# The Key Oceanic Regions Responsible for the Interannual Variability of the Western North Pacific Subtropical High and Associated Mechanisms

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## ABSTRACT

The western North Pacific subtropical high (WNPSH) is an important circulation system that impacts the East Asian summer climate. The interannual variability of the WNPSH is modulated by tropical air-sea interaction. In order to make it clear which oceanic regions are crucial to the interannual variability of the WNPSH, the research progresses in this regard in the past decade are reviewed. Based on the review, it is recognized that five oceanic regions are responsible for the interannual variability of the WNPSH in summer, including the equatorial central–eastern Pacific Ocean, tropical Indian Ocean, subtropical western North Pacific, the vicinity of the maritime continent, and the tropical Atlantic Ocean. The mechanisms how the sea surface temperature anomalies (SSTAs) in these regions affect the WNPSH are elaborated. The formation mechanisms for the SSTAs in these five regions are discussed. Strengths and weaknesses of the climate models in simulating and predicting the WNPSH are also documented. Finally, key scientific problems deserving further studies are proposed.

**Key words:** western North Pacific subtropical high, interannual variability, air-sea interaction

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## 1. Introduction

In summer, the North Pacific Ocean is controlled by a basin-wide high pressure system, i.e., the North Pacific subtropical high (NPSH). The NPSH is centered at the eastern North Pacific off the western coast of North America, and its ridgeline extends into the western North Pacific toward East Asia. The western part of the NPSH is usually called western North Pacific subtropical high (WNPSH). The WNPSH is a key system to the East Asian climate. From late spring to summer every year, the northward leaps of the ridgeline of WNPSH are associated with the northward advances of the East Asian rain belt, i.e., the sequential onset of the rainy season in South China, Yangtze-Huaihe River, and North China (Tao and Chen, 1987).

The WNPSH is characterized by strong interannual variability. In fact, the western North Pacific (WNP) is the region with the strongest interannual variability among the subtropical Northern Hemisphere (Lu, 2001; Sui et al., 2007; Wu and Zhou, 2008; Chung et al., 2011). A stronger (weaker) WNPSH is associated with an anomalous anticyclone (cyclone) over the WNP. When the WPNSH is stronger than normal, its ridgeline is displaced southward, and excessive rainfall is seen along the mid to lower reaches of the Yangtze River due to water vapor transport anomalies associated with anomalous WNPSH (Chang

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et al., 2000; Zhang et al., 2003; Zhou and Yu, 2005; Gao et al., 2014). Anomalous strong WNPSH is also responsible for heat waves south of the Yangtze River (Zhang et al., 2004; Guan et al., 2010; Shi et al., 2013; Wang et al., 2011), and cold damages in Northeast China (Li, 1989). When the WNPSH is weaker than normal, its ridgeline is displaced northward, and excessive rainfall is seen over the Huaihe River valley (Zhou and Yu, 2005; Zhao et al., 2012; Liu et al., 2013). The close connection in the climate anomalies between WNP and East Asia was reviewed in Lu and Fu (2009).

Given the substantial impact of WNPSH on East Asian climate, great attention has been paid to the mechanisms for the interannual variability of WNPSH. Earlier studies by Chinese scholars demonstrated the possible influence from El Niño–Southern Oscillation (ENSO) in the preceding winter (Chen, 1977; Fu et al., 1979; Huang, 1986; Li and Hu, 1987; Li, 1989), and the influence of developing ENSO on WNPSH in summer (Huang and Wu, 1989; Zhang et al., 1999). With the progress in observational data and climate models in the recent decade, multiple oceanic regions were revealed as key regions for the interannual variability of WNPSH and their mechanisms were proposed. The purpose of this paper is to review the recent research progress in the interannnual variability of WNPSH in the past decade. The mechanisms proposed by previous studies are elaborated, and the scientific problems remain to be solved are discussed.

## 2. The five key oceanic regions responsible for the interannual variability of WNPSH and associated mechanisms

Five key oceanic regions are revealed to be responsible for the interannual variability of the WNPSH, and their mechanisms are also proposed by previous studies. For brevity, the mechanisms are elaborated in terms of anomalous strong WNPSH in the following discussion, and the mechanisms for an anomalous weak WNPSH are vice versa. Unless particularly stated, the sea surface temperature (SST) anomaly refers to SSTA in summer.

