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**Variations of Mid-Pacific Trough and Their Relations to the Asian-Pacific-North
American Climate: Roles of Tropical Sea Surface Temperature and Arctic Sea Ice**

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Abstract

The mid-Pacific trough (MPT), occurring in the upper troposphere during boreal summer, acts as an atmospheric bridge connecting the climate variations over Asia, the Pacific, and North America. The first (second) mode of empirical orthogonal function analysis of the MPT, which accounts for 20.3 (13.4) percent of the total variance, reflects a change in its intensity on the southwestern (northeastern) portion of the trough. Both modes are significantly correlated with the variability of tropical Pacific sea surface temperature (SST). Moreover, the first mode is affected by Atlantic SST via planetary waves that originate from the North Atlantic and propagate eastward across the Eurasian continent, and the second mode is influenced by the Arctic sea ice near the Bering Strait by triggering an equatorward wave train over the Northeast Pacific.

A stronger MPT shown in the first mode is significantly linked to drier and warmer conditions in the Yangtze Basin, southern Japan, and northern U.S. and a wetter condition in South Asia and northern China, while a stronger MPT shown in the second mode is associated with drier and warmer southwestern U.S. In addition, an intensified MPT (no matter in the southwestern or the northeastern portion) corresponds to more tropical cyclones (TCs) over the western North Pacific (WNP) and less TCs over the eastern Pacific (EP) in summer, which is associated with MPT-induced ascending and descending motions over the WNP and the EP, respectively.

1. Introduction

The mid-Pacific trough (MPT) is one of the most prominent upper tropospheric circulation features in the Northern Hemisphere (NH). It is also known as the tropical upper tropospheric trough (Krishnamurti 1971; Sadler 1976, 1978) and the mid-oceanic trough over the central Pacific (Colton 1973; Kousky and Gan 1981). The trough extends from the mid-latitudes into the subtropics along a northeast-southwest direction (Sadler 1967) and peaks in the upper troposphere during boreal summer. Although it is believed that the MPT may be affected by many factors such as convection in the intertropical convergence zones (Webster 1972; Hoskins and Rodwell 1995) and radiative cooling over the North Pacific (Zhao et al. 2007), the exact mechanisms have never been fully understood.

The MPT can be decomposed into stationary and transient eddy parts (Ferreira and Schubert 1999). The stationary part features a climatological appearance of the trough, while the transient part refers to the synoptic-scale disturbances. Previous effort has been devoted to investigations of the interaction between the MPT and tropical cyclones (TCs) (Kelley and Mock 1982; Price and Vaughan 1992; Whitfield and Lyons 1992; Patla et al. 2009). On the one hand, the MPT affects the origin and development of TCs by modifying the vertical wind shear in which TCs are embedded (Gray 1968; Pfeffer and Challa 1992; Montgomery and Farrell 1993; Hu et al. 2017). On the other hand, the MPT disturbances provide the initiation to TCs by extending the trough into the middle-lower troposphere in some cases (Hodanish and Gray 1993). In turn, TCs could also affect the MPT through Rossby wave energy dispersion associated with the TCs (Ferreira and Schubert 1999). Patla et al. (2009) proposed

a conceptual model about how MPT influences TC tracks, offering a useful operational guidance for weather forecasters. Recently, Wu et al. (2015) found that the MPT experienced a pronounced westward shift during the past three decades in all of the available reanalysis data sets, suppressing TC genesis in the eastern portion (east of 145°E) of the western North Pacific due to the enhanced vertical wind shear associated with the MPT shift.

Moreover, the MPT can act as an atmospheric bridge connecting the eastern and western hemispheres as well as tropical and extratropical regions. Recent studies have suggested possible associations of the MPT with various atmospheric teleconnections. For example, Zhang et al. (2005) noted that a stronger South Asian high (SAH) was accompanied by a stronger and more extensive western North Pacific (WNP) subtropical high (WNPSH). The enhancement and expansion of WNPSH could then push the MPT eastward, which subsequently results in a stronger Mexican high. Thus, the MPT bridges the climate variations in Asian-Pacific-American regions. In addition, as the MPT tilts along a southwest-northeast direction over the subtropics, it could promote exchanges of heat and momentum between different latitudes (Magaña and Yanai 1991; Waugh and Polvani 2000). Indeed, the MPT can sometimes extend so far south into the tropics that the equatorial winds over the south of MPT are switched from the trade easterlies to westerlies, forming the so-called equatorial “westerly duct” that allows atmospheric disturbances to propagate from one hemisphere into the other (Webster and Holton 1982; Webster and Yang 1989; Tomas and Webster 1994).

