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Responses of the western North Pacific Subtropical High to global warming under RCP4.5 and RCP8.5 scenarios projected by 33 CMIP5 models: The dominance of tropical Indian Ocean – tropical western Pacific SST gradient

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Abstract

Using the outputs of 33 coupled models participated in the Fifth Phase of Coupled Model Intercomparison Project (CMIP5), the changes of the western North Pacific subtropical high (WNPSH) in the 2050-2099 period under RCP4.5 and RCP8.5 scenarios relative to the 1950-1999 period are analyzed. Under both scenarios, the projected changes in the WNPSH intensity are approximately zero in the multi-model ensemble mean (MME), and large inter-model spread is seen. About half of the models project an enhanced WNPSH and about half of the models project a weakened WNPSH under both scenarios. As revealed by both diagnostic studies and numerical simulations, the projected change in the WNPSH intensity is dominated by the change in the zonal Sea Surface Temperature (SST) gradient between the tropical Indian Ocean (TIO) and the tropical western Pacific (TWP). A stronger (weaker) warming in the TIO is in favor of an enhanced (weakened) WNPSH, and a weaker (stronger) warming over the TWP is also in favor of an enhanced (weakened) WNPSH. The projected change of the WNPSH modulates the climate change over eastern China. Under both RCP4.5 and RCP8.5 scenarios, all of the models with a significantly increased (decreased) WNPSH are associated with a significant increase in the precipitation over the northern (southern) part of eastern China, and an enhanced (weakened) southerly wind.

Keywords: western North Pacific subtropical high, global warming, zonal SST gradient, CMIP5
1. Introduction

The western North Pacific Subtropical High (WNPSH) in the lower troposphere is a crucial system to the summer climate in East Asia. The winds associated with the WNPSH transport water vapor from the tropical oceans into East Asia via the low level southerly wind on its western edge (Zhou and Yu 2005). The major rain belt in East Asia is located on the northwestern edge of the WNPSH where the southerly wind encounters the cold air mass. From late spring to summer every year, the northward jumps of the WNPSH ridge correspond to the northward jumps of the major rain belt in East Asia (Tao and Chen 1987).

The variability of the East Asian climate in summer is regulated by the WNPSH on both interannual and interdecadal time scales. The interannual variability of the circulation over the western North Pacific (WNP) is the largest among the subtropical Northern Hemisphere (Lu et al. 2001; Sui et al. 2007; Wu and Zhou 2008; Chung et al. 2011), which greatly affects the summer precipitation anomaly over East Asia. The WNPSH connects El Niño-Southern Oscillation (ENSO) signal with the climate in East Asia (Tao and Zhang 1998; Chang et al. 2000). The Yangtze-Huai River Valley along 30°N over East Asia usually suffers excessive precipitation during the decay phase of the El Niño events when the WNPSH is anomalously strong and displaced southward (Tao and Zhang 1998; Zhang and Tao 2003; Wu et al. 2009). The interdecadal change of the WNPSH also modulated the late 1970s’ decadal climate regime shift in East Asia (Zhou et al. 2009a; Xie et al. 2010a; Huang et al. 2010).

The dynamical and physical processes that affect the interannual variation of the
WNPSH have been well understood. Although El Niño events usually decay in boreal spring, their impact on the summer WNPSH can be maintained by the air-sea interaction in the Indo-Pacific warm pool. The warm Sea Surface Temperature (SST) anomaly in the tropical Indian Ocean (TIO) increases the local rainfall and triggers a warm Kelvin wave emanating into the tropical western Pacific (TWP), with low pressure over the TIO and the equatorial western Pacific. The combined effects of the pressure gradient and friction within the Ekman layer drive an anomalous divergent motion and anticyclonic circulation over the WNP. The above mechanism is called Kelvin wave induced Ekman divergence, which explains the impact of TIO SST on the WNPSH (Yang et al. 2007; Li et al. 2008; Xie et al. 2009; Wu et al. 2009; Kosaka et al. 2013). The cold SST anomaly over the equatorial Pacific is also in favor of an enhanced WNPSH via stimulating anticyclonic Rossby wave to its northwest (Wang et al. 2013; Xiang et al. 2013). Therefore, it is recognized that the increased zonal SST gradient between a warm TIO and a cold tropical Pacific Ocean enhances the WNPSH (Terao and Kubota 2005; Chen et al. 2012; Cao et al. 2013). The WNPSH can also be enhanced by the descending branch of the enhanced local Hadley circulation induced by the warm SST anomaly over the maritime continent (Sui et al. 2007; Wu and Zhou 2008; Chung et al. 2011), or enhanced by anticyclonic Rossby wave generated by local cold SST anomaly over the WNP (Wang et al. 2000; Wu et al. 2010; Wang et al. 2013).