### *2.1 Equatorial central–eastern Pacific*

Earlier studies emphasized that the warm SSTA over equatorial eastern Pacific in summer is in favor of a stronger WNPSH. In the El Niño decaying summer, the equatorial eastern Pacific is still controlled by warm SSTA. An anomalous overturning circulation ascends from equatorial eastern Pacific and descends over the subtropical WNP, which is called the anomalous "quasi-Walker circulation." The warm SSTA over equatorial eastern Pacific stimulates an anomalous strong WNPSH via anomalous quasi-Walker circulation (Ying and Sun, 2000). In addition, the SSTA over equatorial western Pacific is relatively cold during El Niño events, and it is in favor of suppressed local convection. The negative heating anomaly associated with suppressed convection stimulates an anomalous anticyclone on its northwest (Zhang et al., 1996), which favors an anomalous strong WNPSH (Zhang et al., 1999).

Recent studies revealed that cold SSTA over equatorial central Pacific favors an anomalous strong WNPSH. The precipitation over equatorial central Pacific is suppressed by the local cold SSTA; therefore, a pair of anticyclonic Rossby waves is stimulated on the northwest and southwest of the negative heat source (Gill, 1980). The anomalous anticyclone on the northwest of equatorial central Pacific is in favor of an anomalous strong WNPSH (Wang et al., 2013; Xiang et al., 2013). The cold SSTA over equatorial central Pacific in summer is contributed by developing La Niña or persistent La Niña events (Wang et al., 2013). Numerical simulations with atmospheric General Circulation Models (AGCMs) also confirm that cold SSTA over equatorial central Pacific is in favor of an anomalous strong WNPSH (Wu and Liu, 1992; Wang et al., 2013).

El Niño events can be divided into two groups according to the location of the warm SSTA, i.e., eastern Pacific El Niño and central Pacific El Niño (Ashok et al., 2007). Both observational analyses and numerical simulations have shown that the impacts of ENSO on the WNPSH and East Asian rainfall are different between these two types of ENSO. The WNPSH is more impacted by the developing phase of central Pacific El

Niño events than by that of eastern Pacific El Niño events (Hong et al., 2011; Yuan and Yang, 2012; Chen et al., 2014). In El Niño decaying summers, the WNPSH is more affected by eastern Pacific El Niño, compared with central Pacific El Niño (Yuan and Yang, 2012). Both central Pacific La Niña and eastern Pacific El Niño events favor anomalous anticyclones over subtropical WNP, and are associated with excessive rainfall in the mid-lower reaches of the Yangtze River valley. Both central Pacific El Niño and eastern Pacific La Niña events favor anomalous cyclones over subtropical WNP; however, excessive rainfall over South China is seen during central Pacific El Niño events but no significant rainfall anomaly can be seen during eastern Pacific La Niña events (Karori et al., 2013; Chen et al., 2014). The different impacts of the two types of ENSO on East Asia–West Pacific climate are reviewed in Zhou et al. (2014).

### *2.2 Tropical Indian Ocean (TIO)*

The interannual variability of TIO SST is characterized by two distinct modes. The first mode is the Indian Ocean basin (IOB) mode with uniform warming or cooling across the entire TIO basin. The second mode is the Indian Ocean dipole (IOD) mode, which is characterized by opposite SST anomalies between the eastern and the western TIO. The IOB mode is the forced response to ENSO events, whereas the second mode is independent of ENSO but interacts with ENSO (Saji et al., 1999; Webster et al., 1999; Li et al., 2003). The IOB mode usually peaks in boreal spring and persists until summer via the local air-sea interactions (Klein et al., 1999; Du et al., 2009), while the IOD mode usually onsets in summer and peaks in autumn (Li et al., 2003). The IOB mode modulates the interannual climate variability over East Asia–West Pacific in summer, whereas the impacts of IOD mode on the East Asian climate are stronger in winter than in summer (Guan and Amagata, 2003; Yang et al., 2010).

