Simulation of the western North Pacific subtropical high in El Niño decaying summers by CMIP5 AGCMs

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ABSTRACT
The performances of CMIP5 atmospheric general circulation models (AGCMs) in simulating the western North Pacific subtropical high (WNPSH) in El Niño decaying summers are examined in this study. Results show that most models can reproduce the spatial pattern of both climatological and anomalous circulation associated with the WNPSH in El Niño decaying summers. Most CMIP5 AGCMs can capture the westward shift of the WNPSH in El Niño decaying summers compared with the climatological location. With respect to the sub-seasonal variation of the WNPSH, the performances of these AGCMs in reproducing the northward jump of the WNPSH are better than simulating the eastward retreat of the WNPSH from July to August. Twenty-one out of twenty-two (20 out of 22) models can reasonably reproduce the northward jump of the WNPSH in El Niño decaying summers (climatology), while only 7 out of 22 (8 out of 22) AGCMs can reasonably reproduce the eastward retreat of the WNPSH in El Niño decaying summers (climatology). In addition, there is a close connection between the climatological WNPSH location bias and that in El Niño decaying summers.

1. Introduction
The western North Pacific subtropical high (WNPSH) is an essential component of the East Asian summer monsoon system (Lu 2001; Kawatani, Ninomiya, and Tokioka 2008; Park et al. 2010; Wang, Xiang, and Lee 2013). Water vapor can be transported northward along the western flank of the WNPSH, which is an important moisture source for summer precipitation in East Asia. An anomalous shift of the WNPSH away from its normal location can influence the transport of moisture to East Asia, resulting in an abnormal summer climate in the region. For instance, following the 1997–1998 super El Niño event, the WNPSH was located westwards and southwards compared to its climatology, contributing to heavy rainfall and catastrophic flooding over the middle to lower reaches of the Yangtze River Valley in East China (Liu, Zhang, and Wang 2008). Thus, understanding the variability of the WNPSH is of central importance to East Asian scientists.

Much attention has been paid to the variability of the WNPSH. Previous studies have shown that the interannual variation of the WNPSH can be influenced by El Niño–Southern Oscillation (ENSO)—an important natural variability at the interannual timescale with global impact. The most significant impact of ENSO on the WNPSH and the associated East Asian summer monsoon (EASM) takes place in the decaying summer of ENSO through the western North Pacific anticyclone anomaly (Wang, Wu, and Fu 2000; Xie et al. 2009). Besides the interannual timescale, the WNPSH also exhibits notable subseasonal variation. Two abrupt northward jumps of the WNPSH have been identified—one in mid-June and the other in late July (e.g. Su, Xue, and Zhang 2014), which can separate the EASM into three different subseasonal stages (i.e. early, middle, and late summer). The characteristics of these stages are rather different (e.g. Wu, Li, and Zhou 2010; Xiang et al.

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the characteristics of the WNPSH between 1981 and 2013, under the condition of a similar weak La Niña sea surface temperature (SST) anomaly. They found that, although the location of the WNPSH in June and July was close to the climatology, the WNPSH exhibited an opposite anomaly during August in these two years, with a rapid eastward retreat in 1981 and an unusual westward extension in 2013.

Climate models have emerged as essential scientific tools in the climate community. Recently, the experimental output of the Fifth Phase of the Coupled Model Intercomparison Project (CMIP5) have been made available to the community (Taylor, Stouffer, and Meehl 2012). The performances of these models in simulating the WNPSH have been evaluated in different aspects (He and Zhou 2014; Liu et al. 2014; Dong and Xue 2016). For example, He and Zhou (2014) investigated the performances of atmospheric general circulation models (AGCMs) from CMIP5 models in simulating the two leading modes of the WNPSH and found that the first mode can be reproduced reasonably by these AGCMs driven by observed SST, while the second mode can only be moderately reproduced by the multi-model ensemble (MME) mean of these models.

In the present study, the performances of CMIP5 AGCMs in simulating the WNPSH in El Niño decaying summers are examined, including summer mean results and subseasonal variation. We focus on the decaying summer of El Niño because, according to previous studies (e.g. Wu and Wang 2002; Feng, Wang, and Chen 2014; Dong 2016), El Niño affects the EASM more significantly in its decaying years, as compared to its developing years. Our main aim is to answer the following two questions: (1) How do the CMIP5 AGCMs perform in simulating the WNPSH in El Niño decaying years? (2) Can the CMIP5 AGCMs capture the subseasonal variability of the WNPSH?