In comparison to the interannual variability, how the WNPSH responds to global warming is not well understood. Climate model projections show a weakened Walker
circulation and Hadley circulation under global warming (Lu et al. 2007; Vecchi and Soden 2007; Gastineau et al. 2009; Bony et al. 2013; Ma and Xie 2013). The projected change of large scale rainfall pattern exhibits a “wet-get-wetter” (Held and Soden 2006) or a “warmer-get-wetter” pattern (Xie et al. 2010b) over tropical oceans. The low level southerly wind associated with the East Asian Summer Monsoon may become stronger, as a result of the enhanced low level thermal contrast between the East Asia and the WNP (Chen et al. 2011; Sun and Ding 2011; Jiang and Tian 2013). A stronger interannual variability is projected for the East Asian summer rainfall (Lu and Fu 2010). In comparison to these studies, less effort has been devoted to the changes of the WNPSH (Li et al. 2012). In this study, we aim to answer the following questions: How would the intensity of the WNPSH change under global warming scenarios? What is the driving mechanism? How would the projected change of WNPSH affect East Asian climate?

This remainder of the paper is organized as follows. Section 2 describes the models, data and methods. A brief model evaluation is done in Section 3. Section 4 documents the projected change of the WNPSH, its connection with the tropical warming pattern, and its association with the precipitation in eastern China. Section 5 summarizes the major findings.

2. Model, data and method

The 33 coupled models employed in this study are from the Fifth Phase of Climate Model Intercomparison Project (CMIP5) (Taylor et al. 2012), which are used in the Fifth Assessment Report of Intergovernmental Panel on Climate Change. The
information about the 33 models is listed in Table 1. For each model, the outputs of “Historical”, “RCP4.5” and “RCP8.5” experiments are selected for analysis. The RCP4.5 is a radiative forcing pathway to 4.5 W/m² (equivalent to 650 ppm CO₂ concentration) by 2100 without overshoot, and the RCP8.5 is a rising radiative forcing pathway leading to 8.5 W/m² (equivalent to 1370 ppm CO₂ concentration) by 2100 (Vuuren et al. 2011). Since very few models contain multiple realizations in the “RCP4.5” and “RCP8.5” experiments, only the first realization (r1i1p1) of each model is adopted in most parts of this paper. To examine the impact of the natural variability of the climate system, multiple realizations from three models (IPSL-CM5A-LR, MIROC5, and MPI-ESM-LR) are analyzed.

Given the uncertainty of observation (Collins et al. 2013; Sperber et al. 2013; Jourdain et al. 2013), multiple observational and reanalysis data (hereafter referred to as “observation”) are employed to evaluate the models. The rainfall data used in this study include the GPCP v2 precipitation data (Adler et al. 2003) and the CMAP precipitation data (Xie and Arkin 1997). The reanalysis data used in this study include NCEP1 (Kalnay et al. 1996), NCEP2 (Kanamitsu et al. 2002), ERA40 (Uppala et al. 2005), ERAIM (Dee et al. 2011), and JRA25 (Onogi et al. 2007) datasets.

We focus on the boreal summer season (June, July and August, JJA for short). All the model data are interpolated onto the same 2.5°×2.5° grid as the NCEP2 data before analysis. Since the geopotential height systematically increases along with global warming according to the hydrostatic equation (Yang and Sun 2003; He et al. 2013), it is hard to distinguish whether an increase of the geopotential height in a certain region
is associated with an enhanced anticyclonic circulation or not. Therefore, we mainly focus on the wind field instead of geopotential height field. To quantitatively evaluate the WNPSH intensity, a WNPSH index is defined as the difference of the zonal wind at 850 hPa between 25°N-35°N, 120°E-150°E and 10°N-20°N, 130°E-150°E. This kind of index denotes the anticyclonic wind shear over the WNP and has been widely used in monsoon diagnostic and modeling studies (Wang et al. 2008; Xie et al. 2009; Zhou et al. 2009b; Huang et al. 2010).

To evaluate the model performances on the mean state and the interannual WNPSH-SST relationship, we compare the 1980-1999 period of Historical run with the observation, due to the available time scope of the observation. The precipitation, 850 hPa wind and geopotential height are examined in the mean state evaluation. In the evaluation of the interannual WNPSH-SST relationship, 8-year high-pass Fourier filter is applied on the WNPSH index and SST to obtain the interannual variation.

For the projection of climate change, we focus on the difference between the 2050-2099 period in the RCP4.5/RCP8.5 experiment and the 1950-1999 period in the Historical experiment. The multi-model ensemble mean (MME) is calculated as the algebraic average of the 33 models. This MME technique is helpful to suppress model drift and internal variability (Gupta et al. 2013). We use “inter-model consistency” to evaluate the robustness of the MME projected changes. For a scalar field (e.g., zonal wind), “inter-model consistency” is defined as the percentage of the individual models which project the same sign of change as the MME. For a vector field (e.g., wind), the “inter-model consistency” is defined as the maximum of the inter-model consistencies.
of the zonal wind and the meridional wind. Scatter diagrams are also shown for the individual models, to diagnose the relationship between the changes in the WNPSH index and the changes in other variables. Student’s t test is performed to determine the significance of the inter-model relationship in the scatter diagrams. The 95% and 99% confidence levels for a correlation of 33 models are ±0.34 and ±0.44, respectively.