Therefore, understanding the variations and characteristics of the MPT is helpful for untangling the interconnected weather events and climate anomalies in the

Asian-Pacific-North American regions. Although the synoptic features of the MPT and its influence on TCs have been studied previously, the interannual and interdecadal variations of the MPT and their climate impact are poorly understood so far. In fact, the MPT is often regarded as a passive circulation feature induced from the upstream SAH, with its impact on the climate in the remote regions being considered negligible. Given this belief, few studies have been conducted about the multi-scale variations of the MPT, leaving an unanswered question about the interannual variability of the MPT and its climate effect.

Given that the MPT connects the Asian and North American climate, as well as the tropics and the mid-latitudes, the present study focuses on the interannual variation of MPT, its possible effect on the Asian-Pacific-North American climate, and the responsible physical mechanism. Although ENSO is the dominant mode of the climate variability in this region, the ENSO alone could not fully explain the variability of MPT (Wang and Wu 2016). It is important to seek and analyze other climate impacting factors for possible improvement over the MPT-related climate forecasts.

The rest of the paper is organized as follows. Section 2 describes the data sets and analysis methods applied. Section 3 discusses the climatological and interannual features of the MPT. Sections 4 and 5 present the associated atmospheric circulation anomalies and discuss the possible factors underlying the MPT variability. The effects of MPT on the Asian-Pacific-North American climate are illustrated in section 6, followed by a summary and a further discussion in section 7.

2. Data and Method

This study uses the monthly mean sea surface temperature (SST) data from the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST version 4 (Huang et al. 2015). The SST data set has a horizontal resolution of $2^{\circ} \times 2^{\circ}$ and is available from 1854 to the present. The monthly precipitation data is obtained from the Global Precipitation Climatology Center (GPCC, Schneider et al. 2011), with a horizontal resolution of $1^{\circ} \times 1^{\circ}$ for the period of 1901-present. Surface air temperature anomalies are acquired from the Goddard Institute for Space Studies (GISS/NASA), with a horizontal resolution of $2^{\circ} \times 2^{\circ}$ for the period of 1880-present. The monthly mean sea ice concentration data provided by Japanese Reanalysis (JRA; Hirahara et al. 2014), with a horizontal resolution of $1^{\circ} \times 1^{\circ}$ for the period of 1850-present, is available from the website at <https://www.esrl.noaa.gov/psd/data/gridded/data.cobe2.html>. The JRA sea ice data merged the satellite observations from the Nimbus-5 Scanning Multichannel Microwave Radiometer (SMMR) from October 1978 to July 1987 and the Special Sensor Microwave Imager (SSM/I) and the Special Sensor Microwave Imager/Sounder from August 1987 to December 2010. The JRA sea ice data for the Arctic Ocean before the satellite era from January 1870 to November 1978 was taken from Walsh and Chapman (2001), which used various regional datasets based primarily on ship reports and aerial reconnaissance. To explore the impact of the MPT on tropical cyclones, we also analyze the tropical cyclone data sets from the Joint Typhoon Warning Center (JTWC) and the Tropical Prediction Center (TPC) best track reanalysis from website at <http://weather.unisys.com/hurricane/>. In this study, we examine the linear relationships between the dominant modes of MPT and the tropical cyclone genesis

126 numbers over the WNP and the East Pacific (EP) during the mid-summer.

127 The atmospheric data, including geopotential height and three-dimensional velocity at
128 multiple levels, are obtained from the NCEP–NCAR Reanalysis (Kalnay et al. 1996). The
129 geopotential height and horizontal wind obtained from the ERA-Interim for 1979-present are
130 also used to compare with the NCEP-NCAR data. The Niño-3.4 index is downloaded from
131 the NOAA Environmental Systems Research Laboratory’s (ESRL) website at
132 <http://www.esrl.noaa.gov/psd/data/climateindices>. The analysis period of this study is
133 1948-2014.

134 We apply an empirical orthogonal function (EOF) analysis on the mean horizontal winds
135 to capture the dominant modes of the MPT during the mid-summer (July and August) when
136 the MPT reach the maximum intensity (see Fig. 1), with an equal area weighting at each grid
137 point by multiplying the square root of the cosine of latitudes due to the decrease in area
138 toward the pole (North et al. 1982). This vector-EOF analysis enables a more thorough
139 analysis of wind components than scalar analyses (Legler 1983). Linear regression/correlation
140 analysis is performed by regressing/correlating the anomalous atmospheric circulation,
141 precipitation, and other physical quantities on/with the principle components. This study
142 focuses on the mid-summer [i.e., July–August (JA)], and so each set of successive 2-month
143 season is considered with physical fields leading or lagging the PCs [e.g., May-June (MJ) and
144 June-July (JJ) lead the PC in JA by two months and one month, respectively, while
145 August-September (AS) lag the PC in JA by one month].