2. Data, models, and methods

To validate the performances of CMIP5 models in simulating the WNPSH, NCEP–NCAR Reanalysis-1 data are used in this study (Kalnay et al. 1996). Besides, the sea level pressure (SLP) provided by version 2 of the Met Office Hadley Centre’s data-set data (HadSLP2; Allan and Ansell 2006) is used to examine the associated circulation. The horizontal resolution of HadSLP2 is 5° × 5°. We adopt 22 CMIP5 AGCMs, information on which can be found via the website of the PCMDI (Program for Climate Model Diagnosis and Intercomparison), and in many previous studies (e.g. He and Zhou 2014). The time period examined in this study is from 1979 to 2008. All model data are interpolated into a uniform horizontal resolution (2.5° × 2.5°) — the same as the reanalysis data. As in Feng, Wang, and Chen (2014), the following nine El Niño events are selected for the present analysis: 1982–1983, 1986–1987, 1987–1988, 1991–1992, 1994–1995, 1997–1998, 2002–2003, 2004–2005, and 2006–2007. An El Niño event is selected when the normalized winter (December–February) mean Niño-3.4 index (SST anomalies averaged over (5°S–5°N, 170°–120°W)) is greater than 0.5 standard deviations (Yoon and Yeh 2010; Feng, Wang, and Chen 2014). Thus, the simulation of the WNPSH by the CMIP5 AGCMs in the decaying summers of these El Niño events can be analyzed through composite analysis.

To evaluate the simulation of the WNPSH’s location, we adopt the methods that have been used to define the WNPSH (Su, Xue, and Zhang 2014). The ridgeline latitude is the latitude of the ridgeline of the WNPSH averaged over 110°–150°E, which can describe the movement of the WNPSH in the north–south direction. The westward extension is the westernmost longitude along the WNPSH contour over 90°E–180°, which can portray the movement of the WNPSH in the west–east direction. Note that instead of using the 5880 gpm contour to denote the WNPSH, we adopt another method (He et al. 2013). Owing to the WNPSH being a relatively high platform compared to the subtropical zonal band, we first calculate the deviation of the original 500 hPa geopotential height field at each grid point from the zonal average over 0°–45°N. Then, the zero contour is adopted to denote the WNPSH, instead of the traditional 5880 gpm contour. A similar idea has also been used in previous studies to investigate the WNPSH (He et al. 2015).

3. Results

3.1. Summer mean

Figure 1 shows the observed and simulated spatial pattern of the long-term mean SLP and wind field at 850 hPa in the East Asia and western North Pacific region. The WNPSH is located in the North Pacific region, along with the relatively low pressure over the East Asian continent. This west–east pressure gradient favors southerly wind along the east coast of East Asia, which is a prominent component of the EASM. Almost every model can reproduce this climatological circulation pattern, with a location bias to a greater or lesser degree depending on the individual model. The pattern correlation coefficient of the MME mean SLP with observation reaches 0.96.

To examine the performances of the models in simulating the WNPSH and associated anomalous circulation in El Niño decaying summers, nine El Niño events (Section 2) are selected and the anomalous circulation pattern in El Niño decaying summers in both observation and simulation are shown in Figure 2. Observation shows that a positive SLP anomaly is located in the western North Pacific region in El Niño decaying summers, along with an anticyclonic
wind anomaly at 850 hPa. This is consistent with previous studies in which it was stated that an anomalous western North Pacific anticyclone can extend the influence of El Niño on East Asia to the following summer (Wang, Wu, and Fu 2000). Both local air–sea interaction over the western North Pacific and the influence from the Indian
Ocean through Kelvin-wave stimulation and associated Ekman divergence can contribute to the maintenance of the western North Pacific anticyclone from El Niño mature winter to the following summer (Wang, Wu, and Fu 2000; Xie et al. 2009; Wu, Li, and Zhou 2010). Most AGCMs can capture the positive SLP anomaly in the western North
by the MME. Besides, the internal variability caused by atmospheric internal dynamics may also be suppressed in the MME. Because climate models possess systematic bias, it may be unreasonable to use a uniform contour (e.g. 5880 gpm) to denote the WNPSH. Thus, we first calculate the deviation of the original 500 hPa geopotential height field at each grid point from the zonal average over 0°–45°N, and then use the zero contour to denote the WNPSH (Section 2). The observed and simulated WNPSH

Figure 3. Observed and simulated WNPSH (western North Pacific subtropical high) in the climatology (black line) and El Niño decaying summers (red line). OBS denotes observation and MME denotes the multi-model ensemble mean.

