GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L18611, doi:10.1029/2006GL026082, 2006

An observational study of the impact of the North Pacific SST on the atmosphere

Qinyu Liu,[1] Na Wen,[1,2] and Zhengyu Liu[3,4]

Received 24 February 2006; revised 4 August 2006; accepted 9 August 2006; published 28 September 2006.

[1] To investigate the observed atmospheric response to SST variability in the North Pacific, the Maximum Covariance Analysis is performed between the monthly sea surface temperature anomaly (SSTA) and the 500-hPa geopotential height anomaly over the North Pacific using observations of the period 1958–1993. In addition to the strong remote ENSO impact in winter months, the MCA analysis suggests a significant local atmospheric response, with the summer atmosphere corresponding to the preceding winter SST over the North Pacific. In this local response, a horseshoe SSTA in winter, with a positive SSTA loading over the central-western North Pacific surrounded by a negative SSTA, appears to persist into the spring and summer, eventually leading to an atmospheric response in summer with a wave-train over the mid-latitude North Pacific. This local response may imply some predictability of the North Pacific summer atmospheric circulation with a lead time of up to 6 months. **Citation:** Liu, Q., N. Wen, and Z. Liu (2006), An observational study of the impact of the North Pacific SST on the atmosphere, *Geophys. Res. Lett.*, *33*, L18611, doi:10.1029/2006GL026082.

1. Introduction

[2] The North Pacific SST exhibits significant variability at interannual and decadal timescales [e.g., *Zhang and Battisti*, 1997]. This SST variability, however, is largely forced by the atmospheric forcing [*Davis*, 1976; *Cayan*, 1992] by either atmospheric internal variability or remote variability from the tropics through teleconnection [*Alexander et al.*, 2002; *An and Wang*, 2005]. It has remained unclear if the extratropical North Pacific SST can impact the atmosphere either in the observation or in modeling studies. In the observation, the identification of North Pacific oceanic impact on the atmosphere is hampered severely by the overwhelming climate noise related to the atmospheric internal variability. In modeling studies, the atmospheric response to extratropical SST variability has exhibited greatly diverse results [e.g., *Kushnir et al.*, 2002; *Liu and Wu*, 2004; *Wu et al.*, 2005].

[3] Recently, using the lagged Maximum Covariance Analysis (MCA), *Czaja and Frankignoul* [1999, 2002] (hereafter collectively CF) identified a significant atmospheric response to the North Atlantic SSTA, with a later summer Atlantic horseshoe SSTA forcing the following winter atmospheric North Atlantic Oscillation (NAO) by up to 6 months. Such a long SSTA leading impact on the atmosphere is interpreted in the framework of the stochastic climate model, reflecting the forcing of a persistent Atlantic SSTA on NAO.

[4] Motivated by CF, this work attempts to use a similar lagged MCA analysis to identify potential atmospheric responses to the SSTA in the North Pacific region. The MCA analysis is performed between the North Pacific SSTA and North Pacific atmospheric Z500 after removing the tropical Pacific impact. In contrast to the North Atlantic that is dominated by a winter atmospheric response to the preceding summer SSTA, it is found that, over the North Pacific region, the local atmospheric response is dominated by a summer atmospheric response to the preceding winter SSTA.

2. Data and Method

[5] We used the monthly geopotential height anomaly at 500-hPa (Z500) and the SST anomaly (SSTA) over the period of 1958–1993. The Z500 is derived from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996], binned to a $5^\circ \times 5^\circ$ resolution, while the SSTA is obtained from the COADS datasets, binned to a $4^\circ \times 4^\circ$ resolution. A linear trend is removed at each grid point for both Z500 and SSTA.