The impact of TIO SSTAs on WNPSH was first revealed by Chinese scientists (Wu et al., 2000). Numerical simulations had also been performed, and the results confirmed the importance of TIO SSTAs on summer rainfall anomalies in China (Guo et al., 2004). In recent years, more and more studies have paid attention to the linkage between TIO SSTA and East Asia–West Pacific climate (e.g., Yang et al., 2007; Li et al., 2008; Xie et al., 2009; Wu et al., 2010a; Yang et al., 2010; Kosaka et al., 2013; Liu et al., 2014; Song and Zhou, 2014). Up to now, two mechanisms have been proposed to explain how the WNPSH is strengthened by the warm SSTA over TIO. These two mechanisms are elaborated as follows.

(1) “Two-stage thermal adaption” mechanism. This mechanism emphasizes the contribution of northern TIO. During the first stage thermal adaption, a low-level cyclone anomaly is triggered by surface sensible heating associated with the warm SSTA over the northern TIO. The anomalous southerly wind on the eastern flank of this low-level cyclone transports water vapor into South China and causes excessive rainfall there. The anomalous strong latent heating associated with the positive rainfall anomaly is characterized by a maximum heating in the mid troposphere; thus southerly wind anomaly on the western flank of WNPSH is induced by this anomalous heating profile. Therefore, the WNPSH on the east of the anomalous latent heating region is strengthened. The first-stage sensible heating and the second-stage latent heating together explain the influence of TIO SSTA on the WNPSH (Wu et al., 2000).

(2) “Kelvin wave induced Ekman divergence” mechanism. Warm Kelvin wave is emanated as a response to the warm SSTA over TIO, characterized by anomalous low pressure over TIO and tropical western Pacific. As a result of the pressure gradient and Ekman pumping, divergence and anticyclone anomalies are seen over the subtropical WNP. Therefore, the WNPSH is enhanced by Kelvin wave induced Ekman divergence (Terao and Kubota, 2005; Wu et al., 2009a; Xie et al., 2009). Since the warm SSTA over TIO in spring and summer is forced by El Niño in the preceding winter, the TIO plays a role as a capacitor, which prolongs the impact of El Niño on WNPSH. In the El Niño peak phase (in the preceding winter), the TIO

SSTA rises under the forcing of El Niño, similar to a recharge process. After the El Niño decay (in summer), warm SSTA over TIO modulates the WNPSH via Kelvin wave induced divergence, similar to the " discharge" process (Xie et al., 2009). The warm SSTA over TIO is sustained from spring to summer via local air-sea interaction during the El Niño decay phase (Du et al., 2009).

Compared with the decaying summer of central Pacific El Niño events, the warm SSTA over TIO is stronger in the decaying summer of eastern Pacific El Niño events (Yuan et al., 2012). After the late 1970s, the warm SSTA over TIO lasts longer into the late summer during El Niño decaying phase, and therefore, the impact of TIO SSTA on the WNPSH is strengthened (Huang et al., 2010; Xie et al., 2010). Multiple observational datasets during 1870–2007 showed that decadal oscillation is evident in the strength of the TIO capacitor effect. The TIO capacitor effect is weaker during 1910–1977 but stronger before 1910 and after 1977 (Chowdary et al., 2012). Future climate projection studies based on coupled models showed that the TIO capacitor effect strengthens in response to global warming. This is because the atmospheric specific humidity rises along with global warming, therefore stronger atmospheric Kelvin wave can be triggered by TIO SSTA via moist-adiabatic adjustment, although the amplitude and periodicity of ENSO do not change significantly (Tao et al., 2015).

Some recent studies emphasized the importance of the zonal SST gradient between TIO and tropical Pacific on the WPNSH (Terao and Kubota, 2005; Chen et al., 2012; Cao et al., 2013). The anomalous zonal SST gradient between warmer TIO and colder tropical Pacific Ocean drives an anomalous easterly wind over equatorial western Pacific, and induces anomalous strong WNPSH through Ekman divergence over subtropical WNP (Terao and Kubota, 2005). This mechanism can be regarded as the combined influence of warmer TIO SSTA and colder tropical Pacific SSTA. It was found that the WNPSH is stronger during faster decaying El Niño events than during slower decaying El Niño events (Chen et al., 2012), which can be explained by the impact of zonal SST gradient anomalies. The faster the El Niño decays, the stronger the zonal SST gradient and easterly wind anomalies between warmer TIO and colder tropical Pacific are seen in summer (Lindzen and Nigam, 1987). In coupled model projection studies, it was found that the TIO and tropical Pacific Ocean both warms; however, the intensity of the low-level WNPSH follows the zonal SST gradient between TIO and tropical Pacific Ocean (He and Zhou, 2015a).