Pacific region in El Niño decaying summers. However, there is large uncertainty with respect to the simulated location and magnitude of the anticyclone anomaly. It is interesting that the MME mean performs better than most individual AGCMs in simulating both the SLP anomaly and low-level wind anomaly. The pattern correlation coefficient of the MME mean SLP with observation is 0.7. This is larger than for most individual AGCMs, for which there are at least two explanations. First, random model error may be suppressed by the MME. Besides, the internal variability caused by atmospheric internal dynamics may also be suppressed in the MME. Because climate models possess systematic bias, it may be unreasonable to use a uniform contour (e.g. 5880 gpm) to denote the WNPSH. Thus, we first calculate the deviation of the original 500 hPa geopotential height field at each grid point from the zonal average over 0°–45°N, and then use the zero contour to denote the WNPSH (Section 2). The observed and simulated WNPSH
in the long-term mean (black line) and El Niño decaying summers (red line) are shown in Figure 3. It can be seen in the observation that the WNPSH extends westwards in El Niño decaying summers, as compared with its climatological location, which has been extensively explored in previous studies (e.g. Zhang, Sumi, and Kimoto 1996). Most AGCMs in CMIP5 can capture this westward shift of the WNPSH in El Niño decaying summers. Besides, it can be seen that the MME location of the WNPSH has an eastward bias compared with observation. Observation shows that the WNPSH ridge line latitude (westward-extended longitude) is around 24°N (110°E), with a slightly westward- and southward-shifted location in El Niño decaying summers compared with the climatology (Figure 4(a) and (b)). It is clear that there is large spread with respect to the individual AGCM simulations. The MME mean location has an eastward and northward bias, e.g. the WNPSH ridge line latitude (westward-extended longitude) is around 26°N (130°E). This conclusion can also be drawn from Figure 3 (comparing observation and the MME).

Figure 4. Scatterplots of the observed and simulated westward-extended longitude (x-axis) and ridgeline latitude (y-axis) of the WNPSH (western North Pacific subtropical high) in El Niño decaying summers (a, c, e) and climatology (b, d, f). The JJA (June–August) mean, July, and August plots are shown, respectively. The red (green) triangle denotes the observed (multi-model ensemble mean–simulated) location of the WNPSH. OBS denotes observation and MME denotes the multi-model ensemble mean.
be seen that the bias of the westward-extended longitude and ridge line latitude of the WNPSH in July and August is similar to the summer mean results; that is, the MME mean–simulated WNPSH is located eastwards and northwards compared to observation. In July, the eastward bias of the MME is notable and the northward bias is slightly smaller than in JJA. In August, the northward bias is larger than in July, and a notable eastward bias still exists, as in July and the JJA mean.

Figure 5 shows the shift of the WNPSH from July to August in observation and multiple model simulations. Observationally, the WNPSH has a notable northward jump and eastward retreat from July to August both in the climatology and El Niño decaying summers, which is associated with the subseasonal March of the EASM circulation system. There is considerable spread among the CMIP5 AGCM simulations with respect to the subseasonal mean.

### 3.2. Subseasonal variations

Owing to the fact that in June the contour line used to denote the WNPSH is not a closed curve and the westward-extended longitude and ridge line latitude cannot be identified, we only provide the subseasonal March of the WNPSH from July to August. Observationally, the climatological WNPSH ridge line latitude (westward-extended longitude) is around 24°N (115°E), 26°N (117°E), and 29°N (122°E) in JJA (June–July) mean, July, and August, respectively (Figure 4(b), (d), and (f)). Besides, the westward extension in El Nino decaying years, compared to climatology, can also be identified (Figure 4(a), (c), and (e)). Compared with observation, there is large spread with respect to the models, and the MME mean–simulated location of the WNPSH has a notable eastward bias (~15°) in the JJA mean. The northward bias of the MME mean WNPSH (~2°) is much smaller than the eastward bias. It can be seen that the bias of the westward-extended longitude and ridge line latitude of the WNPSH in July and August is similar to the summer mean results; that is, the MME mean–simulated WNPSH is located eastwards and northwards compared to observation. In July, the eastward bias of the MME is notable and the northward bias is slightly smaller than in JJA. In August, the northward bias is larger than in July, and a notable eastward bias still exists, as in July and the JJA mean.

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variation of the WNPSH. However, it can be seen that most AGCMs are able to reproduce the northward jump of the WNPSH. Twenty-one out of 22 (20 out of 22) models can reasonably reproduce the northward jump of the WNPSH from July to August in El Niño decaying summers (climatology). Besides, the MME magnitude of the northward jump in El Niño decaying summers is larger than observed (Figure 5(a)) and the climatological magnitude is comparable to observed (Figure 5(b)). With respect to the east–west shift of the WNPSH from July to August, these AGCMs have difficulty in simulating the eastward retreat of the WNPSH. Only 7 out of 22 (8 out of 22) AGCMs can reasonably reproduce the eastward retreat of the WNPSH from July to August in El Niño decaying summers (climatology). The MME mean shows little east–west shift in El Niño decaying summers from July to August and a weak westward shift in climatology, which is opposite to the observation.