146 Considering the dominant correlation between ENSO and other variables, in most of the

correlation/regression analyses the ENSO signal captured by the Niño-3.4 index is removed via a simple linear regression method. It should be noted that it is impossible to remove the influence of ENSO completely by only the Niño-3.4 index (Hu et al. 2016), as ENSO signal is not always linear and stationary in time (Capotondi 2015). To investigate the interannual variations of MPT and its climate effects, we also remove the linear trend of MPT before conducting the correlation/regression analysis. We used the Student's t -test to assess the statistical significance of results from correlation analysis. A value of correlation above 0.33 (0.24), for a 36-yr (65-yr) length of 1979–2014 (1948–2014), is used to estimate the 95% confidence level. Here the correlation (r) is defined as

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}},$$

in which $\bar{x}$ and $\bar{y}$ are the sample mean of x_i and y_i from $i=1$ to $i=n$ (n is the sample size, and $n-2$ is the so called degree of freedom). The threshold of correlation coefficient $|r_0|$ for the 95% confidence level is defined as: $|r_0| = \frac{t}{\sqrt{t^2 + (n-2)}}$, where t can be acquired by checking tables about the critical values of Student's t distribution with $n-2$ degrees of freedom (Storch and Zwiers 2002).

3. Climatological and interannual features of MPT

Figure 1 shows the monthly climatological patterns of 200-hPa geopotential height (H200) and its departures from the annual mean for all 12 months. Within the annual cycle, the largest changes occur over East Asia and the North Pacific, accompanied by a shift in the

phase of planetary-scale stationary waves. In winter (from December to February), distinct trough and ridge are seen over East Asia and the west of North America, respectively, due to strong land-ocean thermal contrast (Smagorinsky 1953; Wang and Ting 1999). From late spring to early summer (May and June), the atmospheric circulations undergo a dramatic change when the East Asian trough and the Alaskan ridge weaken rapidly, while the Asian summer monsoon and the SAH are quickly established (Yeh et al. 1959; Webster and Yang 1992). In northern mid-summer (July and August), the SAH, the MPT, and the North American ridge dominate the northern subtropics, due mainly to monsoon heating (Wang and Ting, 1999). In particular, the SAH and the MPT evolve approximately in tandem, and both reach their maximum intensities in July and August. After September, the SAH and the MPT weakens quickly and winter patterns appear again.

Figure 2 shows more details about the climatological characteristics of MPT and its surrounding atmospheric circulation in mid-summer (JA), when the MPT reaches the peak intensity. As seen in Fig. 2a, the upper-level SAH and MPT are corresponding to the lower-level Asian monsoon low and WNPSH, respectively, implying that the atmospheric circulations in the northern subtropics are completely out of phase in the vertical direction. Figure 2b shows the vertical cross section of zonally asymmetric height and vertical velocity along 30°N. It indicates that vigorous upward motions occur under the western side of the MPT due to the monsoon-related convection over East Asia and the WNP. Besides, strong descending motions are found under the eastern side of the MPT, which seem to be linked to the Pacific subtropical high.

Figure 3a shows the standardized deviations of upper-tropospheric horizontal winds, in which the largest values appear over the mid-latitudes and the equatorial Pacific regions, which could be attributed to the intrinsic large variability of the westerly jet streams (Joseph and Sijikumar 2004; Schiemann et al. 2009) and the large variability associated with ENSO (Yang and Hoskins 2013; Kim et al. 2014). There is, however, substantial variability over the subtropical Pacific, coinciding with the MPT area. Overall, one expects the subtropics to be stable with small variability due to the relatively weaker coupling between the upper troposphere and the low troposphere (Charney 1963). Thus, it is interesting to explore why large variability exists in the MPT region and whether such variability is forced locally or remotely?

Figure 3b further shows the frequency distribution of MPT centers during the period of 1948-2014. The MPT centers are identified as the locations of minimum zonally-asymmetric geopotential height at 200 hPa. In general, the MPT centers are distributed along a northeast-southwest direction, concentrating around 30°N of latitude, with a maximum frequency of 9 years located at 152.5°W and 32.5°N. In extreme cases, MPT centers can shift as far northeast as to 130°W and 40°N. It can also be seen that the MPT centers tend to shift more frequently in east-west direction than in south-north direction.

4. Dominant modes of MPT and associated circulation anomalies

a. Vector-EOF modes of MPT variability

To better classify MPT variability, an area-weighted vector-EOF analysis is applied to the 200-hPa horizontal winds. The analysis domain is 160°E-120°W and 15°N-50°N, as

outlined by the blue box in Fig. 3a, covering the area of both maximum subtropical variability and climatic position of the MPT. The first two modes respectively explain 20.4 and 13.1 percent of the total variance (26.5% and 14.7% for the ERA-Interim data set, 1979-2014), which are statistically distinguishable from the rest of the eigenvectors according to the rule by North et al. (1982).

