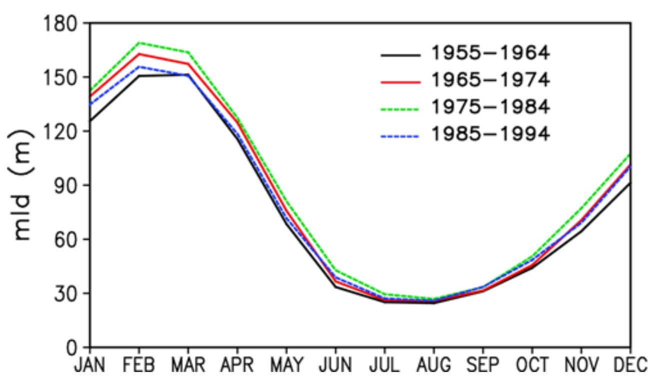

Figure 9. Seasonal changes of mixed layer depth averaged over the North Pacific (150°E∼140°W, 30°N∼50°N) in 1955–1964 (black solid line), 1965–1974 (red solid line), 1975–1984 (green dashed line), and 1985–1994 (blue dashed line).

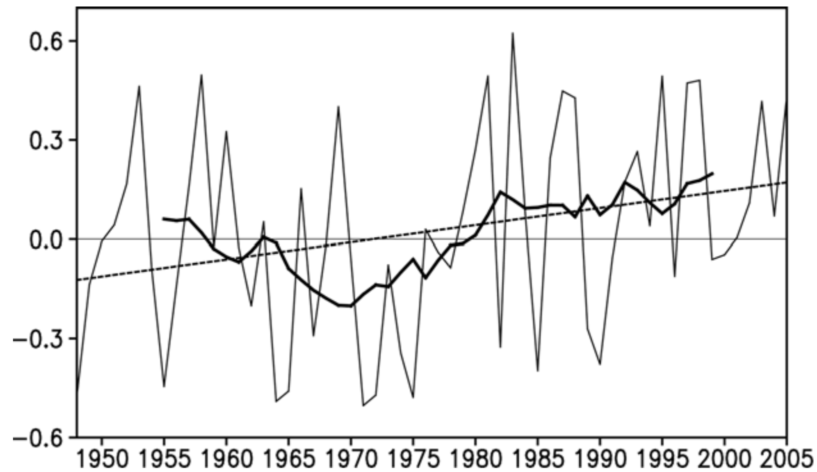

Figure 10. Same as Figure 6 but for the annual mean PNA index.

etary boundary layer (PBL), thereby limiting the evaporation of cloud water and increasing low clouds [*Klein and Hartmann*, 1993]. The increasing low clouds will lead to a further decrease of SST. Through this positive feedback process between the clouds and SST, the SST will persistently decrease and the low cloud cover will persistently increase. The SST and low cloud cover persistence could therefore be effectively enhanced. *Park et al.* [2006] showed that positive cloud feedback enhances SST autocorrelation (~0.1–0.3) from late spring to summer in the central and western Pacific and from late summer to fall in the subtropical eastern Pacific. Figure 12 shows that the summer low cloud cover in the North Pacific has considerably increased after the 1980s, exhibiting opposite tendencies with the summer SST. These trends could contribute to the inverse relationship between the SST and low cloud cover. Figure 13 shows that the inverse relationship between the SST and low cloud cover has enhanced from the mid-1980s to the mid-1990s. It is indicated that the positive feedback between the SST and clouds in the North Pacific becomes stronger from the mid-1980s to the mid-1990s, which contributes to the longer SST persistence in summer in this period. The persistence of summer low cloud cover in the North Pacific has also increased after the late 1970s (Figure 14), which is nearly consistent with the change of SST persistence in summer. The results show that the positive feedback between the SST and clouds plays an important role in the strong summer SST persistence in the North Pacific from the mid-1980s to the mid-1990s.