### 3.3. Relationship between the bias in climatology and El Niño decaying years

Comparing the left and right panels in Figure 4, it can be inferred that there may be a relationship between the simulated climatological WNPSH and that in El Niño decaying years. However, it can be seen that most AGCMs are able to reproduce the northward jump of the WNPSH. Twenty-one out of 22 (20 out of 22) models can reasonably reproduce the northward jump of the WNPSH from July to August in El Niño decaying summers (climatology). Besides, the MME magnitude of the northward jump in El Niño decaying summers is larger than observed (Figure 5(a)) and the climatological magnitude is comparable to observed (Figure 5(b)). With respect to the east–west shift of the WNPSH from July to August, these AGCMs have difficulty in simulating the eastward retreat of the WNPSH. Only 7 out of 22 (8 out of 22) AGCMs can reasonably reproduce the eastward retreat of the WNPSH from July to August in El Niño decaying summers (climatology). The MME mean shows little east–west shift in El Niño decaying summers from July to August and a weak westward shift in climatology, which is opposite to the observation.

**Figure 6.** Relationship of the simulated westward-extended longitude (a, c, e) and ridgeline latitude (b, d, f) bias of the WNPSH (western North Pacific subtropical high) between the climatology and El Niño decaying summers. The JJA (June–August) mean, July, and August plots are shown, respectively. The line in each plot is the regression line between the two axes, which can indicate the linear relation between the two biases. The green triangle denotes the multi-model ensemble mean–simulated bias of the WNPSH. OBS denotes observation and MME denotes the multi-model ensemble mean.
summers. To further investigate the simulated WNPSH bias between the climatology and El Niño decaying summers, Figure 6 shows the relationship between the two biases in the summer mean, July, and August, respectively. The left (right) panel shows the westward-extended longitude (ridge line latitude) of the WNPSH. It can be clearly seen that there is a close relationship with respect to the simulated WNPSH location between the climatology and El Niño decaying summers. The regression coefficients between the two biases are about 1 (0.85, 0.72, and 0.87 for the westward-extended longitude bias in JJA, July, and August; 1.07, 0.94, and 1.09 for the ridge line latitude bias in JJA, July, and August, respectively). That is to say, the performances of these models in simulating the WNPSH in El Niño decaying summers largely depend on the associated reproducibility of the models to simulate the climatological location of the WNPSH. This connection between climatological bias and that in El Niño decaying years is reasonable because the simulation of climatology can reflect the basic ability of a climate model to capture climate phenomena and is very important to a climate model. If a model shows considerable bias in simulating the climatological WNPSH location, this model can be expected to simulate a similar bias in El Niño decaying summers.

It can also be derived from Figure 6 that the MME mean–simulated WNPSH has an eastward and northward bias in the summer mean, July, and August, both in the climatology and El Niño decaying summers. Besides, the spread of the simulated WNPSH in August is to some extent larger than that in July, indicating that there is larger uncertainty with respect to the simulation of the WNPSH in August, and so more attention should be paid to this period (late summer).

4. Conclusions

The performances of 22 CMIP5 AGCMs in simulating the WNPSH in El Niño decaying summers are examined in this study. Specifically, we seek to answer the following two questions: (1) How do the CMIP5 AGCMs perform in simulating the WNPSH in El Niño decaying years? (2) Can the CMIP5 AGCMs capture the subseasonal variability of the WNPSH? In answer to the first question, our analysis shows that most models can reproduce the spatial pattern of the climatological SLP and 850-hPa wind field that are associated with the WNPSH in the western North Pacific region. In El Niño decaying summers, these models can also portray the positive SLP anomaly and associated anticyclonic circulation anomaly at 850 hPa, but with the MME mean performing better than most individual models. Although the MME mean location of the WNPSH has an eastward bias compared with observation, most CMIP5 AGCMs can capture the westward shift of the WNPSH in El Niño decaying summers.

With respect to the second question, most AGCMs can reproduce the northward jump of WNPSH from July to August. Twenty-one out of twenty-two (20 out of 22) models can reasonably reproduce the northward jump of the WNPSH in El Niño decaying summers (climatology). However, these AGCMs have difficulty in simulating the eastward retreat of the WNPSH from July to August. Only 7 out of 22 (8 out of 22) AGCMs can reasonably reproduce the eastward retreat of the WNPSH in El Niño decaying summers (climatology). Besides, there is a close relationship with respect to the simulated WNPSH location between the climatology and El Niño decaying summers. That is to say, models with less bias in simulating the climatological WNPSH location may also have less bias in simulating the WNPSH location in El Niño decaying summers.

Disclosure statement

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