The spatial patterns of the first two modes of MPT are presented in Figs. 4a and 4c, in terms of the correlation coefficients between H200 and the principal components (PC1 and PC2). The first mode is dominated by significant anomalies in the southwestern side of the MPT (Fig. 4a), which reflects a change in MPT intensity over the WNP. The second mode, however, is related with the significant anomalies in the northeastern side of the MPT (Fig. 4c), and it reflects the change in MPT intensity over the eastern North Pacific. The corresponding time series of the two modes are illustrated in Figs. 4b and 4d. The first mode exhibits strong interannual signals, combined with multi-decadal variations with a shift from a predominantly negative phase to a positive phase around the 1990s. On the other hand, the second mode shows a significant decreasing trend for the period of 1948-2014. The time series calculated from the ERA-Interim data set are also included in Figs. 4b and 4d, which are consistent with those from the NCEP-NCAR product.

We also repeat the vector-EOF analysis to a larger domain covering most of the Northern Hemisphere (20°E-60°W, 20°N-80°N). The spatial patterns related to the first mode of MPT is very similar to those patterns from the analysis of the smaller domain (with a correlation coefficient of 0.77 between the two corresponding PC1), although the variance

explained drops to 10.5%. The previous second mode of MPT variability falls to the third mode for the extended domain (with a correlation coefficient of 0.52 between the corresponding PC2). These results further demonstrate the robustness of the first two modes of MPT.

b. Atmospheric circulation anomalies associated with the dominant modes of MPT

Figure 5 shows the regressions of atmospheric circulation and Plumb wave activity fluxes (WAF; Plumb 1985) onto the dominant modes of MPT, in which the linear trends of the PCs and the field variables have been subtracted. The first mode corresponds to higher pressure across the entire mid-latitude belts (Fig. 5a), covering North Africa, South and East Asia, the North Pacific, North America, and the Atlantic. Several isolated positive centers are identified along the entire mid-latitude belts, with most prominent anomalies over the East Asia, North Pacific, North America, and the North Atlantic. Meanwhile, remarkable anomalies of alternative cyclonic and anti-cyclonic circulations are seen over the western North Pacific. In comparison, the second mode of MPT reveals predominant signals over the eastern North Pacific (Fig. 5b), which are oriented in a north-south direction, connecting the tropics and the Arctic region.

Figures 5a and 5b show the association of WAFs with the dominant modes of MPT. The first mode is associated with southward and eastward propagating wave trains, which diverge over East Asia and converge in the southwestern portion of the MPT, resulting in intensification of the trough at its first mode. Similarly, the second mode is related with an equatorward propagating wave train, which originates from the northeastern Pacific and

converges in the northeastern portion of MPT, leading to strengthening of the MPT at its second mode. Besides, the second mode of MPT also corresponds to a relatively weak wave train originating from the central Pacific, which could be related to the central Pacific warming that is shown in Fig. 6b. The anomalous WAFs seem to appear at the exit of East Asian westerly jet, which may be related to the meridional displacements and the changes in intensity of the jet stream. As seen in Figs. 5c-5d, an intensified MPT in the first mode is significantly related to the northward shift of the jet stream over East Asia and the western North Pacific, while the intensified MPT in the second mode corresponds to the weakening jet stream over the eastern North Pacific. These results suggest that the wave trains associated with MPT variability may be sensitive to the subtle westerly jet structure. Thus, we have also computed the WAF proposed by Takaya and Nakamura (2001, TN01) to understand the impact of uneven basic flow. The regressed patterns of TN01 WAFs reveals a similar pattern as the Plumb's WAF (figure not shown), showing two splitting wave trains over the western (first mode) and the eastern (second mode) North Pacific. One propagates eastward along the westerly jet stream, and the other propagates southeastward that affects the variability of MPT. Compared to the Plumb's WAFs, the equatorward propagating wave trains of TN01 WAFs associated with the MPT seem to be more prominent, implying the possible effect of zonally-asymmetric westerlies on MPT variability.

The variabilities of MPT seem to largely originate in extratropical regions. Indeed, when ENSO signals were removed (figure not shown), the features of regression patterns remained almost unchanged. For the first mode, the negative height anomalies over the WNP and

sub-Arctic regions experience a slight decrease, and the positive height anomalies over the mid-latitudes remain the same and even become somehow stronger, particularly over North America and the Atlantic. For the second mode, the negative height anomalies over the Arctic region become even more significant. These results imply that the dominant modes of MPT variability may be also affected by other forcing sources beyond ENSO.

