GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L13701, doi:10.1029/2008GL034584, 2008

Oceanic origin of the interannual and interdecadal variability of the summertime western Pacific subtropical high

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Received 7 May 2008; accepted 2 June 2008; published 3 July 2008.

[1] A recent study found that the western Pacific Subtropical High (WPSH) exhibits both quasi-biennial (2–3 years) and low-frequency (3–5 years) oscillations. While the quasi-biennial oscillation is prominent in 1990s, the 3–5 year oscillation is dominant in 1980s. The two oscillations were attributed to the atmospheric response to the remote forcing of sea surface temperature (SST) in the maritime continent and equatorial central-eastern Pacific, respectively. The present study confirms this hypothesis. When forced by observational SST, the ensemble simulation with the NCAR CAM2 model reasonably reproduces the main characteristics of quasi-biennial oscillation and low-frequency oscillations of the WPSH. The quasi-biennial oscillation is associated with anomalous overturning circulation characterized by enhanced convection over the maritime continent and subsidence over the western North Pacific. The low-frequency oscillation is mainly modulated by remote forcing of SSTA in the equatorial central-eastern Pacific. The model reasonably reproduces the interdecadal transition of the WPSH from low-frequency oscillation in 1980s to quasi-biennial oscillation in 1990s, suggesting that the SST forcing is an essential factor to modulate the interdecadal variation of the WPSH. **Citation:** Wu, B., and T. Zhou (2008), Oceanic origin of the interannual and interdecadal variability of the summertime western Pacific subtropical high, *Geophys. Res. Lett.*, *35*, L13701, doi:10.1029/2008GL034584.

1. Introduction

[2] The western Pacific Subtropical High (WPSH) is one of the most important components of East Asian Monsoon [*Tao and Chen*, 1987]. The intensity and position of the WPSH show complex seasonal evolution. Especially in summer, with it reaching the northernmost position, the WPSH influences rainfall over China and Japan [*Tao and Chen*, 1987]. The WPSH exhibits significant interannual [*Huang and Sun*, 1992; *Chang et al.*, 2000a, 2000b; *Lu*, 2001; *Zhou and Yu*, 2005] and interdecadal variability [*Hu*, 1997; *Wang*, 2001; *Yu et al.*, 2004; *Yu and Zhou*, 2007].

[3] A recent study found that the WPSH has two distinctive oscillations at interannual time scale, corresponding to quasi-biennial (2–3 year) and lower-frequency (3–5 year) timescale, respectively. The 2–3 year oscillation is dominant in 1990s, while the 3–5 year oscillation is prominent in 1980s [*Sui et al.*, 2007]. Sui et al. proposed that these two modes may be associated with different physical processes: the 2–3 year oscillation may be caused by local monsoon-warm pool interaction [*Li et al.*, 2006; *Wang et al.*, 2008], while the 3–5 year oscillation may be associated with ENSO-East Asia teleconnection [*Wang et al.*, 2000]. However, the mechanism warrants further study. The main motivation of this study is to answer the following questions: (1) Can sea surface temperature (SST) forcing reproduce the two distinctive oscillations of the WPSH? (2) Does the interdecadal variability of the WPSH come from SST forcing? To answer these questions, we examine how well Atmospheric Global Circulation Model (AGCM) forced by observational SST simulates the two oscillations of the WPSH. In nature, there are many factors that may cause the variation of the WPSH, such as local air-sea interaction [*Chang et al.*, 2000a] and land-air interaction [*Wu and Qian*, 2003]. In this strategy, we separate SST forcing from other factors and make the mechanism simple.

2. Model and Data Description

[4] The model datasets come from the National Center for Atmospheric Research (NCAR) CAM 2.0.1 global SST-forced 15-member ensemble simulation. Fifteen simulation runs were carried out using CAM 2.0.1 (hereinafter CAM2) and observational SST from January 1949 to October 2001 by NCAR climate variability working group. The model is a global primitive equation spectral model with T42 triangular truncation and 26 vertical levels. Details of the model are described at the NCAR website (http://www.ccsm.ucar.edu/models/ccsm2.0.1/cam/camUsersGuide/). Output of the ensemble simulation has been used in many studies, e.g. the forcing of El Nino to the Southern Annular Mode [*Zhou and Yu*, 2004]. The data used in the analysis covers 1950–2000.

