A Dynamic Index for the Westward Ridge Point Variability of the Western Pacific Subtropical High during Summer

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(Manuscript received 5 June 2016, in final form 3 January 2017)

ABSTRACT

Based on the ridge line of the western Pacific subtropical high (WPSH) and the theory of gradient wind approximation, a dynamic index for the westward ridge point (WRPI) of the WPSH is defined. Owing to its definition, the new dynamic index can be used to analyze the evolution of the WPSH at various time scales over most isobaric surfaces. The WRPI comprises two dimensions labeled ZWRPI and MWRPI, which depict the zonal and meridional movement, respectively, of the westward ridge point of the WPSH. The rationality and reliability of the dynamic index were validated using reanalysis atmospheric circulation, outgoing longwave radiation, surface air temperature, and rainfall data. The WRPI series revealed that the westward ridge point of the WPSH generally advances poleward while withdrawing eastward. Furthermore, there were close relationships between the WRPI, atmospheric circulation, outgoing longwave radiation, and precipitation over East Asia and the western Pacific in summer. The significant correlation coefficients indicated that the ZWRPI and the MWRPI can reflect the impact of the zonal and meridional movement of the WPSH on the climate over East Asia and the western Pacific. The ZWRPI has no significant linear trend at the interdecadal time scale, indicating that the WPSH did not significantly extend westward in summer. The slight decrease of the MWRPI suggests that the WPSH moves southward but with an insignificant trend. Compared with indices proposed in previous studies, the WRPI showed advantages in objectivity, reliability, predictability, practicability, and therefore extensive potential for application.

1. Introduction

Owing to its shape, intensity, and position, the western Pacific subtropical high (WPSH) dominates the summer climate over Asia by influencing the temporal–spatial distribution of precipitation, and has therefore been well studied (e.g., Tao and Xue 1962; Tao and Chen 1987; Ding 1994; Zhou and Yu 2005; Cao et al. 2009; Huang et al. 2015; Zhang 2015; Zhu et al. 2016). To describe the WPSH’s evolution, some studies have proposed WPSH indices to describe the area, intensity, ridge lines, northern extension, and western boundaries of the WPSH using the geopotential height at 500 hPa (Wang and Zhao 1984; Huang and Wang 1985; Zhao 1999). Five operational indices based on the 588 geopotential dekameter (gpdm) contour are announced monthly by the National Climate Center in China (NCCC). Yang and Sun (2003) used the relative vorticity averaged over the area 22.5°–30°N, 115°–140°E at 500 hPa to study the zonal displacement of the WPSH in summer. The ZWRPI has no significant linear trend at the interdecadal time scale, indicating that the WPSH did not significantly extend westward in summer. The slight decrease of the MWRPI suggests that the WPSH moves southward but with an insignificant trend. Compared with indices proposed in previous studies, the WRPI showed advantages in objectivity, reliability, predictability, practicability, and therefore extensive potential for application.

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DOI: 10.1175/JCLI-D-16-0434.1

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of the WPSH where the easterlies reverse to westerlies. As the index is applicable for all isobaric surfaces, they developed the concept of a ridge surface. Other studies have used the physical quantities at 850 hPa to study the evolution of the WPSH. For example, Lu (2002) developed two new indices to describe the zonal and meridional displacements of the WPSH in summer. He defined the June–July–August (JJA) mean anomalous geopotential height at 850 hPa averaged over the region 10°–30°N, 110°–150°E as a zonal index to measure the zonal position of the WPSH, and those averaged over the region 30°–40°N, 120°–150°E as a meridional index to measure the meridional position of the WPSH. Lu et al. (2008) defined the zonal index of the WPSH by the JJA mean 850-hPa relative vorticity anomalies averaged over 15°–27.5°N, 125°–150°E. Huang et al. (2010) used the 850-hPa zonal wind anomalies over 5°–15°N, 100°–130°E minus those over 20°–30°N, 110°–140°E as an index for the summer WPSH.

Based on these indices and corresponding physical quantities, some studies have focused on the interdecadal variation of the WPSH. It is worth noting that these studies reached contradicting conclusions. Some studies (e.g., Gong and Ho 2002; He and Gong 2002; Zhou et al. 2009; Matsumura et al. 2015) have suggested that the WPSH has intensified and extended farther westward since the late 1970s. In contrast, Huang et al. (2015) indicated that the WPSH recessed eastward during 1979–2009 relative to 1948–78, because the 850-hPa anticyclonic circulation weakened. This was accompanied by a decrease in sea level pressure, an increase in relative vorticity at the middle and lower levels of the atmosphere (1000–600 hPa), and the maximum meridional wind at each latitude of 17.5°–32.5°N moving eastward. Huang and Li (2015) further studied the interdecadal variation of the WPSH using the 10-m contour of eddy geopotential height. Their results further confirmed that the WPSH has weakened since the late 1970s. He et al. (2015) pointed out that, according to the hydrostatic equation, an intensified WPSH will occur if the increased geopotential height has not been considered under a warming climate, and suggested that the WPSH described by the 0-m contour of eddy geopotential height derived from the model projections of phase 5 of the Coupled Model Intercomparison Project shows a robust weakening and eastward retreat in the middle troposphere. Wu and Wang (2015) found that the summer WPSH had not extended farther westward since the late 1970s after removing the increment of geopotential height at 500 hPa, and suggested that a new index describing the zonal movement of the WPSH should be defined.