### *2.3 Western North Pacific (WNP)*

Cold SSTA over subtropical WNP favors an anomalous strong WNPSH. Cold SSTA over WNP is usually forced by the warm SSTA over equatorial central–eastern Pacific through atmospheric bridges, during the mature phase of El Niño in winter (Wang et al., 2000; Alexander et al., 2002; Lau and Nath, 2003). In response to cold SSTA over WNP, anticyclonic Rossby wave is stimulated by the negative atmospheric heat source associated with the suppressed convection over WNP (Gill, 1980). Therefore, an anomalous anticyclone is seen on the northwestern side of the cold SSTA, and the WNPSH is strengthened (Wang et al., 2000, 2013; Wu et al., 2010a; Xiang et al., 2013). In addition, some studies emphasized the importance of zonal SST gradient between northern Indian Ocean and WNP. The zonal SST gradient with a warmer northern Indian Ocean and colder WNP favors a stronger WNPSH (Ohba and Ueda, 2006; Wu et al., 2014).

The anomalous WNPSH is not only forced by the SSTA over WNP, but also interacts with the local SSTA. In El Niño mature winter and the subsequent spring, the total wind speed on the eastern flank of the anomalous WNPSH is increased by the anomalous northeasterly wind superimposed on the mean state northeasterly trade wind. As a result, the upward heat flux from ocean to atmosphere is increased, and the cold SSTA over WNP is sustained via this local wind–evaporation–SST feedback (Wang et al., 2000; Lau and Nath, 2003; Wang et al., 2013). The anomalous strong WPNSH and cold SSTA over WNP persist into summer with the aid of this positive air–sea feedback (Wang et al., 2013; Xiang et al., 2013).

In El Niño decaying summer, the anomalous strong WNPSH is still sustained by anticyclonic Rossby waves forced by local cold SSTA, as been verified by numerical simulations (Wu et al., 2010a). After the WNP summer monsoon onset in July, the mean state wind over WNP turns into southwesterly wind, and the local wind–evaporation–SST feedback is weakened due to the unfavorable mean state wind. It is not surprising that the cold SSTA over WNP is damping in El Niño decaying summer (Wu et al., 2010a). However, the anomalous WNPSH persists through the whole summer, and it is even enhanced in late summer (Wu et al., 2010a; Xiang et al., 2013). There are two possible causes for this phenomenon as listed below.

1) The anomalous strong WPNSH is sustained by the local cold SSTA in early summer (June) but by TIO SSTA in mid and late summer (July–August). Although the warm SSTA over TIO persists through the whole summer, it contributes to the maintenance of WNPSH anomaly only in mid and late summer, after the onset of WNP summer monsoon. This is because the response of WNPSH to remote forcing over TIO relies on the local mean state rainfall. The mean state rainfall over WNP increases sharply after the WNP summer monsoon onset. Under a more rainy mean state in late summer, stronger negative rainfall anomaly and stronger anticyclone anomaly over WNP can be stimulated by the Kelvin wave induced Ekman divergence originating from TIO forcing (Wu et al., 2010a; Jiang et al., 2013).

2) The local air–sea positive feedback becomes stronger after WNP summer monsoon onset. As a result of the increased mean state rainfall after WNP summer monsoon onset, greater rainfall anomaly is induced by local SSTA, and the associated greater latent heating anomaly induces greater atmospheric circulation anomaly. Therefore, the atmospheric circulation becomes more "sensitive" to the local SSTA after the WNP summer monsoon onset. Although the cold SSTA over WNP is damped, stronger response of WNPSH to local SSTA is expected in late summer (Xiang et al., 2013).