To investigate the inter-model relationship between the changes in the WNPSH and the SST warming pattern, each model is treated as a sample and inter-model regression is done by regressing the mean state changes in SST onto the changes in the WNPSH index. Similar regression analysis is done for the precipitation and tropospheric temperature fields, to diagnose the air-sea relationship and the possible forcing mechanisms. Following previous studies (Xie et al. 2009), the tropospheric temperature is examined to identify the tropical waves (Kelvin wave and Rossby wave). The tropospheric temperature is calculated as the difference of the geopotential height between 200 hPa and 850 hPa multiplied by a constant, according to the hydrostatic equation.

To reveal which part of the regressed SST pattern is responsible for the inter-model spread of WNPSH changes, numerical experiments are done using Community Atmospheric Model version 4 (CAM4) (Neale et al. 2010). CAM4 is one of the best models in simulating the leading interannual mode of the WNPSH (He and Zhou 2014). The CAM4 is run with a finite-volume dynamic core, at a resolution of approximately 1.9°×2.5° in the horizontal and 26 hybrid \( \sigma-p \) levels in the vertical. Control run is done for 20 years forced by observational monthly SST climatology.
Several sensitivity experiments are performed, forced by modified SST. The modified SST is obtained by adding SST anomaly to the observational SST climatology over a specific region. Each sensitivity experiment contains 20 ensemble members, which are initialized at each May 1st in the 20-year Control run. Each ensemble member is run for four months until Aug 31st, and the outputs of JJA are analyzed. Student’s $t$ test is performed on the composite of the 20 ensemble members to determine the significant forced signals against atmospheric internal noise.

3. Model evaluation on the mean state and the interannual WNPSH - SST relationship

The climatological circulation over the WNP in summer is characterized by a low level WNPSH, the ridgeline of which extends to the southeast coast of China. Abundant rainfall is seen on the periphery of the WNPSH, covering the western coast of the Philippines, eastern China and Japan (Fig. 1a). The climatological precipitation and low level circulation is reasonably reproduced by the MME of the CMIP5 models, including the anticyclonic winds and the abundant rainfall on the periphery of the WNPSH (Fig. 1b). The major bias in the circulation field is the northward displaced ridgeline, as evidenced in the wind and eddy geopotential height fields (eddy geopotential height is the deviation of geopotential height from its zonal mean). The northward displacement of the WNPSH ridgeline is also a common bias in CMIP3 models (Inoue and Ueda 2009).

The difference of the climatological winds between the MME and the NCEP2 (vectors in Fig. 1c) is characterized by a cyclonic anomaly over southern WNP
(10°N-30°N) and an anticyclonic anomaly over northern WNP (30°N-45°N), consistent with the northward displaced ridgeline in the MME. This mean state wind bias is consistent among the five reanalysis datasets (figure not shown). Excessive (deficient) rainfall is seen over the southern (northern) periphery of the WNPSH when compared to GPCP data (shading in Fig. 1c) or CMAP data (contours in Fig. 1c), consistent with the previous findings that coupled models generally underestimate the Meiyu-Baiu rain belt (Sperber et al. 2013). Large discrepancy between GPCP and CMAP data is seen around the Philippines. The climatological precipitation rate of the MME is greater than the GPCP data but smaller than the CMAP data over the South China Sea (SCS), and approximately equivalent to the GPCP data but smaller than the CMAP data off the eastern coast of the Philippines. The uncertainty among precipitation datasets has been noted by many previous studies (e.g., Collins et al. 2013; Sperber et al. 2013; Jourdain et al. 2013).

Since the interannual variability of the WNPSH is regulated by the tropical SST, the simulated correlation of the WNPSH with the SST at interannual time scale is evaluated against the observation. In the observation, the most prominent feature of the correlation pattern is the positive correlation between the WNPSH and the TIO SST, while negative correlation between the WNPSH and the WNP SST is also seen (Fig. 1d). These WNPSH-SST relationships on interannual time scale can be captured by the MME, but with weaker magnitude (Fig. 1e).

The above evaluation shows the northward displaced ridgeline is the major bias in the mean state simulation, while the positive correlation between WNPSH and TIO
SST is the most prominent feature on the interannual time scale. To quantitatively evaluate the model performance, scatter diagram for the five reanalysis datasets and the 33 models is shown in Fig. 1f. The abscissa of Fig. 1f is the latitude of the climatological ridgeline (defined as the 130°E-150°E averaged latitude of the interface between the trade easterlies and the mid-latitude westerlies), and its ordinate is the correlation coefficient between WNPSH index and TIO SST on interannual time scale (TIO is referred to as 10°S-10°N, 50°E-100°E, see the box in Fig. 1d).

Among the five reanalysis datasets (the red letters “1”, “2”, “3”, “4”, “5” in Fig. 1f), the climatological locations of the ridgeline range from 24.7°N (NCEP1 and NCEP2) to 25.5°N (JRA25), with small observational uncertainty. The location of the WNPSH ridge is 26.9°N in the MME, which is displaced northward compared with the observation. The locations of the ridgeline range from 21.9°N (FGOALS-g2) to 31.7°N (CESM1-BGC and CSIRO-Mk3.6.0), and the northward displacement of the ridgeline is seen in 25 of the 33 models. The correlation coefficient between the WNPSH index and the TIO SST is approximately 0.64 for all the reanalysis datasets. This positive correlation is captured but underestimated by the MME (0.24) and most of the individual models.