Given the previous studies reviewed above, there are two methods for defining indices describing the spatiotemporal variation of the WPSH. One method adopts the contour of geopotential height (e.g., 588-gpdm contour at 500 hPa) or the contour of eddy geopotential height (e.g., 1-gpdm contour of eddy geopotential height at 500 hPa), and the other method calculates a physical quantity in a fixed region. However, for the first method, the characteristic 588- or 1-gpdm contour does not always exist over the western Pacific at 500 hPa; the same problem exists over the western Pacific at 850 hPa. In addition, different studies may adopt a different contour of eddy geopotential height (e.g., Huang and Li 2015; He et al. 2015). This may decrease the objectivity of the obtained results. For the second method, the selected key region differs between studies. Consequently, no general index exists to study the variability of the WPSH, especially the zonal displacement of the WPSH, on various time scales. Thus, it is necessary to develop a new objective index with clear physical meanings to objectively describe the displacement of the WPSH.

The rest of this paper is organized as follows. Section 2 describes the datasets used in this study. Section 3 defines a dynamical index of the westward ridge point of the summer WPSH using the horizontal wind field at 500 hPa, and analyzes its relationships with the 588-gpdm contour and previous indices describing the zonal displacement of the WPSH. Section 4 presents the 500-hPa atmospheric circulation, surface air temperature, precipitation, and outgoing longwave radiation anomalies in relation to the new dynamical index of the westward ridge point of the summer WPSH. In section 5, we investigate the interdecadal variation of the summer WPSH revealed by the new WRPI. Section 6 presents the predictability of the WPSH based on the new WRPI. Section 7 provides a summary and discussion.

2. Data

The atmospheric circulation reanalysis data were obtained from the ERA-40 and ERA-Interim monthly data of the European Centre for Medium-Range Weather Forecasts (ECMWF; Simmons et al. 2004; Uppala et al. 2005; Dee et al. 2011). The Global Precipitation Climatology Project (GPCP) precipitation (version 2.2) and the outgoing longwave radiation (OLR) data were provided by the National Oceanic and Atmospheric Administration Office of Oceanic and Atmospheric Research Earth System Research Laboratory Physical Sciences Division, Boulder, Colorado, from their website (http://www.esrl.noaa.gov/psd/) (Liebmann and Smith 1996; Adler et al. 2003). The data periods were 1958–2002 for the ERA-40 data,
1979–2014 for the ERA-Interim data and precipitation, and 1979–2013 for the OLR data. The resolution of the atmospheric circulation was 2.5° for the ERA-40 data and 1.5° for the ERA-Interim data in latitude and longitude. There were 23 pressure levels for the ERA-40 data, and 37 pressure levels for the ERA-Interim data from 1000 to 1 hPa. The resolution of the OLR and precipitation data was 2.5° in latitude and longitude.

The hindcast data of five models—including the Met Office (UKMO), the Météo-France (MF), the ECMWF, the Leibniz Institute of Marine Sciences at Kiel University (IFM-GEOMAR), and the Centro Euro-Mediterraneo per I Cambiamenti Climatici–Istituto Nazionale di Geofisica e Vulcanologia (CMCC–INGV)—are provided by ENSEMBLES, which is an EU-funded integrated project (Doblas-Reyes et al. 2009; Li et al. 2012). The hindcasts have been performed in 1960–2005 for all five models. For each year and each model, the seasonal hindcasts are initialized on 1 May and are run for 7 months with nine members. The results of the multimodel ensemble (MME) are computed by applying equal weights to all five models. In this study, summer is the months June, July, and August.

3. Definition of the dynamic westward ridge point index of the WPSH

Figure 1 shows the climatological JJA mean of the geopotential height, horizontal wind vector, meridional wind, and WPSH ridge line at 500 hPa. The ridge line of the WPSH is defined as the interface between the westerly in the midlatitudes and the easterly in the tropics in the Northern Hemisphere (i.e., the ridge line is a line along which the zonal wind is zero) (Liu and Wu 2004). It is worth noting that the zonal wind is zero, but the meridional wind tends to increase with the point at the ridge line parting gradually from the WPSH center to WPSH edge (Fig. 1). This pronounced feature satisfies the theory of gradient wind approximation: the maximum value of the pressure gradient and the maximum value of wind velocity are more likely to occur around the edge of a high (Holton 2004). Based on the theory of gradient wind approximation, the westward ridge point (WRP) of the WPSH was therefore defined as the point on the ridge line with a maximum meridional wind at the western edge of the WPSH. According to studies of the WRP (Wang and Zhao 1984; Huang and Wang 1985; Zhao 1999), the domain used to identify the western boundary of WPSH is located at 10°–45°N, 90°–150°E.