### *2.4 The vicinity of the maritime continent (VMC)*

The VMC is referred to the oceanic regions within 10°S–10°N, 100°–150°E. The VMC is a part of the warm pool region, and the SSTA over VMC can effectively stimulates local convection anomaly and latent heating anomaly. As a response to warm SSTA over VMC, the local Hadley circulation anomaly ascends over VMC and descends over WNP, suppressing the precipitation over WNP and enhances the WNPSH (Lu et al., 2006; Sui et al., 2007; Wu et al., 2009a; Chung et al., 2011). The remote forcing of SSTA over VMC on the WNPSH can be validated by AGCM (Chung et al., 2011). The warm SSTA over VMC is usually associated with simultaneous phase transition from El Niño to La Niña, and it is probably forced by developing La Niña in the central Pacific (Sui et al., 2007; He and Zhou, 2015b).

The interannual variability of WNPSH is characterized by two dominant periods, i.e., 2–3- and 3–5-yr oscillations. The 2–3-yr oscillation is characterized by an equivalent barotropic vertical structure, and it is forced by the anomalous local Hadley circulation originating from VMC (Sui et al., 2007; Chung et al., 2011; Chen and Zhou, 2014). The 3–5-yr oscillation is characterized by a baroclinic vertical structure, and it is forced by the SSTA over WNP (Sui et al., 2007; Chung et al., 2011) or TIO (Chen and Zhou, 2014). The interannual variability of WNPSH is dominated by 3–5-yr oscillation before the early 1990s whereas 2–3-yr oscillation after the early 1990s. Enhanced forcing from the SSTA over VMC is responsible for this decadal change (Chen and Zhou, 2014).

### *2.5 Tropical Atlantic Ocean*

As revealed by many recent studies, the warm SSTA over tropical Atlantic Ocean favors an enhanced WNPSH (Lu and Dong, 2005; Rong et al., 2010; Ham et al., 2013; Hong et al., 2014). As a warm Kelvin wave response to warm SSTA over tropical Atlantic Ocean, easterly wind anomaly dominates from TIO to equatorial western Pacific. The WPNSH is enhanced by the Ekman divergence induced by this warm Kelvin wave (Lu and Dong, 2005; Rong et al., 2010). In addition, the precipitation over equatorial central Pacific is suppressed by the anomalous zonal overturning circulation stimulated by warm SSTA over tropical Atlantic. As a Rossby wave response to the negative latent heating anomaly over equatorial central Pacific, the WNP is dominated by an anomalous anticyclone and the WNPSH is enhanced (Hong et al., 2014).

As revealed by the case study for the year 1998, the SSTA over tropical Atlantic is crucial for simulating the anomalous WNPSH and rainfall anomaly over southern China. The tropical Atlantic SSTA is as important as the SSTA over global oceans outside tropical Atlantic (Lu and Dong, 2005). After early 1980s, the impact of tropical Atlantic SSTA on WNPSH is enhanced, and tropical Atlantic SSTA is less modulated by ENSO after this decadal change (Hong et al., 2014). Under the background of a weaker Atlantic meridional overturning circulation (AMOC), the interannual variability of WNPSH is more intensely modulated by tropical Atlantic SSTA (Chen et al., 2015). In addition, central Pacific La Niña events can be triggered by the anomalous easterly wind on the southern flank of the stronger WNPSH forced by warm SSTA over tropical Atlantic (Ham et al., 2013).

## 3. Simulation and prediction of the WNPSH by climate models

A large group of numerical simulations performed by climate models are collected by the fifth phase of the Coupled Model Intercomparison Project (CMIP5). In Atmospheric Model Intercomparison Project (AMIP) simulation, the atmospheric component model is forced by observed SST. In historical simulation, the air–sea coupled model is driven by prescribed external forcing such as greenhouse gases, aerosols, etc. The mean state WNPSH in summer is captured by both AMIP and historical simulations. However, the ridgeline of the WNPSH is displaced northward in AMIP simulations compared with observation. Northward displaced ridgeline is seen in 26 out of 28 models, with a multi-model averaged bias of 3 degrees and a maximum bias of 7 degrees (He and Zhou, 2014). Corresponding to the northward displacement of WNPSH ridgeline, the simulated Meiyu rainfall is weaker but the rainfall over North China is stronger than observation (Chen et al., 2010; Sperber et al., 2013). The northward displacement of WNPSH ridgeline is slightly reduced but still evident in historical simulations by coupled models, and the multimodel averaged northward displacement is two degrees in historical simulations (He and Zhou, 2015a). Since the northward displacement of WNPSH ridgeline cannot be eliminated by coupling the AGCM with ocean model, it suggests that this bias originates from the AGCM itself.