[5] The observational datasets used in present study consist of: (1) Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) from 1950–2000 [*Rayner et al.*, 2003]; (2) the National Centers for Environment Prediction-National Center for Atmospheric Research (NCEP-NCAR) reanalysis data from 1950–2000 [*Kalnay et al.*, 1996].

3. Results

3.1. Interannual Variability

[6] The climatological mean summer (JJA) geopotential height at 500 hPa (Z500) for the reanalysis and simulation are shown in Figure 1a. We use the isoline of 5880 gpm to represent the WPSH. The interannual variability of the WPSH is measured by the standard deviation of JJA mean Z500 (σ_z). The climatological WPSH simulated by the model is stronger than that in the reanalysis and extends westward excessively. The model reasonably reproduces the location of large σ_z region over the western North Pacific

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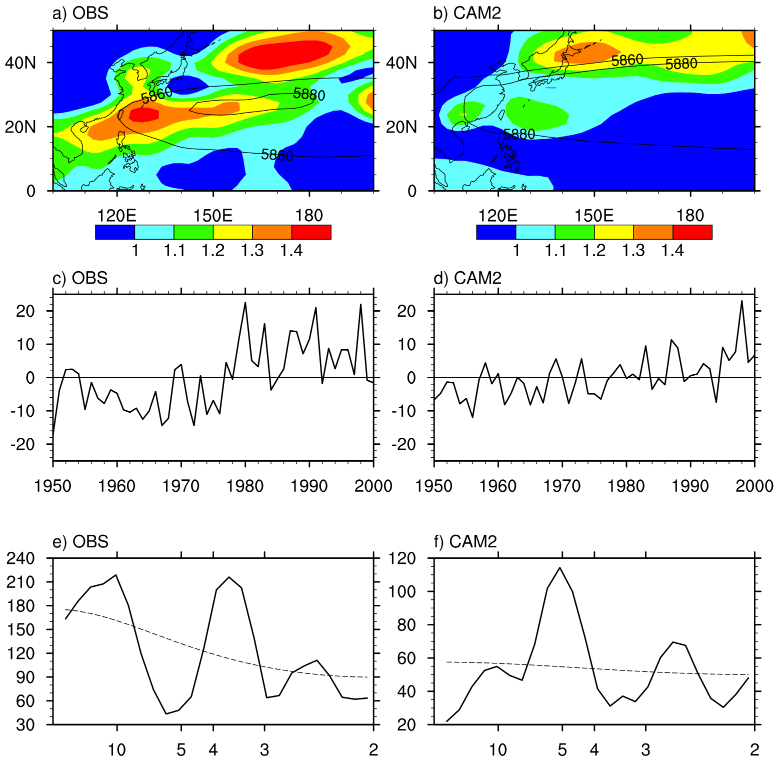

Figure 1. (a) Contours represent climatological 500 hPa geopeotential height (Z500) at 5860 m and 5880 m of observation and shading denotes spatial distribution of standard deviation of Z500 calculated by 2–6 year band-pass filtered data normalized by zonal mean value. (b) Same as Figure 1a except for the CAM2 model. (c) Time series of the observational WPSH index (15–30°N, 120–140°E). (d) Same as Figure 1c, except for the CAM2 model. (e) Power spectrum of time series of WPSH of observation. (f) Same as Figure 1e except for the CAM2 model.

(WNP), but the amplitude is weaker than that in the reanalysis. To quantify the interannual variability of the WPSH, following *Sui et al.* [2007], we define a WPSH index as the regional mean Z500 within 15°–30°N, 120–140°E, a region with large σ_z. The WPSH index time series derived from the reanalysis and the simulation are shown in Figures 1c–1d. The observed interannual variability of the WPSH is well reproduced by the ensemble simulation, having a correlation coefficient of 0.62.

[7] The power spectra of WPSH indices derived from the reanalysis and the simulation are shown in Figures 1e–1f. The reanalysis shows two significant peaks at 2.5 year and 3.6 year, respectively. The simulation has two peaks at 2.5 year and 5 year, respectively. Thus, both the quasi-biennial and low-frequency components of the interannual variability of the WPSH are reproduced by using observational SST forcing, although the simulated time period of low-frequency oscillation is slightly longer than that of the reanalysis.

[8] To separate quasi-biennial and low-frequency signals in the WPSH, we constructed two band-pass filtered time series through Fourier transition within 2–3 year and 3–6 year range. The model results are highly correlated with the observation, having a correlation coefficient of 0.49 for 2–3 year band and 0.60 for 3–6 year band (figure not shown), both of which are statistically significant at the 1% level.