[6] Focusing on the local atmospheric response to SSTA over the North Pacific, we confined our domain of analysis to the extratropics, (20 $\sim$ 60°N, 105°E $\sim$ 115°W) for the SSTA and (20 $\sim$ 70°N, 80°E $\sim$ 80°W) for Z500. Since tropical Pacific ENSO is known to exert a significant impact on the North Pacific atmosphere and ocean [*Alexander et al.*, 2002], at each grid point for both the SSTA and Z500, we filter out the tropical Pacific influence using a regression against the Nino3.4 SSTA of the preceding months. The regression coefficient for the ENSO removal is selected as the maximum regression coefficient within the preceding 6 months, which occurs mostly at lag 2 months for SSTA and 0 month for Z500. Two regression methods are used. The first method assumes a constant regression coefficient and the regression is carried out using all the months year around. The second method assumes a different regression coefficient for each calendar month (a total of 12). This method, in principle, filters the ENSO impact better because the ENSO has a strong seasonality, with the maximum in winter months. However, the calendar month regression coefficient suffers from a larger sampling error due to the smaller number of freedom. Therefore, a modification is made on the second method: a new calendar month regres-

[1]Physical Oceanography Laboratory, Ocean University of China, Qingdao, China.

[2]Now at Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA.

[3]Center for Climatic Research, University of Wisconsin-Madison, Madison, Wisconsin, USA.

[4]Also at Physical Oceanography Laboratory, Ocean University of China, Qingdao, China.

0094-8276/06/2006GL026082$05.00

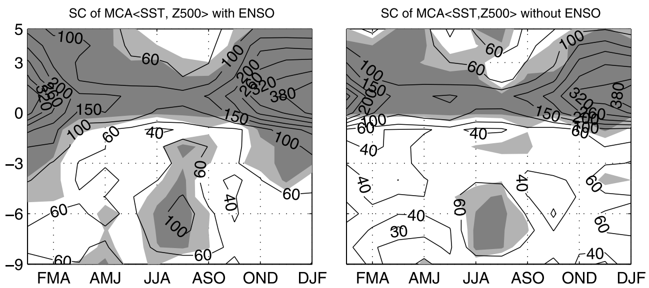

Figure 1. The SC of the first MCA mode between Z500 and SSTA in the North Pacific (20°N–70°N, 80°E–80°W) using the NCEP reanalysis data (left) before and (right) after removing ENSO effect. Shading indicates those past 80% (light), 90% (heavy) and 95% (the most heavy) significance level. The abscissa is the Z500 calendar month, while the ordinate is lag, positive (negative) for Z500 (SST) leading SST (Z500).

sion coefficient is obtained as the 3-month running mean of the original calendar month regression coefficients, and this new coefficient is used for the removal of ENSO impact. Unless otherwise specified, the results discussed below removes ENSO impact using the modified calendar month regressions. It turns out that our major conclusions are not very sensitivity to the regression methods.

[7] After removing the impact from the tropical Pacific, we performed the MCA with a set of SVD performed on the temporal covariance matrix between SSTA and Z500 at various leads and lags, as in CF. To construct the covariance matrix, the monthly anomalies are weighted by the square root of the cosine of latitude, and the covariance matrix is estimated with monthly anomalies binned into groups of 3 months. Also, following CF, the robustness of the MCA modes are assessed on the squared covariance (SC) and the correlation coefficient (CO) between the SSTA and Z500 time coefficients with a Monte-Carlo test, in which the MCA repeated 100 times using the original SSTA but a Z500 of randomly scrambled years.

3. North Pacific Ocean–Atmosphere Interaction

[8] Before and after the removal of ENSO impact, the SC of the first MCA mode between SSTA and Z500 shows a clear dependence on both the lag time and seasonality (Figure 1, left and right respectively). The SC is dominated by a maximum throughout the year when the SST lags the atmosphere (positive lag). More specifically, for each month of Z500, the maximum SC occurs when the SST lags by 1 month (lag = +1) and this maximum SC at lag +1 strengthens towards the winter months, presumably due to the strong internal atmospheric variability in winter. Overall, the tendency of a maximum SC at the SST lagging atmosphere is similar to that in the North Atlantic (CF). This simply confirms that, in both the North Pacific and North Atlantic, local ocean-atmosphere interaction is dominated by the forcing of the atmospheric internal variability on SST.

[9] We now examine the SST-lead (negative lag) MCA, which may infer potential North Pacific SST forcing on the atmosphere (CF). In the presence of ENSO (Figure 1, left), when SST leads, a significant SC center appears as a winter (NDJF) atmosphere lagging SSTs by −1 to −4 months. This broad center, at first sight, seems to correspond to a similar center in the North Atlantic SST analysis by CF. However, this center virtually disappears at 90% significance level after removing the ENSO impact (Figure 1, right). Therefore, this SC center of SST leading winter atmosphere simply reflects the strong ENSO impact on both the Z500 and SST in winter, with the SC peak time and persistence following those of ENSO.