The regressions of SST anomalies (SSTAs) on PCs of MPT are shown in Fig. 6. Both modes are significantly correlated with the Pacific SST. The first mode is significantly related with a La Niña-like pattern, with negative SSTA in the central-eastern Pacific. This mode also exhibits a close relationship with the Atlantic SST. The correlation coefficient between PC1 (PC2) and the Niño-3.4 index is -0.465 (0.23), which exceeds the 99% (90%) confidence level, implying that both the first and second modes of MPT are affected by ENSO, to different a certain extent. It should also be noted that the regressed SST patterns in Figs. 6a and 6b seem to represent the eastern-Pacific (EP) type and the central-Pacific (CP) type of El Niño (e.g., Ashok et al. 2007; Kug et al. 2009), respectively. The EP type of El Niño corresponds to northward propagating waves and anomalous high pressure on the southwestern portion of MPT (Wang and Wu 2016), implying the weakening of MPT at its first mode. However, the CP type of El Niño is correlated with northeastward propagating waves (Fig. 5b), which lead to anomalous low pressure on the northeast portion of MPT, suggesting the intensification of MPT at its second mode. Zhang et al. (2012) have investigated the differences in atmospheric teleconnections associated with different types of El Niño, indicating that the EP type of El Niño was associated with wave trains that tilted

more in north-south direction, while the CP type of El Niño was significantly correlated with wave trains that tilted more in northeast-southwest direction. Their results, though focused on the boreal autumn, were similar to the features shown in Figs. 5a and 5b.

5. Factors and physical mechanisms for the dominant modes of MPT

The maps of lead-lag correlation between global SST and PC1 (also PC2) are shown in Fig. 7, where the linear signal of ENSO is removed by regressing out the Niño-3.4 index from the PCs. The left panels of Fig. 7 indicate that the first mode of MPT is significantly correlated with SSTAs in the equatorial and North Atlantic regions at all lags. In particular, the Atlantic SSTs significantly lead the first mode by more than 4 months. This result implies that the Atlantic SST may be a driver to the variations of the first mode of MPT. In the North Pacific (NP), positive SSTAs are found in the simultaneous correlation. Although the NP SSTAs may also contribute to the variability of MPT by altering the NP storm tracks and triggering planetary waves, we tend to recognize the North Pacific SSTAs as a response to the atmospheric, rather than a cause, because the NP SSTAs associated with the PCs seem to only appear and strengthen during the periods when SST lags MPT.

Moreover, there are significant warmings in the northern Indian Ocean (NIO) and the western Pacific (WP), which tend to lead the MPT by as long as 4 months, evolving gradually from the NIO-WP to the North Pacific. Xie et al. (2009) indicated that the NIO-WP warming could persist through the boreal summer by initiating a series of air-sea interaction, which may also be a source of the North Pacific variability. Indeed, the WP warming is significantly correlated to the so-called Pacific-Japan teleconnection during the boreal summer (e.g., Nitta

1987; Kosaka and Nakamura 2006), which bridges the climate between the Indo-Pacific and North Pacific regions. However, the current study is mainly focused on the Atlantic SST emphasizing its relatively robust signals in intensity and locations.

As seen from the right panels of Fig. 7, the second mode of MPT is only weakly correlated with global SST, except for the North Pacific and Indian Ocean SSTs. It should be mentioned that the Indian Ocean SSTA may be related to the residual signals of El Niño (see Fig. 6b) as it is impossible to remove the non-linear effect of ENSO completely by a regressed method. Significant signals are mainly observed in the correlations when the MPT leads the North Pacific SST, implying that the North Pacific SSTA is a response, rather than causes, to the atmosphere. What factors may be responsible for the second mode of MPT? There are several reasons for exploring the possible impact of the Arctic sea ice. First, it has been shown in Fig. 5b that the geopotential height anomalies associated with the second MPT mode are strongly linked to Arctic signals and an equatorward wave train. Secondly, the decreasing trend in PC2 is a reminiscent of the recent rapid loss of the Arctic sea ice during the boreal summer (Stroeve et al. 2007; Comiso et al. 2008). These reasons lead us to investigate the relationship between the MPT and the Arctic sea ice.

Figure 8 presents the lead-lag correlations between the second mode of MPT and the Arctic sea ice concentration. When the sea ice leads the second mode by 2 months, positive correlations are observed near the Bering Strait. The correlation patterns become more significant and more extensive when the sea ice leads the MPT by 1 and 0 months. It should be noted that both ENSO signals and linear trends have been removed from the PC2,

implying that the Arctic sea ice near the Bering Strait play a role in affecting the second mode of MPT.