4. Projected changes of the WNPSH

The projected change of JJA 850 hPa wind under RCP4.5 scenario by the MME is shown in Fig. 2a, with the inter-model consistency among the models. Since the region with low model consensus is also a useful information indicating insensitivity to climate change (Power et al. 2012), the regions where the projected change is
smaller than the inter-model standard deviation of projected changes are marked with red crosses. An anomalous southerly wind is seen in eastern China and the inter-model consistency is larger than 70% over North China, indicating an enhanced monsoon circulation, which is consistent with previous studies (Sun and Ding 2011; Jiang and Tian 2013). Although westerly wind seems to be enhanced off the southern coast of Japan, the inter-model consistency is less than 70% over the WNP, and the MME projected change is smaller than the inter-model standard deviation of the projected changes by the individual models. These suggest a large spread among the model results. The trade easterlies along the equatorial Pacific are weakened, which is consistent with previous findings that the Walker circulation will weaken due to global warming (e.g. Vecchi and Soden 2007), but this weakening is evident in less than 70% of the models.

Under RCP4.5 scenario, the changes of the WNPSH index are closely related to the changes of the 500 hPa vertical velocity and the precipitation among the models, in a manner that increased (decreased) WNPSH index corresponds to enhanced (weakened) descending motion and decreased (increased) precipitation over the WNP (Figs. 2b,c). The correlation coefficients with the WNPSH index are 0.67 and -0.49 for the local vertical velocity and precipitation respectively, which are statistically significant at the 99% confidence level based on $t$ test. As the WNPSH index based on the zonal wind is physically consistent with the vertical velocity and the precipitation, it is referred to as “WNPSH intensity” hereafter. The projected changes of WNPSH intensity under RCP4.5 scenario by the individual models are between a decrease of
1.31 m/s (CMCC-CM) and an increase of 1.69 m/s (HadGEM2-AO) (Fig. 2b, c, abscissa).

Under RCP8.5 scenario, the projected change of wind over the WNP shares similar spatial pattern with the RCP4.5 scenario but with stronger amplitude (Fig. 2d). The inter-model consistency is still lower than 70%, and the MME projected change is still small than the inter-model standard deviation over the WNP. Under RCP8.5 scenario, the projected change of WNPSH intensity are between a decrease of 1.73 m/s (CMCC-CM) and an increase of 2.30 m/s (MIROC5) for the individual models (Fig. 2e, f, abscissa). This range is larger than that of RCP4.5 scenario, since stronger external forcing is imposed on the models. The MME projected change in WNPSH intensity remains approximately zero (Fig. 2e, f). The MME projects unchanged vertical velocity at 500 hPa (Fig. 2e) and an increase of precipitation over WNP (Fig. 2f), indicating this increase of precipitation is caused by the increased water vapor content in the troposphere (Bony et al. 2004; Held and Soden 2006). The correlation coefficients between the projected changes in the vertical velocity (precipitation) and the changes in WNPSH intensity is 0.61 (-0.55), which are statistically significant at the 99% confidence level based on t test.

The WPNSH intensity here is defined as the zonal wind shift between a northern box and a southern box. The locations of the northern and the southern boxes are unified for all the models. As shown in Fig.1f, the mean state locations of the WNPSH ridgeline are biased in many models. Is the projected change of the WNPSH intensity related to the bias in the mean state? To address this question, we shifted the...
meridional location of the northern and the southern boxes for each model, so that
these two boxes are located symmetrically about the ridgeline of the model. It is found
that the projected changes of this modified WNPSH index is highly consistent with
the WNPSH intensity index used in this study (figure not shown). Under both
scenarios, the changes of the WNPSH intensities has little relationship with the
latitude of the climatological ridgeline (figure not shown). These evidences suggest
the biases in the mean state location of the WNPSH ridgeline has little effect on the
projected changes in the WNPSH intensity.

To investigate the relationship between the RCP4.5 projected change and the
RCP8.5 projected change, the projected changes of WNPSH intensities under RCP4.5
scenario versus RCP8.5 scenario are shown as scatter diagram (Fig. 3a). 27 of the 33
models are located in the first or the third quadrant, indicating the signs of changes in
the WNPSH intensity are the same under RCP4.5 and RCP8.5 scenarios for most
models. The inter-model regression equation of Fig. 3a is Y=1.03X-0.06, indicating a
slightly stronger change of the models under RCP8.5 scenario than RCP4.5 scenario.
Among the 33 models, 20 models (60.6%) project an increase and 13 models (39.4%)
project a decrease of the WNPSH intensity under RCP4.5 scenario, 18 models (54.5%)
project an increase and 15 models (45.5%) project a decrease of the WNPSH intensity
under RCP8.5 scenario. In summary, roughly half of the models project an enhanced
WNPSH and half of the models project a weakened WNPSH under both scenarios.