[16] ENSO strongly affects the atmospheric circulation and air-sea heat exchanges over the North Pacific. Although the PNA is a natural mode of climate variability, it is also strongly influenced by the ENSO phenomenon. The positive phase of the PNA pattern tends to be associated with the El Niño events, and the negative phase tends to be associated with the La Niña events. Therefore, ENSO is likely to have an influence on the North Pacific SST persistence. *Park et al.* [2006] showed that the influence of the remote ENSO forcing on SST autocorrelation in the North Pacific varies with season and location with a maximum impact on the correlation magnitude of 0.2–0.3. It has been shown by *Namias* [1986] that the decadal fluctuations of North Pacific SST persistence seem to be related to the SOI. We examine the decadal changes of SOI to understand its linkage to those of the North Pacific SST persistence. Figure 15 shows the annual mean values of SOI

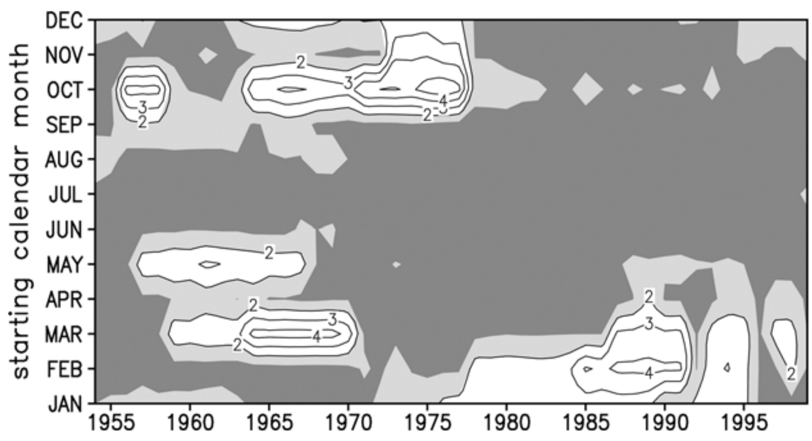

Figure 11. Persistence time (in months) that the lagged correlation coefficient calculated from PNA index within a 13-year moving window drops to 0.3 as a function of starting calendar month and year during 1948–2005. The dark, white, and light regions indicate the persistence time shorter than 1 month, longer than 2 months, and between 1 and 2 months, respectively.

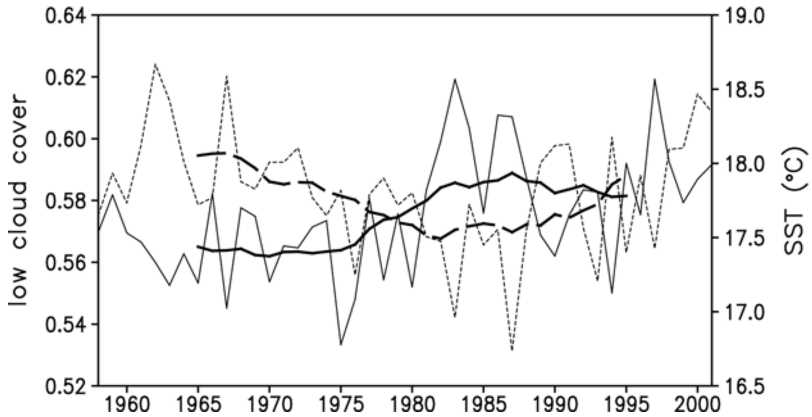

Figure 12. Time series of summer (JJAS) low cloud cover (solid line; left *y* axis) and summer (JJAS) SST (dashed line; right *y* axis) averaged over the North Pacific (30°N∼50°N, 150°E∼140°W) during 1958–2001. The thick solid and dashed lines indicate the 13-year running mean of low cloud cover and SST, respectively.

from 1948 to 2005. A major feature in Figure 15 is a decreasing linear trend that is consistent with the increases in the 700-hPa zonal wind and PNA index. The SOI shows the relatively high values in the late 1960s and the 1970s and relatively low values in the 1980s and the early 1990s, which appears to negatively correlate with the North Pacific SST persistence and associated atmospheric behavior. After the 1980s, El Niño events occur more frequently and in greater magnitude than before [*Trenberth and Hurrell*, 1994; *Gu and Philander*, 1995]. As a remote response to the change of frequency and amplitude of El Niño events, the PNA pattern in winter shifts to more positive values and longer duration time, and this tends to favor the stronger SST persistence in the winter North Pacific. *Park and Leovy* [2004] also found remote ENSO teleconnections over the western North Pacific during summer with low-level cloud decks and large-amplitude SST anomalies in the Kuroshio extension region. The North Pacific SST persistence in summer could therefore be affected by the ENSO. Some recent studies agree that the origin of the North Pacific climate transition in the late 1970s is initiated by changes in the tropical SST over the Pacific and Indian Ocean sectors [*Minobe*, 1997; *Graham*, 1994; *Deser et al.*, 2004]. It is possible that the decadal changes of North Pacific SST persistence originate from the tropics. In addition, the Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that shifts phases on about 20 to 30 years [*Mantua et al.*, 1997; *Zhang et al.*, 1997], with the primary climatic effects concentrating on the North Pacific. In 1947, the PDO shifts to a cold phase. In 1977, the PDO switches to a warm phase. Recently, the PDO shifts back to a cold phase beginning in 1998. The high north persistence SST persistence from the mid-1980s to the mid-1990s seems to coincide with the warm phase of PDO. From this point of view, the decadal changes of North Pacific SST persistence likely also relate to the shifts of PDO phase.