The simulation of WNPSH can be improved under a finer resolution over East Asia–West Pacific in a variable resolution AGCM, and the simulation of the rain belt over East Asia is also improved (Zhou and Li, 2002). By using the same dynamical core of Community Atmospheric Model v3.5 (CAM3.5), it is found that the simulated location and seasonal evolution of East Asian rain belt is sensitive to convective parameterization schemes, but the large-scale circulation of WNPSH is insensitive to the parameterization schemes (Chen et al., 2010). The northward displacement of the WNPSH may originate from the bias in large-scale land–sea thermal contrast in the models (Chen et al., 2010), and convective parameterization scheme may also contributes to a certain extent (Zou et al., 2014).

The interannual variability of WNPSH is characterized by two distinct modes, which can be obtained by Empirical Orthogonal Function (EOF) analysis on the wind vectors (Park et al., 2010; He et al., 2013; He and Zhou, 2014), zonal wind (Lu et al., 2006), precipitation (Zhou et al., 2009a), geopotential height (Wang et al., 2013; Xiang et al., 2013), or water vapor transport field (Li and Zhou, 2012). The first (second) EOF mode based on geopotential height corresponds to the second (first) EOF mode based on wind-related fields, i.e., wind vectors, zonal wind, and water vapor transport. The sum of variances explained by these two modes accounts for 50%–80% of the total interannual variance of WNPSH variability.

The two interannual modes are associated with different tropical SST anomalies, suggesting different air-sea interaction characteristics for these two modes. The first mode is reasonably simulated by AMIP simulations, suggesting that it is an SST-forced phenomenon. Remote SST forcings from TIO (Park et al., 2010; Song and Zhou, 2014), VMC (Sui et al., 2007; Wu and Zhou, 2009a; Chung et al., 2011), and equatorial central Pacific (Wang et al., 2013; Xiang et al., 2013) all contribute to the first mode.

It is still controversial whether the second mode is an SST-forced phenomenon. Some previous studies claimed that the second mode is forced by the forcing of SSTA over the WNP (Sui et al., 2007; Wu et al., 2009a; Chung et al., 2011). Some other studies argued that the second mode is an air–sea coupled phenomenon, which is sustained by local wind–evaporation–SST feedback (Wang et al., 2013; Xiang et al., 2013). Other studies showed that the second mode is driven by atmospheric internal dynamics free from SST forcing (Lu et al., 2006, 2008). Compared with observation, the anomalous anticyclone associated with the second mode is weaker and displaced southwestward in AMIP simulations. Among the five typical years associated with the second mode, the anomalous WNPSH is captured only in 1993 and 1994 but not in 1980, 1981 and 1987. The model skill for the second mode is lower than the first mode, and the second mode is only partially captured by the AMIP experiment. Therefore, the second mode is possibly a hybrid mode of atmospheric internal dynamics and SST forcing, i.e., an atmospheric internal mode modulated by SST forcing (He and Zhou, 2014).

The WNPSH is modulated by tropical SSTA and is highly predictable (Zou et al., 2009; Wang et al., 2013). The anomalous WNPSH in summer can be predicted by using the tier-one and tier-two approaches and statistical models. Forced by the global SSTA predicted by Seoul National University forecasting system, the Grid Atmospheric Model of State Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (GAMIL) is capable in predicting the interannual variability of WNPSH (Zou et al., 2009). The five coupled models participating the ENSEMBLES project are also skillful in predicting the WNPSH with a lead time of one month (Li et al., 2012). The model skill is higher in El Niño years and ENSO neutral years, but lower in La Niña years (Li et al., 2014). In Climate Forecast System Version 2 (CFSv2) developed by NCEP, the WNPSH is forced by local SSTA over WNP in early summer but by TIO SSTA in mid and late summer (Jiang et al., 2013). A linear statistical model is also skillful in predicting the WNPSH, with three predictors including the zonal SST gradient between TIO and WNP in spring, the SST tendency over equatorial Pacific and the North Atlantic Oscillation index. The predicted WNPSH indices have a correlation coefficient of 0.81 with the observation (Wang et al., 2013). The prediction of the East Asian summer rainfall and tropical cyclone over WNP can be improved by the high predictability of the WNPSH (Wang et al., 2013).