Figure 9 shows the lead-lag regression maps of H200 and WAF onto the first two modes of MPT. For the first mode of MPT, significant anomalies of H200 occur over the North Atlantic, North Africa, and the Eurasian continent during the period when the physical fields lead the MPT by 2-3 months. By the period of one-month lead, anomalous high pressures emerge over the North Pacific and strengthen substantially in JA and AS, which are accompanied by enhanced WAFs. In comparison, significant anomalies of H200 associated with the second mode of MPT mainly appear over the Arctic regions, leading the PC2 by 2 months, which subsequently induce an equatorward wave train over the eastern North Pacific in JJ and JA. That is, although significantly antecedent signals associated with the MPT can be found over the Atlantic and Arctic regions, the anomalous wave trains that affect the MPT emerge only one-month in advance, implying that the seasonally-varying basic flow influences the triggering of anomalous wave trains related to the MPT. Moreover, the intensification of the anomalies over the western/eastern North Pacific suggests an interaction between the Atlantic/Arctic forced signals and the Pacific jet stream variability, or the internal atmospheric dynamics that plays an important role.

To better explain how the Atlantic SST and the Arctic sea ice influence the MPT, we define two indices from the domain-averaged values: the Atlantic SST (ASST), calculated as $ASST = SST(A) + SST(B)$, where A and B represent the regions outlined by the black boxes in Fig. 7 and the Arctic sea ice concentration (ASIC), calculated as $ASIC = ASIC(C)$, where

C denotes the region near the Bering Strait outlined in Fig. 8. The selections of boxes A, B, and C are based on the lag-lead correlation relationships between the Atlantic SST / Arctic SIC and the PCs. We have tested with different regions such as the entire North Atlantic (80°W - 10°W , 0 - 55°N) and obtained similar results (not shown).

Figures 10a and 10b show the ASST and ASIC indices. As seen in Fig. 10a, except for the warming trends, the ASST also shows profound interannual and multi-decadal variations, switching from a predominant negative phase to a positive phase around the mid-1990s. The correlation coefficient between ASST (de-trend) and the PC1 is 0.41, exceeding the 95% confidence level. Figures 10(c) and 10(d) show the regression maps of H200 and WAF onto the de-trended ASST and the interannual component of ASST (by subtracting the 9-year low filtering of de-trend ASST), respectively. Although significant anomalies of H200 associated with the de-trend ASST can be observed within the MPT domain (Fig. 10c), the physical mechanism is unclear due to the ambiguity of teleconnection pattern. In comparison, after removing the low-frequency component of ASST, an anomalous wave train is clearly seen over the Eurasian continent (Fig. 10d), which originates from the North Atlantic and eventually affects the southwestern portion of MPT. On the other hand, except for a sharply decreasing trend, the Arctic sea ice also shows considerable interannual variability. The correlation coefficient between ASIC (de-trend) and the PC2 is 0.36, which exceeds the 95% confidence level. As seen in Fig. 10e, the ASIC shows significant correlations with H200 and WAF over the eastern North Pacific. Positive Arctic sea ice anomaly can lower tropospheric geopotential height over the Arctic regions due to surface cooling, which subsequently induces an

equatorward propagating wave train that deepens the MPT on its northeastern portion.

6. Associated Asian-Pacific-North American climate anomalies

a. Precipitation and surface air temperature

Figure 11 shows the correlation of Asian and North American precipitations with the PCs of MPT, in which the linear trends have been removed from the PCs. As shown in Figs. 11a-11b, more precipitation over South Asia, northern China, and eastern U.S. and less precipitation over the Yangtze Basin, southern Japan, and northern U.S. are associated with the first mode of MPT. The features associated with the second mode are quite different. Figures 11c-11d show that correlations are dispersed and less significant over South Asia, and that precipitation is significantly light over southwestern U.S. in association with the second mode.

When ENSO signals are removed, the correlations between Asian precipitation and the PCs decrease substantially, especially over South Asia (figure not shown). Nevertheless, the correlation patterns over North America suffer little change. If the ASST (ASIC) signals are removed, however, the patterns of correlation with the PCs become insignificant over North America, but remain similar with the previous over South Asia, implying the important roles of the Atlantic SST and the Arctic sea ice. It is also possible that both precipitation and MPT patterns may respond to ENSO separately and the link between MPT and the precipitation over South and East Asia may be weak.