The new dynamic WRP indices (WRPIs) of the WPSH in June, July, and August are easily obtained using the WRP definition (Fig. 2). It is clear that the new dynamic WRPI consists of two dimensions. The first dimension of the WRPI associated with longitude denotes the zonal WRPI (ZWRPI), which describes the west–east movement of the WRP of the WPSH. The second dimension associated with latitude denotes the meridional WRPI (MWRPI), which describes the north–south movement of the WRP of the WPSH.

To reveal the relationship between the new dynamic WRPI and the atmospheric circulation during the 36-yr period, the long-term mean position of the WRP of the WPSH, the geopotential height, and the horizontal winds at 500 hPa from June to August are shown in Fig. 3. It can be seen that the position of the WRP of the WPSH averaged over the period 1979–2014 is 20.4°N, 123.0°E; 25.6°N, 119.5°E; and 29.5°N, 125.8°E, for June, July, and August, respectively, and the west end of the closed 588-gpdm contour averaged over the same period is around 21.0°N, 127.5°E; 25.5°N, 124.5°E; and 30.0°N, 133.5°E, respectively. The long-term mean position of the WRP of the WPSH matches well with the west end of the closed 588-gpdm contour. Figure 3 also shows that the position of the WRP of the WPSH has the same evolution trend as the west end of the closed 588-gpdm contour. The different WPSH’s positions in June, July, and August suggest that, if we construct an index in a fixed region to study the variability of the WPSH, the index may induce some errors because of the changing position of the WPSH.

The correlation coefficients between the ZWRPI and MWRPI included in the new dynamic WRPI were 0.65, 0.49, and 0.45 for June, July, and August, respectively (exceeding the 99% confidence level). These correlation results mean that, when the ZWRPI increases (decreases) [i.e., the longitude value associated
with the west end of the WPSH becomes larger (smaller), the MWRPI will also increase (decrease) [i.e., the latitude value related to the west end of the WPSH becomes higher (lower)], indicating that the WPSH generally moves poleward while retreating eastward, and usually shifts equatorward while advancing westward. This marked feature is consistent with previous studies at the long-term mean time scale (e.g., Tao and Chen 1987; Wu and Liu 2003; Ding and Chan 2005).

As all the WPSH indices almost focus on the boreal summer, here we compare the WRPI in the present study with the other WPSH indices in June, July, and August. Table 1 shows the correlation coefficients between the ZWRPI and the other WPSH indices: 3 out of 12 correlation coefficients passed the significance test at the 99% confidence level, 9 out of 12 passed at the 95% confidence level, and 1 out of 12 passed at the 90% confidence level. Only one correlation coefficient related to the relative vorticity averaged over the region 15°–27.5°N, 125°–150°E at 850 hPa did not pass the significance test. These may result from the ridge line of the WPSH at 500 hPa being farther north than the north boundary of the selected key region at 850 hPa in August. In addition, when calculating the correlation coefficients between the ZWRPI and the westward extension index under the NCCC’s criteria, the missing data for July 1984 and August 1986 were ignored, because the 588-gpdm contour did not appear. When calculating the correlation coefficients between the ZWRPI and the westward extension index developed by Huang et al. (2015), the missing data for July 1984, August 1986, August 1996, and August 2006 were ignored, because the 1-gpdm contour did not appear. We further calculate the correlation coefficients between the MWRPI and the same four WPSH indices (Table 1).

FIG. 2. The time series of (a) ZWRPI and (b) MWRPI. The blue, green, and red lines represent June, July, and August, respectively.

FIG. 3. The relationship between the WRPI and the geopotential height at 500 hPa in (a) June, (b) July, and (c) August. The contours denote the climatological mean of the geopotential height at 500 hPa (gpdm), and the vectors denote the climatological mean of horizontal wind at 500 hPa (m s⁻¹). The red circle denotes the position of climatological mean of the WRP of the WPSH. The blue line denotes the contour nearest to the WRP of the WPSH.
It is worth noting that the correlation coefficients between MWRPI and the zonal index with relative vorticity at 850 and 500 hPa (Lu et al. 2008; Yang and Sun 2003) are stronger than those associated with ZWRPI, but the correlation coefficients between MWRPI, the zonal index with 1-gpdm eddy geopotential height at 500 hPa, and the westward extension index under the NCCC’s criteria are much weaker than those associated with ZWRPI. These correlation results indicate that the new WRPI is compatible with previous indices, and the index defined with a physical quantity in a fixed region may reflect the WPSH movement in a south–north direction rather than in an east–west direction.