[10] In contrast, the SST-lead SC also shows a significant maximum center for summer (JJA-JAS) atmosphere lagging winter SST by −5 to −7 months (Figure 1, left). Most importantly, this SC maximum remains robust after the removal of ENSO (Figure 1, right). The correlation of the time series of the SSTA and the summer Z500 are over 0.5, which are also significant over 90–95% level for these lags (not shown). The SST forcing on the summer atmosphere occurs most significantly when the SSTA leads the summer Z500 by about half a year (at lag = −7), and exhibits significant interannual and decadal variability, as seen in the time series of the MCA SST mode (Figure 2). This mode, with the winter SSTA leading summer Z500, likely represents a local response mode of the atmosphere to the local North Pacific SSTA. In contrast to the North Atlantic where is dominated by a winter atmosphere response to summer SST (CF), this North Pacific response mode implies a summer atmospheric response to winter SST. Since the SSTA is always predominantly forced by the atmospheric forcing in the North Pacific [*Davis*, 1976], the local response also implies a SST feedback on the atmosphere locally over the North Pacific. Therefore, this mode will also be referred to as the "feedback mode". This feedback mode in the North Pacific is the major finding of this work.

[11] This feedback mode is unlikely to be affected significantly by a residual impact from the tropical Pacific, which might have occurred if the ENSO impact is not removed completely with our regression. First, this feedback mode appears to be robust with different regression methods. The significant SC also occurs when the NCEP SST is used and the MCA is performed for reduced area, such as (20 ∼ 60°N, 110°E ∼ 110°W) for Z500 (not shown). Second, the time series of the MCA SST first mode associated with the feedback mode (Figure 2) has little correlation with ENSO, the correlation coefficients between time series of feedback mode and Nino3 index (after removal the long time trend) are smaller than 0.3 and insignificant, when Nino3 index lags time series of feedback mode from −7 months to 7 months. This follows because

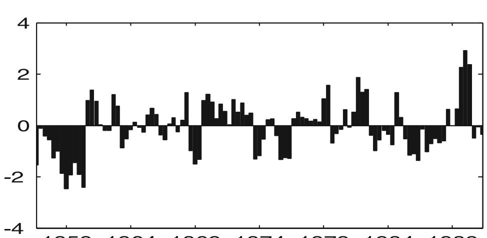

Figure 2. Normalized SSTA time series obtained from the 1st MCA mode between NDJ SSTA and JJA *Z*500 after 6 months (patterns in Figure 3a).