[9] The quasi-biennial and low-frequency oscillations are featured with different circulations in the reanalysis [*Sui et al.*, 2007]. To examine whether the ensemble simulation can reproduce the associated circulations, we show the simulated 850 hPa wind, 500 hPa vertical pressure velocity (w500) and Z500 corresponding to 2–3 year and 3–6 year oscillations in Figure 2. All fields are shown as correlation coefficients between variables and 2–3 (3–6) year WPSH index time series. A Pacific-Japan (PJ) pattern

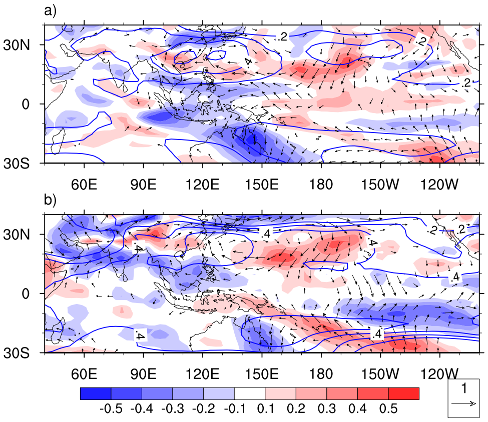

Figure 2. (a) Spatial distribution of correlation coefficients between the 2–3 year oscillation of the WPSH index and the 850 hPa wind (vector, above 0.2 is shown), 500 hPa geopotential height (contour, above 0.2 is shown) and vertical p-velocity (shading, above 0.1 or below −0.1 is shown) in the ensemble simulation. (b) Same as Figure 2a except for 3–6 year oscillation of the WPSH index.

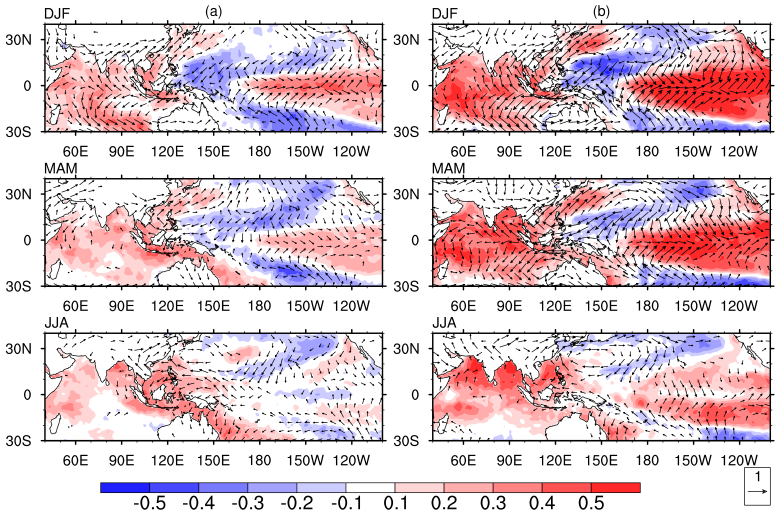

Figure 3. (a) Spatial distributions of lagged correlation coefficients between 2–3 year filtered WPSH index and SSTA (shading, above 0.1 and below −0.1 are shown) and 850 hPa wind (vector, above 0.2 is shown) in the simulation. (b) Same as Figure 3a except for 3–6 year filtered WPSH index.

[*Nitta*, 1987; *Huang and Sun*, 1992] stands out in the w500 field associated with 2–3 year oscillation: a significant ascent is seen over the maritime continent, with subsidence over the Philippine Sea, and ascent extending from the middle and lower reaches of the Yangtze River valley to the south of Japan. The anomalous low-level anticyclone over the WNP and the enhanced WPSH are related to the subsidence over the Philippine Sea. The circulation anomalies closely resemble the observation [*Sui et al.*, 2007].

[10] For the 3–6 year oscillation, the anomalous subsidence and corresponding anomalous low-level anticyclone and enhanced WPSH are also seen over the WNP (Figure 2b). However, contrast to the 2–3 year oscillation, the subsidence over the WNP is mainly related to significant ascent over the equatorial central-eastern Pacific. We note that the ascent center is located to the south of the equator, which is consistent with the reanalysis. The suppressed convection over the maritime continent is not able to suppress convection over the WNP through anomalous meridional overturning circulation.