4. Anomalies associated with the WRPI

a. Atmospheric circulation at 500 hPa

Anomalous WRPI years with an absolute value exceeding 0.75 standard deviation were chosen, as shown in Table 2 for June, July, and August. According to these samples, composite studies were performed for the circulation system at 500 hPa in June–August. Figure 4 shows the composites for the farther eastward (positive ZWRPI) and the farther westward (negative ZWRPI) WRP of the WPSH during June–August. In the positive ZWRPI case (Figs. 4a–c), the negative geopotential height anomalies, which passed the significance test exceeding the 90% confidence level, dominate the area around 130°E. The anomalous winds around the west end of the closed 588-gpdm contour passed the significance test exceeding the 95% confidence level in June and July. These phenomena suggest that the lower-than-normal geopotential height anomalies around 130°E correspond well to the eastward retreat of the WPSH. In fact, the west end of the closed 588-gpdm contour just reaches the western Pacific. The position of the WPSH shows an obvious contrast between the positive and negative ZWRPI years. In the negative ZWRPI case, the positive geopotential height anomalies, which passed the significance test exceeding the 90% confidence level, occupy the area around 120°E. The anomalous winds around the west end of the closed 588-gpdm contour passed the significance test exceeding the 95% confidence level in June–August. Compared with Figs. 4a–c, it can be clearly seen from Figs. 4d–f that the west end of the closed 588-gpdm contour crosses the western Pacific, extends into the South China Sea (SCS) in June, and reaches the east edge of the main land of East Asia in July and August. These results indicate that the higher-than-normal geopotential height anomalies around 120°E agree with the westward extension of the WPSH.

Figure 5 is the same as Fig. 4 but for the farther northward (positive MWRPI) and the farther southward (negative MWRPI) WRP of the WPSH in June–August. In the positive MWRPI case (Figs. 5a–c), the negative geopotential height anomalies, which passed the significance test exceeding the 90% confidence level, dominate the area around 30°N in June and 40°N in July and

<table>
<thead>
<tr>
<th>Month</th>
<th>ZWRPI Positive years</th>
<th>ZWRPI Negative years</th>
<th>MWRPI Positive years</th>
<th>MWRPI Negative years</th>
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| Table 1. Correlation coefficients with WPSH indices. |
|----------------|----------------|----------------|----------------|----------------|----------------|
|                | ZWRPI          | MWRPI          |                |                |                |
|                | Jun  | Jul   | Aug  | Jun  | Jul   | Aug  |                |                |                |
| Zonal index with relative vorticity at 850 hPa (Lu et al. 2008) | 0.42a | 0.39a | 0.23 | 0.40a | 0.58b | 0.25 |                |                |                |
| Zonal index with relative vorticity at 500 hPa (Yang and Sun 2003) | 0.30c | 0.51b | 0.35a |                |                |                |                |                |                |
| Zonal index with 1-gpdm eddy geopotential height at 500 hPa | 0.50b | 0.39a | 0.36a |                |                |                |                |                |                |
| Westward extension index under the NCCC’s criteria | 0.34a | 0.87b | 0.36a | 0.28a | 0.40a | 0.07 |                |                |                |

* The correlation coefficient passed the significance test at the 95% confidence level.
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August. The anomalous winds around the northwest boundary of the closed 588-gpdm contour passed the significance test exceeding the 95% confidence level in summer. The north boundary of the closed 588-gpdm contour can reach 30°N in June and July and 40°N in August, suggesting that the higher-than-normal geopotential height anomalies over the north WPSH is consistent with the northward shift of the WPSH. The position of the WPSH in the negative MWRPI years shows an obvious contrast to the positive MWRPI years. In the negative MWRPI case, the positive geopotential height anomalies, which passed the significance test exceeding the 90% confidence level, mainly appeared southwest of the boundary of the closed 588-gpdm contour. The anomalous winds around the west end of the closed 588-gpdm contour passed the significance test exceeding the 95% confidence level in June–August. Compared with Figs. 5a–c, it is clear that the northern boundary of the closed 588-gpdm contour just reaches around 27°N in June and July and around 30°N in August (from Figs. 5d–f). These results indicate that the higher-than-normal geopotential height anomalies over 10°–20°N, 100°–150°E are well related to the WPSH moving northward. These composite results associated with the ZWRPI and MWRPI agree well with previous studies (e.g., Zhou and Yu 2005; Zhao et al. 2012; Liu et al. 2013; He et al. 2015), indicating that the anomalous movement of the WPSH can be well illustrated by the WRPI in summer.

b. Surface air temperature, precipitation, and OLR

To test whether the WRPI can reflect the WPSH impact on droughts and floods over East Asia in summer, we investigated the relationship of the ZWRPI and the MWRPI with temperature, precipitation, and OLR. As the geopotential height anomalies in positive years almost mirror with those in negative years (Figs. 4 and 5), regression analysis and correlation analysis were adopted to reveal the capability of the ZWRPI for expressing the climate anomalies over the western Pacific and East Asia.