Table 2 lists the models in which the WNPSH intensities are significantly
changed at the 95% confidence level according to t test based on the interannual
variability. The models with a significant increase (decrease) of the WNPSH intensity are referred to as P-type (N-type) models. Among the 33 models, there are 7 P-type models under RCP4.5 scenario and 9 P-type models under RCP8.5 scenario. Only 5 models (FOALS-g2, IPSL-CM5A-MR, MIROC-ESM, MIROC-ESM-CHEM, and MIROC5) belong to P-type under both RCP4.5 and RCP8.5 scenarios. The P-type models are not highly consistent between RCP4.5 and RCP8.5 scenarios, maybe due to the natural variability of the climate system. The N-type models are exactly the same under RCP4.5 and RCP8.5 scenarios, including CMCC-CM, inmcm4, IPSL-CM5B-LR, and MPI-ESM-LR. The P-type (N-type) models are colored in red (blue) in Figs. 2b-c, and Figs. 2e-f. Apart from the P-type and N-type models, the other 22 (20) models project no significant change in the WNPSH intensity under RCP4.5 (RCP8.5) scenario.

How large is the natural variability? Can the natural variability overwhelm the forced response in the difference between the RCP4.5 (or RCP8.5) run and the Historical run? To answer this question, three models (IPSL-CM5A-LR, MIROC5, and MPI-ESM-LR) which contain multiple realizations are selected. Under both scenarios, MIROC5 belongs to P-type models, MPI-ESM-LR belongs to N-type models, and IPSL-CM5A-LR projects no significant change in the WNPSH intensity (Table 2). Fig. 3b shows the projected changes in the WNPSN intensity for all possible combinations of the ensemble members. It can be seen from Fig. 3b that the natural variability is not large enough to overwhelm the forced response, since the multiple realizations of one model is clearly distinguishable from another model. It
can also be inferred that the inter-model spread (e.g., Fig. 3a) can not be explained by natural variability, but is related to the different forced responses of different models.

Why do the WNPSH intensities increase in some models but decrease in some other models under the same external forcing? Previous studies showed evidences that the SST pattern of tropical oceans affects the WNPSH at interannual and inter-decadal time scales (e.g., Terao and Kubota 2005; Xie et al. 2009; Zhou et al. 2009a; Wu et al. 2010; Wang et al. 2013). To examine the relationship between the changes in WNPSH and the tropical SST pattern, we show the inter-model regression of changes in SST and 850 hPa winds onto the changes in WNPSH intensity under RCP4.5 scenario in Fig. 4a. The regressed pattern under RCP8.5 scenario (figure not shown) is similar to Fig. 4a.

As seen in Fig. 4a, the changes of the SST pattern associated with an enhanced WNPSH is characterized by stronger warming of SST over the TIO, the Bay of Bengal and South China Sea (BOB&SCS, 10°N-20°N, 80°E-120°E), the Niño3 region (5°S-5°N, 150°W-90°W) and mid-latitude Pacific, and relatively weaker warming of SST over the tropical western Pacific (TWP, 10°S-10°N, 150°E-180°). This SST pattern resembles the interannual SST-WNPSH relationship (Fig. 1d). Associated with the zonal SST gradient between strongly warmed TIO and weakly warmed TWP, easterly wind is seen from TWP to TIO in the regressed wind field, consistent with the mechanism of low-level wind response to SST gradient (Lindzen and Nigam 1987). Although warmer SST is seen in Niño3 region (Fig. 4a), it may not be responsible for the enhanced WNPSH, according to previous studies (Wang et al. 2013; Xiang et al.
The inter-model regression of the changes in precipitation and tropospheric temperature onto the changes in WNPSH intensity under RCP4.5 scenario is shown in Fig. 4b. The spatial pattern is similar as Fig. 4b for the RCP8.5 scenario (figure not shown). The enhanced WNPSH is associated with increased precipitation over the TIO, which may be forced by the warmer SST over the TIO. Negative rainfall anomalies are seen over BOB&SCS, accompanied by warmer SST (see Fig. 4a), indicating the warmer SST in this region may be forced by the atmosphere. The WNP is dominated by negative rainfall anomaly but warmer SST, suggesting the negative rainfall anomaly (and anticyclonic wind anomaly) is not locally forced but remotely forced.

The tropospheric temperature field is characterized by two prominent features associated with enhanced WNPSH (Fig. 4b). The first is a wedge-like warm anomaly centered over the TIO and pointing eastward into the TWP along the equator. This pattern suggests a Kelvin wave forced by the positive heat source over the TIO (Gill 1980; Xie et al. 2009). The second is two relatively cold anomalies over the WNP and Australia, which are symmetric about the equator and are located on the northwest and southwest side of the colder SST of TWP (see Fig. 4a). This pattern may be induced by Rossby wave response to the relatively cold SST of TWP (Gill 1980; Wang et al. 2013; Xiang et al. 2013). The above mentioned features indicate the inter-model spread may be dominated by the forcing from TIO/TWP or both of them.