[11] Previous study suggested that coupled ocean-atmosphere processes are crucial in the Asian-Australian monsoon regions where atmospheric feedback to local SST is very significant; treating monsoon as a slave would result in the failure of simulation [*Wang et al.*, 2005; *Wu and Kirtman*, 2007]. However, the observed oscillations of the WPSH are reasonably simulated by the CAM2 model with only SST forcing, suggesting that remote forcing of SST anomalies (SSTA) should play important roles in modulating the interannual variability of the WPSH. To reveal the contribution of SSTA, we show evolutions of SSTA from preceding winter to summer associated with two oscillations in Figure 3. The pattern is revealed by calculating lag correlations between SSTA and filtered WPSH index. For the 2–3 oscillation, an anomalous low-level anticyclone, which is believed to be a Rossby wave response to a negative heating due to cold water in situ, fully establishes over the WNP in winter. Warm SSTA are seen in the equatorial central-eastern Pacific and entire tropical Indian Ocean. In the following spring, the anticyclone maintains in the WNP. The warm SSTA in the equatorial central-eastern Pacific and cold SSTA in the WNP gradually weaken, but the Indian Ocean SSTA still maintains. In summer, warm SSTA in the equatorial central-eastern Pacific and cold SSTA in the WNP decay, but the cold SSTA surrounding the maritime continent still maintain, which play an essential role in supporting the WNP anticyclone through strengthening the local Hadley circulation.

[12] For the 3–6 year oscillation (Figure 3b), the evolution of SSTA resembles that of 2–3 year oscillation in winter and spring except for stronger intensity. A significant difference is seen in summer: the warm SSTA still exist in the equatorial central-eastern Pacific, although with a weaker amplitude relative to that in the preceding winter and spring. The strongest warming of the Indian Ocean is located in the Northern Hemisphere, as evidenced in the observation [*Sui et al.*, 2007].

[13] In summary, although there are some discrepancies, the model results confirm that the quasi-biennial oscillation of WPSH is primarily forced by SSTA in the maritime continent through Hadley circulation anomalies, while the low-frequency variability may be primarily caused by the ENSO remote forcing.

3.2. Interdecadal Variability

[14] In observation, two oscillations of the WPSH show significant interdecadal variability, with the 1980s saw dominant low-frequency, and the 1990s saw prominent quasi-biennial oscillation [*Sui et al.*, 2007]. To examine whether this interdecadal variability can be reproduced by prescribed SST forcing, we perform wavelet analysis on the WPSH indices derived from both the reanalysis and the simulation (Figure 4). The amplitude of interannual variability of the WPSH in the simulation (Figure 4b) is weaker than that in the reanalysis (Figure 4a). Nonetheless, the observed interdecadal transition of the WPSH at the end of 1980s is reasonably reproduced. The time period of low-frequency oscillation during 1970s and 1980s in the simulation is longer than that in the observation, with 4-5 year

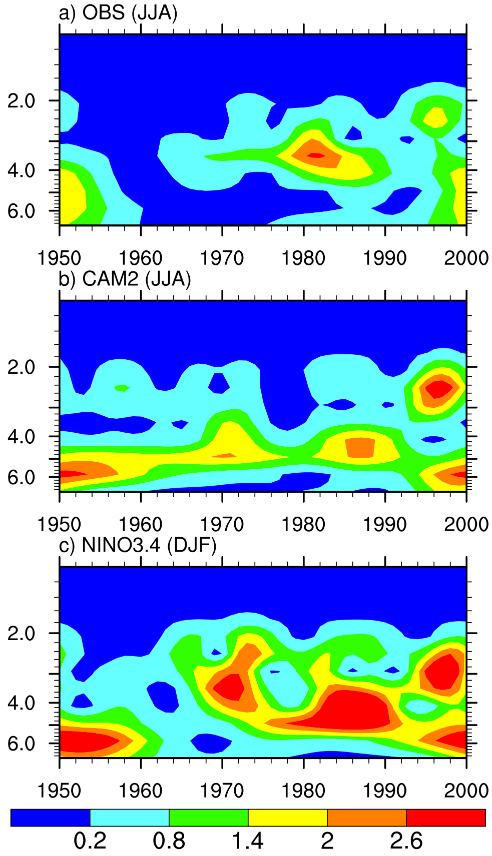

Figure 4. Wavelets power spectrum of (a) JJA WPSH index of observation, (b) JJA WPSH index of CAM2, and (c) previous DJF NINO3.4 index. All the indices are standardized.