The surface air temperature was regressed onto the normalized ZWRPI and the normalized MWRPI. Figure 6 shows that when the ZWRPI is larger than normal, the western WPSH is farther east than normal. The significant positive surface air temperature anomalies mainly occur over the area controlled by the WPSH, and the significant negative surface air temperature anomalies mainly appear in the region surrounding the WPSH (Fig. 6). This feature gradually becomes more remarkable from June to August. For example, the significant positive anomalies appear around 35°N, 150°E with a center value exceeding 0.4°C in July because Earth’s surface absorbs more shortwave radiation.
and the air parcel sinks adiabatically in the area controlled by the WPSH. However, the significant negative anomalies of surface air temperature mainly occur around 20°N, 120°E with a center value below −0.3°C because these areas are located west and south of the west end of the WPSH (Fig. 6b), where relatively stronger precipitation reduces downward shortwave radiation reaching Earth’s surface (Trenberth and Shea 2005). The significant anomalous pattern oriented from southwest to northeast gradually moves northward from 20° to 40°N. The distributions of the significant precipitation anomalies related to the ZWRPI are similar to the pattern of the significant surface air temperature anomalies but with the opposite signs (Figs. 6d,e) [i.e., the positive (negative) anomalies of precipitation usually fit well with the negative (positive) temperature anomalies in summer]. For example, the significant positive precipitation anomalies prevail over 15°–25°N, 100°–170°E with a center value exceeding 2 mm day$^{-1}$, while the significant negative surface air temperature anomalies dominate the same area with a center value below −0.3°C in July. The results of summer OLR regressed onto the ZWRPI also agree well with those associated with precipitation and surface air temperature (Figs. 6g–i), in which the positive (negative) OLR anomalies usually correspond to the negative (positive) precipitation anomalies, but to the positive (negative) surface air temperature anomalies. These results in relation to OLR further confirm the spatial configuration between precipitation anomalies and temperature anomalies.

Figure 7 shows that when the MWRPI is larger than normal, the west end of the WPSH is farther north than normal. The significant positive surface air temperature anomalies mainly occur over the area controlled by the WPSH, and the significant negative surface air temperature anomalies mainly appear south of the WPSH (Figs. 7a–c). This anomalous pattern is maintained and moves northward from June to August. For example, the significant negative surface air temperature anomalies appear south of 25°N with a center value below −0.2°C over the whole summer. However, the significant positive surface air temperature anomalies mainly occur between 30° and 40°N with a center value exceeding 0.4°C. The significant anomalous pattern orientated from south to north tends to shift northward from 30° to 40°N. The distribution of the significant precipitation anomalies related to the MWRPI resembles the pattern of the significant surface air temperature anomalies but with the opposite signs (Figs. 7d,e). For example, the significant positive precipitation anomalies mainly occur south of 20°N with a center value exceeding 2.5 mm day$^{-1}$, while the significant negative surface air temperature anomalies dominate the same area with a center value below −0.2°C in July. The results of summer OLR regressed onto the MWRPI are consistent with those associated with precipitation and surface air temperature (Figs. 7g–i). The spatial
configuration between precipitation anomalies and temperature anomalies shown in Fig. 7 resembles that shown in Fig. 6, but the anomalous pattern associated with the MWRPI is quasi-south–north (Fig. 7), and that associated with ZWRPI is quasi-southwest–northeast (Fig. 6). When the ZWRPI (MWRPI) is lower than normal, the west end of the WPSH is farther west (south) than normal, and the condition with the opposite signs in Fig. 6 (Fig. 7) occurs. The negative relationship between precipitation and temperature can also be explained by the radiation budget (Trenberth and Shea 2005).

These anomalous features of temperature, precipitation, and OLR in relation to the WRPI are consistent with the results associated with temperature and precipitation anomalies over East Asia during summer revealed by Trenberth and Shea (2005) and Wu et al. (2013). This indicates that the WRPI can reflect the leading modes of summer temperature and precipitation anomalies over East Asia and the western Pacific. The quasi-south–north movement of the anomalous patterns associated with the WRPI suggests that the ZWRPI can also capture the intraseasonal characteristics of temperature, precipitation, and OLR influenced by the WPSH.