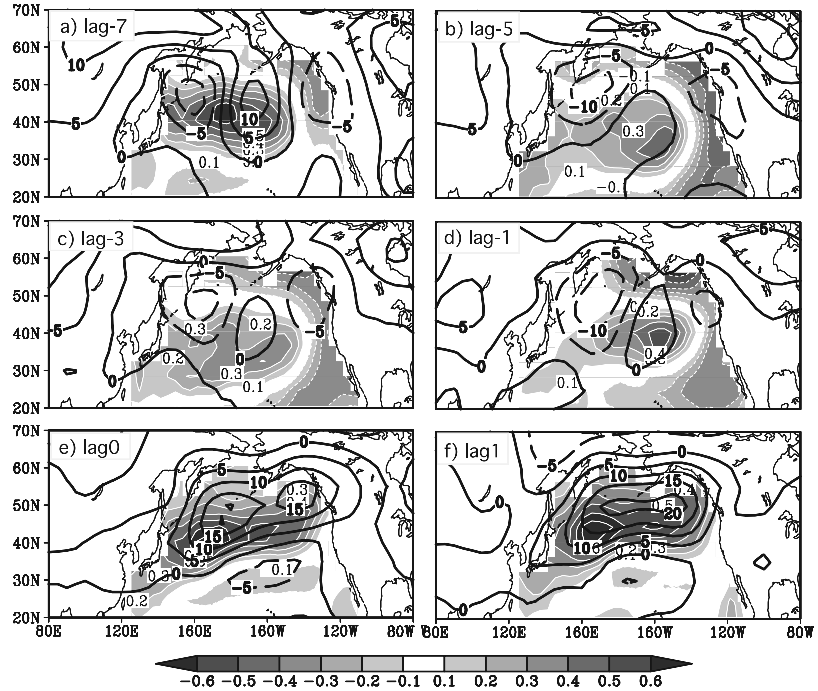

Figure 3. The associated homogeneous map of SST (shading with white contours, in °C) and heterogeneous map of Z500 (contours, in gpm), with Z500 fixed on the summer (JJA) and the SST lagging by −7,−5,−3,−1,0 and 1 month. Solid contours for positive and dash contours for negative.

ENSO tends to peak in winter and therefore tends to force both the SST and atmosphere in the North Pacific in winter. Indeed, this winter ENSO impact can be identified clearly in the MCA analysis on the original data of Z500 and SSTA, as discussed before (Figure 1, left). Furthermore, the SST-lead SC decreases with the lag such that the SC becomes almost symmetric with the positive and negative lags (say, from −4 to +4 months) for the winter atmosphere. This quasi-symmetric lead-lag relation between the North Pacific SST and Z500, as well as the long persistence time of up to half a year, are clear indications that both the SST and Z500 are forced by a third factor – the tropical ENSO.

[12] In a SVD analysis between the simultaneous SST (whole Pacific) and geopotential height (North Pacific), *An and Wang* [2005] identified two leading modes as the ENSO mode (tropical forcing on the North Pacific) and the North Pacific mode (North Pacific atmospheric forcing on the SST). Our monthly stratified MCA analysis, along lag zero, further shows a clear seasonality of the these two modes, the ENSO mode is dominant only in winter, while the North Pacific mode persists throughout the year albeit with the maximum in winter (Figure 1).

4. The Feedback Mode: A Local SST Impact on the Atmosphere

[13] We now further examine the feedback mode. First, the patterns associated with the local feedback mode can be obtained from the homogeneous SSTA map and heterogeneous Z500 map, which are obtained as the regression patterns against the SSTA mode time coefficient. Figure 3 presents a series of maps for the SSTA lagging the summer (JJA) Z500 by −7, −5, −3, −1, 0 and 1 month. At lag 1 and 0, the SSTA/Z500 is characterized by a basin-wide anomalous warm/high over the North Pacific, which is consistent with an atmospheric forcing on North Pacific SST in summer.

[14] The feedback mode represents the SST forcing on the atmosphere, which occurs most significantly when the SSTA leads the summer Z500 by about half a year (at lag = −7). Now, the summer Z500 pattern exhibits a high wave number wave train across the North Pacific, with an anomalous high sandwiched in between two anomalous lows. The high wave number of atmospheric wave train may be consistent with the weaker mean westerly wind in summer, which permits stationary Rossby waves of shorter scales relative to the winter. The corresponding winter SST pattern is characterized by a basin-wide horseshoe pattern, with the warming in the central-western Pacific roughly coincident with the Kuroshio Extension region, and a cooling around it. This horseshoe pattern of SSTA is similar to the 1st EOF of winter SSTA in the North Pacific (Figure 4a), which explains 47% of the total variance (excluding ENSO impact on SSTA in North Pacific). The wave-train pattern of Z500 for feedback mode also seems to have some resemblance to the 1st EOF of the summer Z500 (JJA) after removing ENSO impact (Figure 4b), which explains 32% of the total variance (excluding ENSO impact on atmosphere). Therefore, the feedback mode seems to account for a substantial part of the ocean/atmosphere variability (excluding ENSO impact).

[15] The significant SC of summer atmosphere to winter SST seems to have some relation to a persistent SST from the preceding winter. In the MCA analysis, this coupled pattern of horseshoe SSTA and summer wave-train Z500 seems to show a persistence as the SSTA progresses from winter to spring (Figure 3, lag = −7, −5, −3). This