versus 3–4 year. We speculate that the results are associated with the prescribed ENSO forcing. Paralleling wavelet analysis on Nino3.4 index, i.e. regional average of SSTA over 5°S–5°N, 190°–240°E, is shown in Figure 4c. The result closely resembles Figure 4b, with the power mainly concentrating within the band of 4–5 years during 1980s. This close resemblance suggests that the equatorial central-eastern Pacific SSTA are the dominant forcing mechanism responsible for the low-frequency oscillation of the WPSH in the simulation. The relatively shorter period of observational low-frequency oscillation, compared with that of Nino3.4 index, indicates that the SSTA should not be the unique mechanism driving the oscillations of the WPSH in nature. Previous study suggested that the accumulated winter snow over the Tibetan Plateau tends to modulate the geographical location of the WPSH in the subsequent summer through changing land-sea thermal contrast [*Wu and Qian*, 2003].

4. Summary and Discussion

4.1. Summary

[15] A recent observational analysis found that the interannual variation of the WPSH has two dominant time scales: quasi-biennial oscillation (2–3 year) and low-frequency oscillation (3–6 year). The two types of oscillations show significant interdecadal variability [*Sui et al.*, 2007]. By employing AMIP model approach, we have shown that major features of two oscillations of WPSH and their interdecadal variability are highly reproducible from atmospheric response to observational SST forcing. The model results confirm that the two oscillations of WPSH are attributed to different remote forcing. The quasi-biannual oscillation is caused by the SSTA in the maritime continent, while the low-frequency oscillation is resulted from remote forcing of SSTA in the equatorial central-eastern Pacific. The two oscillations of the WPSH follow an ENSO event in preceding winter. The most prominent difference between two oscillations is whether the equatorial central-eastern Pacific SSTA decay in summer. In quasi-biennial oscillation, with the decay of the equatorial central-eastern Pacific SSTA, the enhanced convection over the maritime continent suppresses convection over the WNP through anomalous meridional circulation. On the contrary, in the low-frequency oscillation, the equatorial central-eastern SSTA maintain from preceding winter to summer. The warm SSTA enhance convection over the equatorial central Pacific, which in turn suppresses convection over the WNP and the maritime continent.

[16] The two interannual oscillations of the WPSH show significant interdecadal variability, with the 1980s saw the low-frequency oscillation, while the 1990s saw a prominent quasi-biennial oscillation. This interdecadal scale transition is reasonably reproduced by an AGCM, indicating that it may be attributed to the corresponding interdecadal variation of the SST in the equatorial central-eastern Pacific.

4.2. Discussion

[17] The study substantiates the proposed mechanism that the SST forcing in the tropics plays a crucial role on the variability of WPSH. The study also demonstrates a certain predictability of WPSH if global SST can be reasonably predicted. This result should be useful for climate predictability in East Asia. It is also important to acknowledge the limitations of the study. First, the time period of low-frequency oscillation of the WPSH in the simulation is close to that of Nino3.4 index, implying that the variability of the WPSH in the simulation is purely a response to El Nino forcing. In observation, however, the time period of low-frequency oscillation of the WPSH is shorter than that of Nino3.4 index. This difference should be resulted from the absence of some other forcing mechanisms in the simulation. Second, for the low-frequency oscillation of the WPSH, the response of the model to North Indian Ocean SSTA has some biases. Observational analysis shows no significant ascending motion over the North Indian Ocean associated with a warm SST, suggesting that the warm SST is a passive response to atmospheric forcing [*Sui et al.*, 2007]. In the model results, however, a strong ascending motion is seen over the North Indian Ocean, which may contribute to the easterly over the Philippine Sea through suppressing the convection over the WNP.

[18] In addition, previous studies argued that in the regions where SSTA is partly forced by the atmosphere, the AMIP-type simulation is unable to correctly reproduce the observed precipitation anomalies [*Wang et al.*, 2005; *Wu and Kirtman*, 2007]. Our results show that although WNP is a significant region where atmosphere forces ocean in summer [*Wang et al.*, 2005], the AMIP-type simulation still

captures the main features of the interannual and interdecadal variation of the WPSH. Thus we may not simply conclude that AMIP-type simulation has no skill in the regions where the atmosphere forces the ocean.

[19] **Acknowledgments.** This work is jointly supported by the National Basic Research Program of China (2006CB403603) and the National Natural Science Foundation of China under grants 40523001, 40628006, and 40625014. We also appreciate the comments from the reviewer.

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