To compare the efficiency of the new dynamic WRPI of the WPSH with previous indices describing the zonal movement of the WPSH, temperature, precipitation, and OLR were also regressed onto the zonal indices of the WPSH developed by Lu et al. (2008), by Yang and Sun (2003), and by Huang et al. (2015) (Figs. 8, 9, and 10, respectively). It can be clearly seen that Fig. 8 shows “negative around 20°N and positive around 40°N” anomalies for surface air temperature and OLR, but “positive around 20°N and negative around 40°N” anomalies for precipitation in summer. This remarkable feature oriented in a quasi-south–north direction shares the same pattern as Fig. 7 associated with the MWRPI.
to a large degree, but differs from the pattern shown in Fig. 6 to some extent. The anomalous distributions of temperature, precipitation, and OLR (Fig. 9) associated with the zonal index of the WPSH developed by Yang and Sun (2003) are very similar to those associated with the zonal index of the WPSH developed by Lu et al. (2008). These results suggest that the two zonal indices of the WPSH developed in previous studies may mainly reflect the movements of the WPSH in a quasi-south–north direction rather than in a quasi-west–east direction, which is caused by their definition (i.e., these indices were defined with a physical quantity averaged at a fixed rectangle). The anomalous patterns of temperature, precipitation, and OLR (Fig. 10) developed by Huang et al. (2015) almost share the same patterns as Fig. 6 associated with the ZWRPI. Figure 10 is also similar to Fig. 11 in the area passing significance test to a larger degree. Further compare Figs. 6–10 with Fig. 11, which shows the correlation coefficient between observational data and their values fitted by both ZWRPI and MWRPI. It can be found that the area passing significance test in Fig. 11 is obviously larger than those in Figs. 6–10. The results of these comparisons suggest that the seasonal and annual variability of the WPSH could be described more comprehensively by the new dynamical WRPI, because Fig. 11 combines the advantages of Figs. 6–10 together.

5. The interdecadal variation of the summer WPSH’s position

The new dynamic WRPI can describe the interdecadal variation of the WPSH’s position in summer. Figure 12a shows the 586- and 588-gpdm contours averaged in the period 1958–2002 (black line), 1958–76 (blue line), 1979–2002 (red line) with the ERA-40 data, and 1979–2002 with the ERA-Interim data. The most pronounced feature is that the west ends of the 586- and 588-gpdm contours averaged in the period 1979–2002 extend more westward than those averaged in the period 1958–76. To further test whether the evolution trend of the west ends of 588-gpdm contour is significant, its summer
positions are calculated with the ERA-40 and the ERA-Interim data. If the 588-gpdm contour misses at a certain year, its position is replaced by the maximum in the same series. As the correlation coefficient between the positions of the west end of the 588-gpdm contour obtained by the ERA-40 data and those obtained by the ERA-Interim data achieves 0.98 in the period 1979–2002, passing the significance test above the 99% confidence level (Fig. 12b), the positions of the west end of the 588-gpdm contour in the period 1958–78 can be regressed onto the position series associated with the ERA-Interim data. Then the summer positions of the west end of the 588-gpdm contour are constructed from 1958 to 2014 (Fig. 12c). Clearly the position series of the west end of the 588-gpdm contour presents a significant decrease in 1958–2014. The linear trend passes the significance test above the 95% confidence level, suggesting that the west end of the 588-gpdm contour significantly extends westward from 1958 to 2014. The result agrees with Zhou et al. (2009). However, some recent studies (e.g., He et al. 2015; Huang et al. 2015; Wu and Wang 2015) pointed that the systematic increase of the geopotential height field caused by the warming climate may misdirect people to deduce a westward extension of the WNPSH, which disaccords with the changes in atmospheric circulation and rainfall. In comparison with the evolution of the west end of the 588-gpdm contour, it can be seen that the position of the west edges of the maximum meridional wind represented by the 2 m s$^{-1}$ contour are kept unchanged to a large degree in different periods and datasets (Fig. 12d). Because the correlation coefficients between the WRPI associated with ERA-40 and that associated with ERA-Interim are 0.93 and 0.88 for MWRPI and ZWRPI (Figs. 12e,g), respectively, the ZWRPI and MWRPI computed by the two different reanalysis data can be merged respectively into two series from 1958 to 2014 by repeating the same regression processes mentioned above (Figs. 12f,h). The ZWRPI presents few trends in 1958–2014 (Fig. 12f), and the MWRPI
exhibits a decreased trend without passing the significance test even at the 90% confidence level (Fig. 12h). The evolution of the ZWRPI and MWRPI reproduces well the most pronounced feature in Fig. 12d. In fact, it can be found that the ZWRPI and MWRPI are calculated using the maximum meridional wind along the ridge line of the WPSH. Without moving any trend these results are consistent with previous studies (e.g., He et al. 2015; Huang et al. 2015; Wu and Wang 2015), indicating that the new WRPI can objectively describe the variation of the WPSH in summer.