The relationships between surface air temperature (SAT) and the dominant modes of MPT are shown in Fig. 12. Corresponding to the first mode (Figs. 12a-12b), warmer SAT

occurs across almost the entire middle latitudes, including the Middle East, East Asia, and northern U.S. Over South Asia, colder SAT is seen with a relation to more precipitation. Associated with the second mode, significantly warmer SAT appears over southwestern U.S., which coincides well with less precipitation over the region. Our analysis reveals a feature (figure not shown) that is identical to the previous: the patterns of correlation between Asian (North American) SAT and the PCs of MPT are strongly modulated by ENSO (Atlantic SSTAs and Arctic sea ice). Indeed, the anomalous atmospheric circulations related to the dominant modes of MPT show a barotropic structure. Under the control of high pressures, enhanced descending motions suppress convection and allow more incoming radiation, which results in less precipitation and warmer surface air temperature, and vice versa.

b. WNP and EP tropical cyclones

Climatologically, the MPT is associated with strong ascending and descending motions under its upstream and downstream portions (Fig. 2b), respectively. Figure 13 shows the correlations between outgoing longwave radiation and the first two PCs of the trough, where both ENSO signals and linear trends have been removed from the PCs based on the ERA-Interim data. An intensified MPT in the first mode is significantly correlated with enhanced convection over the WNP and suppressed convection over the CP. However, an intensified MPT in the second mode corresponds to stronger convection over the WP and the northeastern Pacific, accompanied with suppressed convection over the EP and Central America. Therefore, for both the modes, an intensified MPT tends to contribute upward motions over the WNP/WP and descending motions over the CP/EP, which affect the

occurrence of WNP and EP TCs, given that the WNP TCs and the EP TCs mainly occur and develop beneath the upstream and downstream portions of the MPT, respectively.

Figure 14 shows the scatter diagrams of the TC genesis numbers over the WNP/EP and the PCs. It should be noted that the TC samples used in these figures only include the TCs for the period of 1979-2014 due to the relatively weaker relationship between the MPT and the TC genesis numbers for the earlier period, which could be related to the relatively poor data quality before 1979. Again, both ENSO signals and linear trends in the PCs have been excluded. As seen in Fig. 14a, an intensified MPT in the first mode tends to increase the WNP TC numbers, but their correlation is insignificant, with a coefficient of 0.17. However, the first mode of MPT presents a much stronger relationship with the EP TC numbers and tends to decrease the EP TC numbers (Fig. 14c), with a correlation coefficient of -0.311.

In comparison, the second mode of MPT shows stronger relationships with the TC numbers over both WNP and EP. Figures 14b and 14d indicate that a strengthened MPT in the second mode favors generation of the WNP TCs but suppresses the occurrences of the EP TCs. The coefficient of correlation between the WNP (EP) TC numbers and the PC2 is 0.45 (-0.33), statistically exceeding the 99% (95%) confidence level with an effective degree of freedom of 33 for a total of 35 seasons (1979–2014).

Therefore, for both the first mode and the second mode, an intensification of the MPT is associated with more TCs over the WNP but less TCs over the EP. As shown in Fig. 13, an intensified MPT compels stronger upward (downward) motions in its upstream (downstream) portion, providing favorable (unfavorable) conditions for TC genesis over the WNP (EP). The

relationships of the two MPT modes with WNP/EP TCs are different in several aspects. The first mode is more strongly connected with the EP TCs, compared with the WNP TCs. However, the second mode shows a more robust relationship with the WNP TCs than with the EP TCs. These features should be related to the large-scale circulation conditions that are induced by the MPT.

7. Summary and discussion

This paper has documented the climatological and interannual characteristics of the MPT including the dominant modes of the trough and their associated climate anomalies. The MPT acts as an atmospheric bridge that connects the climate over Asia and North America, with strong ascending (descending) motions on its western (eastern) side. Climatologically, the MPT peaks at the 200-hPa and 150-hPa levels during mid-summer and extends from the mid-latitudes to the subtropics in a southwest-northeast direction. It varies in tandem with the SAH.

The MPT exhibits a large interannual variability. Its first (second) mode reflects a change in the intensity of the trough on its southwestern (northeastern) side. Both modes of the MPT are significantly correlated with the tropical Pacific SST. Moreover, the first MPT mode is significantly correlated to the Atlantic SST, and the second MPT mode is linked with the variation of Arctic sea ice near the Bering Strait. On the one hand, the Atlantic warming would increase the upper-level geopotential height, which triggers an eastward propagating wave train across the Eurasian continent, and intensifies the MPT on its southwestern portion. On the other hand, a positive Arctic sea ice anomaly can lower the upper tropospheric

geopotential height near the Bering Strait due to surface cooling, which induces an equatorward propagating wave train that deepens the MPT on its northeastern portion.

Associated with an intensification of the MPT on its southwestern side, more (less) precipitation occurs over South Asia and northern China (the Yangtze-River basin and South Japan). Correspondingly, warmer (colder) SAT appears over East Asia (South Asia) due to the control of an anomalous high pressure (monsoon convection). However, the second mode of MPT shows sporadic and less significant relationships with Asian precipitation and SAT. The relationship between Asian climate and the MPT is strongly modulated by ENSO. When ENSO signals are removed, the patterns of correlation between the trough and Asian precipitation/SAT over South Asia and East Asia change remarkably.