## 4. Summary and discussion

### *4.1 Summary*

Five oceanic regions are identified as the key regions for the anomalous WNPSH in summer, according to an extensive survey of the research progress in this regard in the recent decade. In general, an anomalous strong WNPSH can be stimulated by warm SSTAs over TIO, VMC, and tropical Atlantic Ocean, and cold SSTAs over equatorial central Pacific and WNP. The geographic location of the key regions is shown in Fig. 1. The WNPSH is enhanced by warm SSTA over TIO through two-stage thermal adaptation or Kelvin wave induced Ekman divergence. Kelvin wave induced Ekman divergence also explains the influence of tropical Atlantic SSTA on WNPSH. Anomalous local Hadley circulation explains how the warm SSTA over VMC enhances the WNPSH. Cold SSTA over equatorial central Pacific intensifies the WNPSH by stimulating anticyclonic Rossby waves on its northwest. The WNPSH can also be intensified by the cold SSTA over WNP, and interacts with the SSTA over WNP via the wind–evaporation–SST feedback. The remote forcings from equatorial central-eastern Pacific and VMC are usually associated with the developing phase of ENSO, while the impacts from TIO, WNP, and tropical Atlantic are mainly associated with the decaying phase of ENSO.

The general characteristics associated with WNPSH are captured by current state-of-the-art climate models. The major bias in mean state simu-

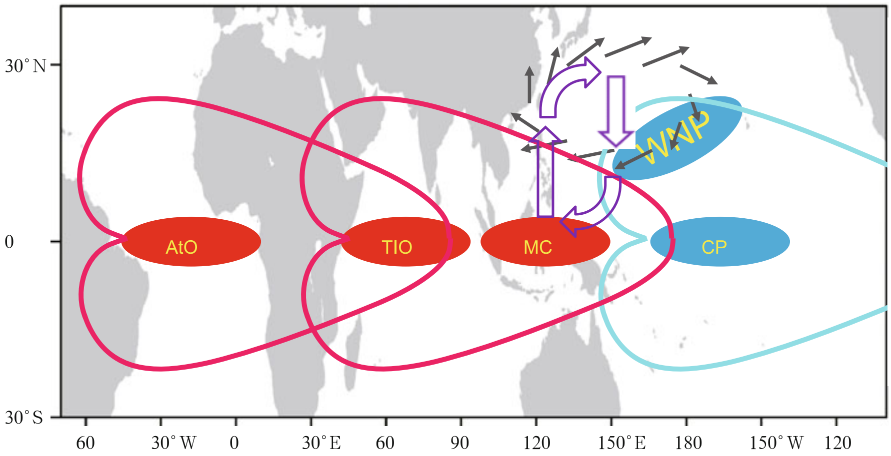

**Fig. 1.** Schematic diagram showing the location of the five key regions and associated mechanisms responsible for the interannual variability of WNPSH. The five key regions include Tropical Atlantic Ocean (AtO), Tropical Indian Ocean (TIO), the Maritime Continent (MC), equatorial Central Pacific (CP), and Western North Pacific (WNP). Red (blue) ovals indicate that the location of warm (cold) SSTAs favors an enhanced WNPSH. The thin black arrows indicate the anticyclonic circulation over WNP associated with an enhanced WNPSH. The thick pink lines represent the Gill type responses to warm SSTAs over AtO and TIO; each includes a pair of Rossby waves on the west and a Kelvin wave on the east of the warm SSTA. The light blue thick lines represent the Gill type response to the cold SSTA over CP. The hollow purple arrows indicate the anomalous local Hadley circulation triggered by the warm SSTA over the vicinity of MC.

lation is the northward displacement of the WNPSH ridgeline, which accounts for the bias in location of the East Asian rain belt. The bias of northward displaced ridgeline is evident not only in the stand-alone AGCMs but also in the coupled models, suggesting that this bias cannot be eliminated by air-sea coupling. The interannual variability of WNPSH is characterized by two distinct modes. The first mode is well reproduced by AGCMs forced with observed historical SST, but the second mode is only partially reproduced. It is probably that the first mode is an SST-forced phenomenon while the second mode is a hybrid mode of atmospheric internal dynamics and SST forcing. The interannual variability of WNPSH can be predicted by climate models by using either tier-one or tier-two approaches. The high predictability of the WNPSH paves a way for improving the prediction of East Asian summer rainfall anomaly.