6. Predictability of the WPSH revealed by the WRPI

Although the WRPI reproduces well the relationship between the preceding winter sea surface temperature (SST) anomaly in the tropical Indian Ocean, the tropical western Pacific, and the tropical eastern Pacific and the following summer WPSH variability obtained by previous studies (e.g., Yang and Sun 2003, 2005; Lu and Dong 2001; Xie et al. 2009; Du et al. 2009; Kosaka et al. 2012) (figure not shown), the predictability of WPSH based on the WRPI is needed to fully assess. Li et al. (2012) studied the predictability of the summer climate over the western North Pacific (WNP) using the ENSEMBLES data of 1-month lead hindcasts. They found that the variation of the WNP summer climate can be successfully predicted at the interannual time scale to a larger degree. Here, we adopt the same ENSEMBLES data predicted from May to calculate the correlation coefficients, the standard deviations (SDs) and the root-mean-square difference (RMSD) between the observational indices describing the movement of the WPSH in summer and the corresponding indices retrospectively forecasted by each model and their MME (Fig. 13). Figures 13a and 13b show that the MME results of the five state-of-the-art coupled models from ENSEMBLES during the period of 1960–2005 predict well the WPSH variability as measured by the WRPI in the interannual time scale. There, the correlation
coefficient associated with ZWRPI (0.40) passes the significance test above the 95% confidence level, and that associated with MWRPI (0.65) passes the significance test above the 99% confidence level. We further test the predictability associated with other indices listed above. The correlation coefficient and RMSD associated with MWRPI are equivalent to those associated with Lu et al.’s (2008) index, but the model SD associated with MWRPI is closer to the observational SD, and the correlation coefficient related to Yang and Sun’s (2003) index does not pass the significance test below the 95% confidence level (Fig. 13). Therefore, the rank of the WPSH predictability based on the different indices from high to low is the MWRPI, Lu et al.’s (2008) index, Huang et al.’s (2015) index, the ZWRPI, and Yang and Sun’s (2003) index. It is worth noting that the modeling results of Météo-France did not appear in Fig. 13c, because the 1-gpdm contour disappeared in approximately half of the 27 years. That the discreteness of the five state-of-the-art coupled models in Fig. 13b is higher than that in Fig. 13c may be caused by the index’s definition.

The MWRPI is defined with data at a point, but Lu et al.’s (2008) index is defined with data over a region. In addition, the correlation coefficients between the modeled MWRPI, Lu et al.’s (2008) index, and Yang and Sun’s (2003) index are significantly higher than those associated with ZWRPI (Table 3). These results resemble the corresponding observations (Table 3), further indicating that the index defined with physical quantities at a fixed region may only describe the WPSH movement in a south–north direction rather than in an east–west direction.

7. Summary and discussion

In this study, we developed a dynamic index that describes the activity of the WRP of the WPSH based on the ridge line of the subtropical high and the theory of gradient wind approximation. The WRP index (WRPI) was defined as the point on the ridge line with a maximum meridional wind. The WRPI has two dimensions: one denoted as ZWRPI describes the zonal movement...
of the WRP of the WPSH, and another denoted as MWRPI depicts the meridional movement of the WRP of the WPSH.

The rationale behind and the reliability of the WRPI were examined by analyzing the relationship between the long-term mean WRPI and the characteristic contour of geopotential height. The long-term mean WRPI corresponded to the west end of the 588-gpm contour in summer. Such results were explained by the fact that the WRPI is calculated using wind rather than geopotential height. On the climatological time scale, the WRP of the WPSH moves poleward while retreating eastward from June to August.

The rationale and reliability of the WRPI were further verified by comparing the WRPI with other WPSH indices in June, July, and August. The comparison showed that 15 out of 24 indices passed the significance test at the 95% confidence level or above, indicating that the WRPI is compatible with previous WPSH indices. The relationship between the ZWRPI, MWRPI, atmospheric circulation, surface air temperature, precipitation, and OLR over East Asia and the western Pacific during summer were analyzed through composite analysis and regression analysis. The results indicated that the ZWRPI and the MWRPI can reflect the atmospheric circulation, surface air temperature, precipitation, and OLR anomalies over East Asia and the western Pacific. In summer, when the ZWRPI (MWRPI) was larger than normal, the position of the WPSH was farther eastward (northward), accompanying anticyclonic circulation anomalies appearing to the east coast of China, which led to below-normal surface temperature and OLR and above-normal summer rainfall from southern China to the western North Pacific, and above-normal surface temperature and OLR and below-normal summer rainfall over the areas between the Yellow River and the Yangtze River. The almost opposite conditions occurred when the ZWPRI and MWRPI were lower than normal (i.e., the position of