Scatter diagrams in Figs. 4c-f show the relationship between the changes in the
WNPSH intensities and the changes in the SST over some key regions, for the RCP4.5 scenario (blue) and RCP8.5 scenario (red), respectively. No matter under RCP4.5 or RCP8.5 scenarios, the changes in the WNPSH intensity are very weakly correlated with the changes in the tropical mean (20°S-20°N averaged) SST (Fig. 4c), the TIO SST (Fig. 4d) and the TWP SST (Fig. 4e), as evidenced by the poor linear relationship of the scatters and the correlation coefficients (Figs. 4c-e). However, the changes in WNPSH intensity and the changes in TIO-TWP SST gradient (defined as TIO SST minus TWP SST) are significantly correlated at the 95% confidence level, with a correlation coefficient of 0.53 and 0.42 for the RCP4.5 and RCP8.5 scenarios respectively (Fig. 4f). These correlation coefficients are 0.64 and 0.57 for RCP4.5 and RCP8.5 scenarios if the outlier model CSIRO-Mk3.6.0 (“L” in Fig. 4f) is excluded, exceeding the 99% confidence level. Previous studies showed 0.5 K SST anomaly over the TIO is enough to stimulate prominent wind anomaly over the WNP at interannual time scale (Xie et al. 2009; Wu et al. 2010). The projected changes in the TIO-TWP SST gradient range from -0.2 K to 0.5 K (Fig. 4f), which are large enough to result in distinct responses of the WNPSH.

To further confirm which regions are responsible for the projected changes in the WNPSH intensity, we examined the response of CAM4 to the SST anomalies of specified regions picked from the regressed field in Fig. 4a, including Niño3 region, BOB&SCS, TIO and TWP (the boxes in Fig. 4a). To obtain stronger model response, the SST anomalies picked from Fig. 4a are multiplied by a factor of 5. The details of the experimental design are described in Section 2 and the responses of the
precipitation and 850 hPa winds over the WNP are shown in Fig. 5.

The response of CAM4 to the warm SST anomaly of Niño3 region in Fig. 4a is characterized by significant westerly wind anomaly over the TWP, without anomalous anticyclonic circulation (Fig. 5a). The response of CAM4 to the warm SST anomaly of BOB&SCS is characterized by an anomalous cyclonic circulation on the southeast coast of China, accompanied by positive rainfall anomaly (Fig. 5b). These indicate neither the Niño3 region nor BOB&SCS are responsible for the inter-model spread of the changes in the WNPSH intensity. Based on the negative rainfall-SST relationship over the BOB&SCS (Figs. 4a, b), it can be inferred that the warmer SST over the BOB&SCS in Fig. 4a is a forced response to atmosphere.

As a response to the warm SST anomaly of TIO in Fig. 4a, the WNP is dominated by anticyclonic wind anomaly at 850 hPa, with suppressed rainfall on its southern flank (Fig. 5c). This response to TIO forcing can be explained by Kelvin wave induced Ekman divergence (Terao and Kubota 2005; Xie et al. 2009). As a response to the SST anomaly over the TWP, the WNP is also dominated by anticyclonic wind anomaly (Fig. 5d), which is located to the northwest of the negative SST anomaly of TWP, reminiscent a Rossby wave response (Gill 1980; Wang et al. 2013; Xiang et al. 2013). If the warm SST anomaly of TIO and the cold SST anomaly of TWP are both picked from Fig. 4a to force CAM4, a significant anticyclonic anomaly and negative rainfall anomaly is also seen over the WNP (figure not shown).

In comparison to the regressed field in Fig. 4a, the CAM4 simulated anomalous anticyclones over the WNP are all displaced southward (Figs. 5c, d). The southward
displacement of this anomalous anticyclone is a common bias in the AGCMs of CMIP3 and CMIP5 (Song and Zhou 2014). Given this model bias, a modified WNPSH index is defined as the difference in the zonal wind between 20°N-30°N, 100°E-130°E and 5°N-15°N, 100°E-130°E (red boxes in Fig. 5a-d), to quantitatively evaluate the response of the WNPSH intensity in CAM4. The responses of the modified WNPSH indices for the five sensitivity experiments mentioned above are shown as bar chart in Fig. 5e. Significant increase in the modified WNPSH index at 95% confidence level is seen when CAM4 is forced by the SST anomalies of the TIO or the TWP or both of them. The increase of the modified WNPSH index is stronger when CAM4 is forced by both TIO and TWP, compared to those forced by TIO alone or TWP alone. Insignificant decrease of the modified WNPSH index is seen when CAM4 is forced by the SST anomaly of the Nino3 region or BOB&SCS. These results confirm that the TIO and the TWP have both contributed to the projected WNPSH intensity, while the Nino3 region and BOB&SCS have not.

The regressed negative SST over the TWP in Fig. 4a actually means relatively weaker warming, instead of cooling. The TWP SST gets warmer in all of the models under both RCP4.5 and RCP8.5 scenarios, and none of them show a cooling in the TWP (Fig. 4e). What is the response of the WNPSH if the SST over the TIO and the TWP both increase but at different amplitudes? To mimic the effect of un-uniform warming, CAM4 is forced by 1K warm SST anomaly in the TIO and 0.5 K warm SST anomaly in the TWP. The model response (Fig. 5f) is characterized by anticyclonic anomaly and negative rainfall anomaly over the WNP, indicating the un-uniform
warming with positive TIO-TWP zonal SST gradient is indeed favorable for an enhanced WNPSH.