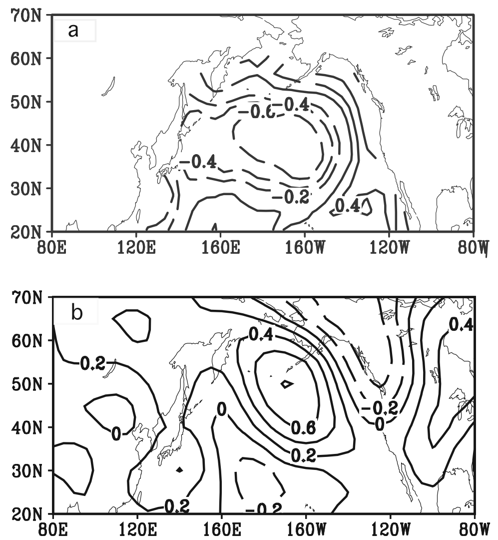

Figure 4. The pattern of the first EOF of (a) the winter (NDJ) SSTA and (b) the summer (JJA) Z500 in the North Pacific (20°N–70°N, 80°E–80°W). Tropical Pacific SST effect has been filtered out before the EOF is performed.

persistence of SST is possible because the deep oceanic mixed layer later winter in the mid-latitude North Pacific tends to generate a SST persistence of several months. Other possibility is that in winter the internal atmospheric variability is stronger and the noise is larger than them in summer, the response of atmosphere to winter SSTA could be statistical significant in summer. The summer atmospheric response may also include the nonlinear atmospheric response [*Ferreira and Frankignoul*, 2005] or may be related to summer "Circumglobal Teleconnection Pattern" [*Ding and Wang*, 2005]. However, it remains unclear to us why, for the summer atmospheric response, the SST forcing is statistically most significant half year earlier (lags −8 to −5), instead of immediately before the summer (lag −4 to −1). A similar problem remains unresolved in the North Atlantic, where the maximum SST-lead SC occurs −4 months preceding the atmosphere, instead of the immediate months preceding the atmosphere. The complex structure of the lagged SC between SST and Z500, we speculate, is caused by the strong seasonal dependence of the atmospheric response [*Peng et al.*, 1997; *Ting and Wang*, 1997; Q. *Liu et al.*, 2006; Z. *Liu et al.*, 2006]. It could also be related to the nonlinearity of the atmospheric response and some remote impact. The physical mechanism for this lagged response is a major task to be studied in the future.

5. Summary

[16] The lagged MCA analysis is used to study the oceanic impact on the North Pacific atmosphere circulation, with the focus on the local atmospheric response to North Pacific SSTA. Our MCA analysis confirms the dominant atmospheric forcing on SST and the remote ENSO impact in winter, as in previous studies. The new finding of this work is a local feedback mode. This mode is characterized by a summer atmosphere responding to the preceding winter SSTA in the North Pacific, with a basin scale horseshoe SSTA and a high wave number atmospheric wave train in the North Pacific. It is rather surprising that this local feedback mode in the North Pacific differs dramatically from that in the North Atlantic with the seasonal phase shifted by about half a year. For the North Atlantic, recent modeling studies suggest that the summer SST impact on early winter NAO may involve remote impact from the tropical Atlantic Ocean. [*Cassou et al.*, 2004; *Peng et al.*, 2005]. It is therefore unclear in the Pacific if the MCA analysis here is able to identify the true local SST forcing on the atmosphere. Although a convincing physical mechanism for the lagged MCA is still lacking, tentatively, we hypothesize that the lagged MCA reflects the summer atmospheric response to a persistent winter SST anomaly. This hypothesis, however, needs to be tested in the future with more sophisticated analysis and modeling studies.

[17] Finally, in the revision stage, we are brought to the attention of an independent study with a similar MCA analysis for the North Pacific, but for the period of 1977–2003 [*Frankignoul and Sennechael*, 2006]. The significant SC center of late summer atmosphere lagging winter SST remains largely consistent, although the SC center is shifted about 2 months later on Z500 and the pattern of the atmosphere differs somewhat. Our further analysis suggests that this time shift is due to the different periods of the data. This may imply a dependence of the atmospheric response to North Pacific SST on the interdecadal shift of the mean climate state – an interesting feature that will be studied in the future.

[18] **Acknowledgments.** We thank E. DeWeaver, M. Ting, H. Wang, S. Peng, Z. Li and P. Chang for discussions on the atmospheric dynamics and D. Vimont for a discussion on the ENSO filtering for different calendar months. We thank two anonymous reviewers for their comments and useful information. We also thank C. Frankignoul for some discussions during the revision of the paper. This work is supported by Chinese NSF 40333030, "Green Card" project of Ocean University of China and the United States' NOAA and DOE.