6. Summary and Discussion

[17] Motivated by the study of *Namias et al.* [1988], the decadal and seasonal dependence of North Pacific SST persistence are investigated using two different SST data sets from 1948 to 2005. It is found that lagged correlations of North Pacific SST anomalies for the period 1948–2005 show a significant decrease in July–September (especially in September), often followed by a substantial recovery. The results confirm the existence of the July–September persistence barrier in the North Pacific SST discovered by *Namias and Born* [1970, 1974]. The seasonal dependence of North Pacific SST persistence can be due to seasonal changes of the wind strength in the oceanic surface layers, because strong winds tend to increase the vertical mixing in the oceanic surface layers.

[18] To investigate the decadal changes of North Pacific SST persistence, the moving lagged correlations for each calendar month are calculated within a 13-year window that moves year by year from 1948 to 2005. Taking all calendar months into account, North Pacific SST persistence is relatively strong from the mid-1950s to the mid-1960s but then weak from the mid-1960s to the mid-1980s, and becomes stronger again from the mid-1980s till the mid-1990s, after which it tends to become weak again. The recurrence of SST anomalies from one winter to the next seems to be related to the strength of SST persistence. The lagged correlation coefficients show strong recurrence from

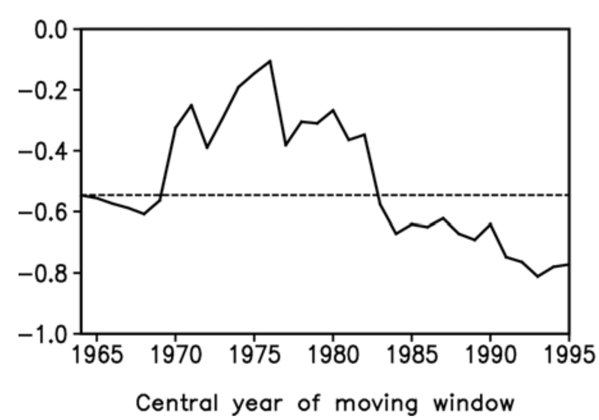

Figure 13. The 13-year sliding correlations between the summer (JJAS) area-averaged SST and low cloud cover over the North Pacific (30°N∼50°N, 150°E∼140°W) during 1958–2001. The horizontal dashed line shows the 0.05 significance level.

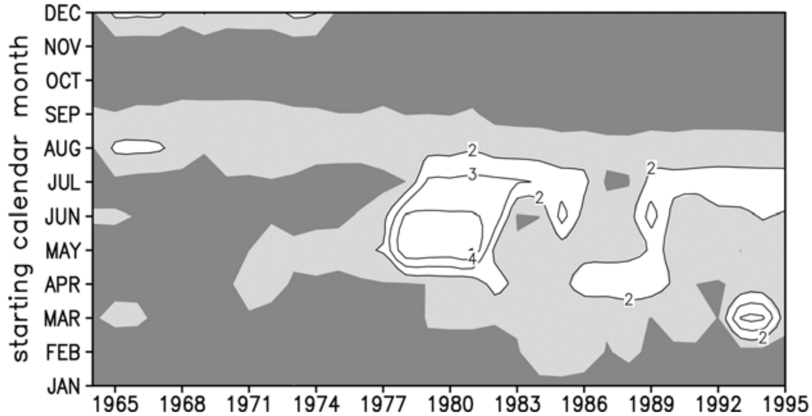

Figure 14. Same as Figure 11 but for the area-averaged low cloud cover over the North Pacific (30°N∼50°N, 150°E∼140°W) during 1958–2001.

the mid-1950s to mid-1960s. Consistent with the weak persistence, no obvious recurrence of lagged correlations is found from the mid-1960s to mid-1980s. Only in the late 1970s, the lagged correlation coefficients show weak recurrence. During the mid-1980s to the mid-1990s, the lagged correlation coefficients also show no obvious recurrence due to high persistence in summer.