How do the different projected changes of the WNPSH affect the monsoon rainfall over eastern China? To answer this question, composite changes in the precipitation and 850 hPa winds are shown for the P-type and N-type models (See Table 2 for which models are P-type or N-type), separately (Fig. 6). Under RCP4.5 scenario, increased precipitation over the northern part of eastern China and enhanced southerly wind are seen following an enhanced WNPSH (Fig. 6a), while increased precipitation over the southern part of eastern China and weakened southerly wind are seen following a weakened WNPSH (Fig. 6b). A decrease of precipitation over the southern part of eastern China is also seen in Fig. 6a, but this decrease is not consistent among the P-type models. Under RCP8.5 scenario, the spatial patterns of the changes in precipitation and wind are similar as the RCP4.5 scenario, but with stronger magnitude (Figs. 6c, d). These results suggest the projected changes in the WNPSH intensity will modulate the rainfall pattern in eastern China.

5. Conclusion and discussion

Using 33 coupled models from the CMIP5 dataset, the future change of the WNPSH under global warming scenarios are investigated, by comparing the 2050-2099 climatology of the RCP4.5/RCP8.5 runs with the 1950-1999 climatology of the Historical run. The results show that the change of WNPSH depends on the change of the zonal SST gradient between TIO and TWP. The main conclusions are summarized as follows:
(1) Although the projected changes of the models under the RCP8.5 scenario is stronger than the RCP4.5 scenario, the MME projected changes in WNPSH intensity are approximately zero under both scenarios. Large projection uncertainty is seen among the CMIP5 models, since about half of the models project an increase and half of the models project a decrease in the WNPSH intensity. Based on the Student’s $t$ test at the 95% confidence level, only 7 (4) models project a significant increase (decrease) of the WNPSH intensity under RCP4.5 scenario, and only 9 (4) models project a significant increase (decrease) of the WNPSH intensity under RCP8.5 scenario.

(2) The projected change in the intensity of the WNPSH is regulated by the change in the TIO-TWP SST gradient, as suggested by the diagnostic study and numerical simulation. Stronger warming in the TIO and weaker warming in the TWP are in favor of enhanced WNPSH, while weaker warming in the TIO and stronger warming in the TWP are in favor of weakened WNPSH.

(3) The projected change in the WNPSH intensity modulates the rainfall pattern in eastern China. Under both RCP4.5 and RCP8.5 scenarios, models with an increased (decreased) intensity of the WNPSH are associated with an increase in the precipitation over the northern (southern) part of eastern China, accompanied by enhanced (weakened) southerly wind.

The relationship between the changes in WNPSH and the tropical SST resembles their relationship on the interannual time scale. The mechanisms which was proposed to explain the interannual variability of the WNPSH (Terao and Kubota 2005; Xie et
al. 2009; Wang et al. 2013) may also apply on the global warming projections. Stronger (weaker) warming in the TIO stimulates warm (cold) Kelvin wave, increasing (decreasing) the WNPSH intensity via wave induced Ekman divergence (convergence). Weaker (stronger) warming in the TWP increases (decreases) the WNPSH intensity via anticyclonic (cyclonic) Rossby wave response to its northwest.

This study focuses the intensity of the WNPSH, while the possible location shift of the WNPSH has not been addressed. Fig. 7a shows the ridgeline of the MME for the Hist, RCP4.5 and RCP8.5 experiments. It is shown that the mean state ridgeline is projected to shift southward slightly under both RCP4.5 and RCP8.5 scenarios compared with Hist experiments. For the MME, the magnitudes of the southward shift averaged within 130°E-150°E are 0.29° under RCP4.5 scenario and 0.46° under RCP8.5 scenario, which are close to zero. The large spread among the individual models is indicated by the error bar (Fig. 7b). The number of models projecting a northward (southward) shift of the WNPSH ridgeline is 14 (19) for the RCP4.5 scenario and 13 (20) for the RCP8.5 scenario. In all, the location of the WNPSH ridgeline may stay unchanged or shift southward slightly, with little inter-model consensus.

The results of this study show a large inter-model spread of the projected change in the WNPSH, suggesting attention should be paid on the WNPSH in the future studies of the climate change in the WNPSH-related regions. The inter-model spread of the projected WNPSH intensity depends on the change in the TIO-TWP zonal SST gradient, but it remains unknown what has led to the different changes of the
TIO-TWP SST gradient in different models, which is worthy of further study.

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Table Captions

Table 1 Information about the 33 coupled models in this study.

Table 2 The models which project significantly enhanced WNPSH intensity (P-type) and significantly decreased WNPSH intensity (N-type) at the 95% confidence level according to t test based on the interannual variability. The models which belong to P-type (or N-type) under both RCP4.5 and RCP8.5 scenarios are in bold.
**Figure Captions**

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in the mean 500 hPa vertical velocity over the WNP (ordinate) as a function of
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run and Historical run. The solid black dots in the scatter diagrams represent the
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the 33 models. The regression equation and the correlation coefficient are
marked on the upper-right corner of each scatter diagram.

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represents the MME and the alphabetical letters represent the individual models
(Please see Fig. 1f for which model each letter stands for). (b) Projected changes
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run and Historical run.