References

Alexander, M. A., I. Blade, M. Newman, J. R. Lanzante, N.-C. Lau, and J. D. Scott (2002), The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans, *J. Clim.*, *15*, 2205–2231.

An, S. L., and B. Wang (2005), The Forced and Intrinsic Low-Frequency Modes in the North Pacific, *J. Clim.*, *18*, 876–885.

Cassou, C., L. Terray, J. W. Hurrell, and C. Deser (2004), North Atlantic winter climate regimes: Spatial asymmetry, stationarity with time, and oceanic forcing, *J. Clim.*, *17*, 1055–1068.

Cayan, D. (1992), Latent and sensible heat flux anomalies over the Northern oceans driving the sea surface temperature, *J. Phys. Oceanogr.*, *22*, 859–881.

Czaja, A., and C. Frankignoul (1999), Influence of the North Atlantic SST on the atmospheric circulation, *Geophys. Res. Lett.*, *26*, 2967–2972.

Czaja, A., and C. Frankignoul (2002), Observed impact of Atlantic SST anomalies on the North Atlantic Oscillation, *J. Clim.*, *15*, 606–623.

Davis, R. E. (1976), Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean, *J. Phys. Oceanogr.*, *6*, 249–266.

Ding, Q., and B. Wang (2005), Circumglobal teleconnection in the northern hemisphere summer, *J. Clim.*, *18*, 3483–3505.

Ferreira, D., and C. Frankignoul (2005), The transient atmospheric response to midlatitude SST anomalies, *J. Clim.*, *18*, 1049–1067.

Frankignoul, C., and N. Sennechael (2006), Observed influence of North Pacific SST anomalies on the atmospheric circulation, *J. Clim.*, in press.

Kalnay, E., et al. (1996), The NCEP/NCAR 40–Year Reanalysis Project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Kushnir, Y., W. A. Robinson, I. Blade, N. M. J. Hall, S. Peng, and R. Sutton (2002), Atmospheric GCM response to extratropical SST anomalies: Synthesis and evaluation, *J. Clim.*, *15*, 2233–2256.

Liu, Q., N. Wen, and Y. Yu (2006), The role of the Kuroshio in winter north Pacific ocean-atmosphere interaction: Comparison of a coupled model and observations, *Adv. Atmos. Sci.*, *23*(2), 181–189.

Liu, Z., and L. Wu (2004), Atmospheric response to North Pacific SST: The role of ocean-atmosphere coupling, *J. Clim.*, *17*, 1859–1882.

Liu, Z., Y. Liu, L. Wu, and R. Jacob (2006), Seasonal and long term atmospheric response to reemerging North Pacific Ocean temperature: Dynamic assessment, statistical assessment and implication to observations, *J. Clim.*, in press.

Peng, S., W. A. Robinson, and M. P. Hoerling (1997), The modeled atmospheric response to midlatitude SST anomalies and its dependence on background circulation states, *J. Clim.*, *10*, 971–987.

Peng, S., W. A. Robinson, S. Li, and M. P. Hoerling (2005), Tropical Atlantic SST forcing of coupled North Atlantic seasonal responses, *J. Clim.*, *18*, 480–496.

Ting, M. F., and H. Wang (1997), Summertime U.S. precipitation variability and its relation to Pacific sea surface temperature, *J. Clim.*, *10*, 1853–1873.

Wu, L., Z. Liu, Y. Liu, Q. Liu, and X. Liu (2005), Potential global climatic impacts of the North Pacific Ocean, *Geophys. Res. Lett.*, *32*, L24710, doi:10.1029/2005GL024812.

Zhang, Y., and D. S. Battisti (1997), ENSO-like interdecadal variability 1900–93, *J. Clim.*, *10*, 1004–1020.

Q. Liu, Physical Oceanography Laboratory, Ocean University of China, 266003 Qingdao, China. (liuqy@ouc.edu.cn)

Z. Liu and N. Wen, Center for Climatic Research, University of Wisconsin-Madison, Madison, WI 53706, USA. (zliu3@wisc.edu)