The mechanisms for the interannual variability of WNPSH are reviewed in the context of oceanic influences. Besides oceanic influence, the land-sea interaction is also important for the interannual variability of WNPSH. Many previous studies showed that anomalous strong sensible heating over the Tibetan Plateau is in favor of a stronger WNPSH (Wang et al., 2008; Zhou et al., 2009). The sensible heating anomaly over the Tibetan Plateau is modulated by the snow cover in spring. Thicker than normal snow depth over the Tibetan Plateau in spring reduces the sensible heating via increasing the surface albedo and increasing the soil moisture content (Zhu et al., 2009), and therefore weakens the WNPSH in summer. The impact of Tibetan Plateau on WNPSH and East Asian summer monsoon has been reviewed by several previous studies (Wu et al., 2007; Zhou et al., 2009; Duan et al., 2014).

### *4.2 Discussion*

Substantial progress has been made on the mechanisms of WNPSH in the recent decade, but plenty of problems remain unsolved. Among to the unsolved problems, the following three issues may draw wide research interest in future.

(1) The impact of air-sea coupled processes on the interannual variability of WNPSH. A basic hypothesis in most of previous studies is that the anomalous WNPSH is forced by SST anomalies. In fact, strong and complicated air-sea coupling is seen over WNP (Wu et al., 2009b; Wang et al., 2013; Lu and Lu, 2014, 2015). In contrast to other tropical oceans, the atmos-

phere interacts with the ocean rather than forced by the ocean over WNP (Wang et al., 2005). The air-sea relationship over WNP is asymmetric between El Niño and La Niña events (Wu et al., 2010b), and between developing and decaying phases of ENSO (Wu et al., 2009b). A comparison between stand-alone regional atmospheric model and coupled regional model showed that the latter performs better than the former in simulating the interannual climate variability over WNP (Zou and Zhou, 2013). Since the air-sea relationship cannot be captured by stand-alone atmosphere models, air-sea coupled models will be a useful tool in the study of climate variability over East Asia–West Pacific.

(2) Prediction of WNPSH anomaly. The East Asian climate variability is modulated by WNPSH and midlatitude systems. The WNPSH is modulated by tropical SSTs, and its predictability is higher than the midlatitude systems (Zou et al., 2009). The prediction of East Asian summer rainfall and tropical cyclone activities over WNP can be improved, if the large-scale circulation anomaly associated with WNPSH is well predicted (Wang et al., 2013). It is useful to improve the prediction of WNPSH anomalies on the interannual scale, and further on the intraseasonal scale.

(3) The impact of global warming and decadal climate variability on the WNPSH. A decadal change in the mean state of WNPSH occurred in the late 1970s, which may have caused a wetter southern China and a drier northern China after this decadal change (Gong and Ho, 2002; Yu et al., 2004; Yu and Zhou, 2007; Zhou et al., 2009b; Huang et al., 2015). The interannual relationship between WNPSH and tropical SSTA has also experienced a decadal change in the late 1970s (Xie et al., 2010; Huang et al., 2010; Hong et al., 2014). The decadal climate change in East Asia–West Pacific may result from either anthropogenic greenhouse gases forcing or natural climate variability (Li et al., 2010; Zhou et al., 2013; Qian and Zhou, 2014; Song et al., 2014). Response of tropical SST to anthropogenic greenhouse gases forcing is characterized by an El Niño-like pattern over tropical Pacific (An et al., 2012; Yeh et al., 2012), and positive IOD-like pattern over TIO (Zheng et al., 2013; Dong and Zhou, 2014). There are still no clear pictures on how the mean state and interannual variability of WNPSH are modulated by global warming and decadal climate variability, and further studies are needed.

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