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Fig. 5 (a-d) The CAM4 simulated response of the precipitation (shading, unit: mm (day)$^{-1}$) and 850 hPa winds (vectors) to SST anomalies over key regions. The SST anomalies used to force CAM4 in (a)-(d) are picked from the Nino3 region, BOB&SCS, TIO and TWP of the regressed SST field in Fig. 4a respectively (the four boxes in Fig. 4a). The red dotted regions and the bold vectors indicate the responses of precipitation and winds are statistically significant at the 95% confidence level based on $t$ test. (e) The responses of the modified WNPSH intensity (defined as the difference in the zonal wind between the northern box and the southern box shown in Fig. 5a) when CAM4 is forced by the SST anomalies in Nino3 region, BOB&SCS, TIO, TWP, and both TIO&TWP picked from Fig. 4a. Solid black bar indicates the response of the modified WNPSH intensity is statistically significant at the 95% confidence level based on $t$ test. (f) The CAM4 simulated response to idealized 1K warming over the TIO and 0.5 K warming over the TWP.

Fig. 6 (a) P-type models’ composite of the projected changes in the precipitation (shading, unit: mm/day) and 850 hPa wind (vectors, unit: m/s) under RCP4.5
scenario. (b) Same as (a) but for the N-type models. (c-d) Same as (a-b) but under the RCP8.5 scenario. Please refer to Table 2 for which models are P-type and N-type under RCP4.5 and RCP8.5 scenarios, respectively. The regions with red dots indicate all of the P-type (or N-type) models agree in the sign of changes in the precipitation.

Fig. 7 (a) The mean state location of WNPSH ridgeline for the MME. The black, blue and red lines are for the ridgelines in Hist, RCP4.5 and RCP8.5 experiment, respectively. (b) Projected changes in the latitude of the WNPSH ridgeline averaged within 130°E-150°E. Positive (negative) value suggests a northward (southward) shift. The blue (red) bar is the MME projected change in RCP4.5 (RCP8.5) scenario compared to Hist experiment. The black error bar show the 20% and 80% percentiles of the individual models.
Table 1 Information about the 33 coupled models in this study

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Fig. 4 (a) The inter-model regression of the projected changes in SST and 850 hPa wind onto the projected changes in the WNPSH intensity under RCP4.5 scenario. (b) The inter-model regression of RCP4.5 projected changes in precipitation (shading, unit: mm/day) and tropospheric temperature (blue contours are -0.01K, -0.03K, -0.05K, and red contours are 0.01K, 0.03K, 0.05K, etc) onto the projected changes in WNPSH intensity. The black dotted regions in (a) and (b) indicate the regressed SST and precipitation exceed the 95% confidence level based on the Student’s t test, respectively. (c-e) Scatter diagrams for the projected changes of SST over the whole tropics (c), the TIO (d), and the TWP (e) as a function of the projected changes in the WNPSH intensity. The “tropical averaged SST” in (c) indicates the mean SST within 20°S-20°N. The TIO (TWP) indicates 10°S-10°N, 50°E-100°E (10°S-10°N, 150°E-180°), shown as boxes in Fig. 4a. (f) The changes of the TIO-TWP SST zonal gradient as a function of the changes in the WNPSH intensity. The TIO-TWP zonal SST gradient is defined as the difference between the TIO SST and the TWP SST. The blue and red markers are for the projected changes under RCP4.5 and RCP8.5 scenarios, respectively. The regression equation and correlation coefficient are shown at the upper-left corner of each panel for the RCP4.5 and RCP8.5 scenarios, respectively.
Fig. 5 (a-d) The CAM4 simulated response of the precipitation (shading, unit: mm (day)$^{-1}$) and 850 hPa winds (vectors) to SST anomalies over key regions. The SST anomalies used to force CAM4 in (a)-(d) are picked from the Nino3 region, BOB&SCS, TIO and TWP of the regressed SST field in Fig. 4a respectively (the four boxes in Fig. 4a). The red dotted regions and the bold vectors indicate the responses of precipitation and winds are statistically significant at the 95% confidence level based on t test. (e) The responses of the modified WNPSH intensity (defined as the difference in the zonal wind between the northern box and the southern box shown in Fig. 5a) when CAM4 is forced by the SST anomalies in Nino3 region, BOB&SCS, TIO, TWP, and both TIO&TWP picked from Fig. 4a. Solid black bar indicates the response of the modified WNPSH intensity is statistically significant at the 95% confidence level based on t test. (f) The CAM4 simulated response to idealized 1K warming over the TIO and 0.5 K warming over the TWP.
Fig. 6 (a) P-type models’ composite of the projected changes in the precipitation (shading, unit: mm/day) and 850 hPa wind (vectors, unit: m/s) under RCP4.5 scenario. (b) Same as (a) but for the N-type models. (c-d) Same as (a-b) but under the RCP8.5 scenario. Please refer to Table 2 for which models are P-type and N-type under RCP4.5 and RCP8.5 scenarios, respectively. The regions with red dots indicate all of the P-type (or N-type) models agree in the sign of changes in the precipitation.
Fig. 7 (a) The mean state location of WNPSH ridgeline for the MME. The black, blue and red lines are for the ridgelines in Hist, RCP4.5 and RCP8.5 experiment, respectively. (b) Projected changes in the latitude of the WNPSH ridgeline averaged within 130°E-150°E. Positive (negative) value suggests a northward (southward) shift. The blue (red) bar is the MME projected change in RCP4.5 (RCP8.5) scenario compared to Hist experiment. The black error bar show the 20% and 80% percentiles of the individual models.