![Fig. 11. The correlation coefficients between the observational data and the corresponding values fitted by both ZWRPI and MWRPI. The areas shaded from light to dark gray denote OLR anomalies passing the significance test at the 90%, 95%, and 99% confidence levels, respectively.](http://journals.ametsoc.org/jcli/article-pdf/30/9/3325/4094535/jcli-d-16-0434_1.pdf)
the WPSH was more westward). In comparison with indices developed by previous studies, the relationships between the WPRI, atmospheric circulation, surface air temperature, precipitation, and OLR over East Asia and the western Pacific during summer are much stronger in correlation intensity and correlation area, passing a significance test above the 95% confidence level. The ZWRPI and MWRPI should be combined when we eventually perform succeeding research and prediction. For example, we could establish a multivariate statistical regression model with two interdependent variables, ZWRPI and MWRPI, which will reveal the impact of WPSH movement at both the zonal and meridional direction on precipitation or temperature. The time series of the west end position of the 588-gpdm contour extended from 1979–2014 to 1958–2014 has a significant decrease trend (i.e., the west end position of the 588-gpdm contour spreads westward). The trend has been proven to be caused by global warming, and the time series related to the geopotential height could not be used to study the WPSH variations. However, the WRPI time series from 1958 to 2014 reconstructed with the regression method does not show any significant trend. The results, agreeing with previous studies (the geopotential height is systematically increasing due to increasing temperature under the warming climate, and the meridional wind is proportionate to the gradient of the geopotential height rather than the geopotential height itself), suggest that the WRPI intrinsically avoids the effect of the warming climate, and could objectively describe the WPSH variations. All the above results indicate that the WRPI can describe the zonal and meridional variability more comprehensively than other indices, especially in the west-east direction, and therefore has good rationality and reliability. The retrospective forecasts of the multimodel ensemble can catch the WPSH variations measured by the WRPI to a large degree, suggesting that the WRPI also has higher predictability. Thus, the predictability of the

![Diagram](http://journals.ametsoc.org/jcli/article-pdf/30/9/3325/4094535/jcli-d-16-0434_1.pdf)
WPSH movement measured by the WRPI is higher in a south–north direction than that in a west–east direction.

In the previous definition of the western ridge point index, when the strength of the WPSH is relatively weak, the characteristic 588-gpdm contour does not exist over the western Pacific at 500 hPa. Under this condition, the position of the western ridge point of the WPSH is determined by its maximum from the historical period (e.g., Wang and Zhao 1984; Huang and Wang 1985; Hu 1997; Zhao 1999). However, some other studies have suggested that global warming may cause an increased isobaric surface at mid-to-lower latitudes (Yang and Sun 2003; Lu et al. 2008). To avoid the increase of the isobaric surface caused by the warming climate, Huang et al. (2015) introduce a new index to describe the west–east movement of the WPSH with eddy geopotential height. However, the index has to face the same problem as the index defined by the characteristic 588-gpdm contour (i.e., the characteristic 1-gpdm contour does not always exist over the western Pacific at 500 hPa). These extreme cases impact the objectivity and reliability of the definition of the WRPI to some extent.

For those definitions with certain physical quantities at a fixed region (e.g., Lu et al. 2008; Yang and Sun 2003, 2005), we find that these indices can describe well the

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<th>Table 3. Summer correlation coefficients.</th>
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<sup>a</sup> The correlation coefficient passed the significance test at the 99% confidence level.

<sup>b</sup> The correlation coefficient passed the significance test at the 95% confidence level.
WPSH variations in summer. However, both the observational and MME results in Figs. 6–9 and in Tables 1 and 3 suggest that these indices appear to describe the WPSH variation in a south–north direction rather than in a west–north direction as expected. Meanwhile, we note that Yang and Sun (2003, 2005) used the relative vorticity averaged over different areas to study the zonal displacement of the WPSH in summer and in the pre-rainy season in southern China. Their results imply that a physical quantity in a fixed region may not be suitable to describe the WPSH variation across all seasons, due to its moving position.

The new dynamic index, WRPI, overcomes the shortcomings of the previously developed indices of the WRP of the WPSH. A wind-stratified definition of the WRPI can always be found around the west end of the WPSH on various time scales, can successfully avoid the interference of warming climate in determining the position of the WPSH in summer because the meridional wind is proportional to the gradient of the geopotential height rather than the geopotential height itself, and has a relatively high predictability. Consequently, the new dynamic WRPI with a clear physical meaning has extensive potential applications, including studying the variation of the WRP of the WPSH from subseasonal to interdecadal time scales. In this study we found that the new dynamic index of the WPSH can describe the variation of the WPSH’s position. The variation of the WPSH’s intensity is not discussed in this study. We will investigate it in future research.

Acknowledgments. This work was supported by the National Key Research and Development Program of China (2016YFA0601600), the National Natural Science Foundation of China (U1502233, 41305043, and 41405001), and the Jiangsu Collaborative Innovation Center for Climate Change.

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