[19] Decadal changes of the PNA pattern, the SST-clouds feedback, and SOI are found to be related to those of North Pacific SST persistence. The PNA index shows a significant upward trend after the 1980s. Besides, the PNA pattern also exhibits a high persistence in winter from the mid-1980s to the mid-1990s. These changes of PNA pattern are favorable to the occurrence of strong SST persistence in winter from the mid-1980s to the mid-1990s. In summer, the positive feedback between the marine boundary clouds and SST enhances the SST persistence in the North Pacific. It is found that the positive feedback between the SST and clouds in the North Pacific during summer becomes stronger from the mid-1980s to the mid-1990s, which would contribute to the longer SST persistence in summer in this period. The SOI shows negative correlation with the North Pacific SST persistence and the PNA index, indicating the remote forcing of ENSO on the North Pacific climate change. In addition, the high north Pacific SST persistence from the mid-1980s to the mid-1990s coincides with the warm phase of PDO. We concluded that the changes in tropical SST or the PDO phase might explain the origin of decadal changes of North Pacific SST persistence.

[20] However, some details of decadal changes of North Pacific SST persistence remain unexplained. For example, the highest SST persistence occurs around October before the late 1960s, shifts to around November in the 1970s, and shifts again to near February from the mid-1980s to the mid-1990s. The timing of the lowest SST persistence also varies from decade to decade (Figure 4). The physical processes responsible for the differences of seasonal dependence of North Pacific SST persistence in different decades need further exploration in the future. In addition, why is the recurrence of SST anomalies in the North Pacific obvious from the mid-1950s to mid-1960s but not obvious after the mid-1960s? We examine the differences in seasonal cycles of 700-hPa zonal wind and ocean mixed layer depth (Figure 9) in different decades, but no obvious differences are found. The result means that other mechanisms are possibly responsible for the decadal changes of the recurrence of SST anomalies in the North Pacific. The results of this study do not include the potential influences of oceanic processes such as advection, eddy mixing, and subduction upon the North Pacific SST persistence. The recent studies of *Qiu* [2002] and *Schneider and Miller* [2001] indicate that the persistence of winter SST anomalies along the Kuroshio

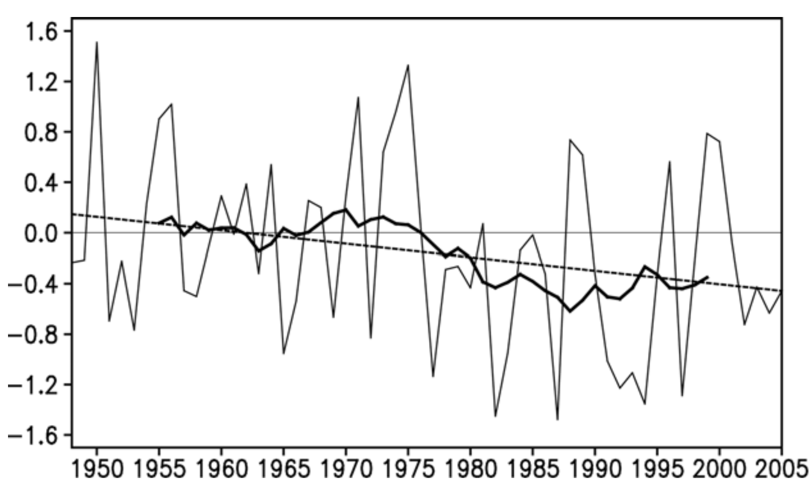

Figure 15. Same as Figure 6 but for the annual mean SOI index.

Current Extension can be significantly enhanced when dynamical ocean processes are taken into account. *Wu et al.* [2005] show that the 1970s North Pacific climate regime shift may be attributed to the coupled ocean-atmosphere interaction over the North Pacific in response to persistent wind stress anomalies in the previous decade. Therefore, further studies including the effects of dynamical ocean processes and ocean-atmosphere interactions are needed for a more complete understanding of decadal changes of North Pacific SST persistence.

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