The first (second) mode of MPT is also significantly related with the precipitation and SAT over northern (southwestern) U.S., attributed mainly to the Atlantic SST (the Arctic sea ice near the Bering Strait). The patterns of correlation between the MPT and North American climate suffer little influence from ENSO, but are strongly affected by the Atlantic SST and the Arctic sea ice near the Bering Strait.

The numbers of tropical cyclone genesis over the WNP and the EP are also closely related to the dominant modes of MPT. Both the first mode and the second mode of MPT are positively (negatively) correlated with the TC numbers over WNP (EP). An intensified MPT is accompanied by more TCs over the WNP and less TCs over the EP. However, the first (second) mode of MPT presents a stronger relationship with the TC numbers over EP (WNP), compared to WNP (EP). Overall, the second mode of MPT is more strongly connected with

the WNP and EP TC numbers than the first mode.

It should be pointed out that although we have presented the relationship between the dominant modes of MPT and the numbers of Pacific tropical cyclones, the cause-and-effect aspect of this relationship deserves more investigations. The tropical cyclones may also influence the MPT through Rossby wave energy dispersion associated with the TCs (Ferreira and Schubert 1999). However, considering the relative spatial and time scales between the MPT and the TCs, it is more likely that the MPT modulates the TC genesis (Hu et al. 2017). In addition, although the dominant modes of MPT are significantly related to the Pacific and Atlantic SSTs and the Arctic sea ice, the impact from the atmospheric intrinsic variability, such as the circumglobal teleconnection, should not be excluded.

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Figure 1. Climatological patterns of H200 (black contours) and its corresponding departures from the annual mean (shadings). Blue contours in July and August outline the locations of MPT. The abbreviations for different months were drawn at the down left corner of each subplot.

Figure 2. (a) Climatological patterns of atmospheric circulation at different pressure levels during boreal mid-summer (July and August, JA). The blue contours and shadings show H200 and H500, respectively. The vectors depict 850-hPa horizontal winds (unit: m s^{-1} ; vectors less than 2 m s^{-1} are omitted). (b) Zonally asymmetric geopotential height from the zonal mean (shadings) and the vertical p -velocity (contours, multiplied by a factor of 100, unit: Pa s^{-1}).

Figure 3. (a) Standard deviations of 200-hPa horizontal winds (Shadings), which are overlaid by climatological H200 and UV200. The blue square box outlines the domain (160°E - 120°W , 15°N - 50°N), which is selected for a vector-EOF analysis that will be used in Fig. 4. (b) Enlargement of the blue-box domain, illustrating the frequency distribution of MPT centers and the climatological zonally asymmetric height. Each of the numbers in (b) indicates the times and locations that the MPT centers repeat.

Figure 4. The left panel depicts the correlation patterns (shadings) between H200 and the first two PCs, which are overlaid by the climatological H200 (contours). The normalized PC1s and PC2s are plotted in (b) and (d), respectively. The green lines in (b) and (d) indicate the PCs calculated from the ERA-Interim data set. The black dashed line in (d) shows a downward trend in PC2, which significantly exceeds the 99% confidence level.

Figure 5. Regressions of H200 (shading, m) and Plumb wave activity fluxes (WAF, $\text{m}^2\cdot\text{s}^{-2}$) on PC1 (a) and PC2 (b). (c) and (d) are similar to (a) and (b) except for U200. Areas enclosed by the white contours in each plot indicate the values significantly exceeding the 95% confidence level. The black contours in (c) and (d) represent the climatology of U200 in JA.

Figure 6. Regression maps of SST and 850-hPa horizontal winds on PC1 (a) and PC2 (b). Areas enclosed by the white contours present the SST anomalies exceeding the 95% confidence level. Wind anomalies with a significant u or v component above the 95% confidence level are plotted.

Figure 7. Lag-lead correlation maps between SST and PC1/PC2 (left/right), where the ENSO signals captured by the Niño-3.4 index have been eliminated from PCs. The leading or lagging months are labelled in each panel (e.g., -2 and -1 mean that the physical fields lead the PCs by two and one months, while +1 denotes that the physical fields lag the PCs by one month). The black square boxes outline the domains (70°W - 10°W , 0°N - 20°N ; 70°W - 20°W , 30°N - 55°N) that are selected to calculate the Atlantic SST index (ASST).

Figure 8. Lag-lead correlation maps between the Arctic sea ice concentration and PC2, where the ENSO signals captured by the Niño-3.4 index have been eliminated from PC2. Areas outlined by the enclosed lines (130°E - 170°W , 70°N - 80°N) are used to calculate the Arctic sea ice index (ASIC).

Figure 9. Lag-lead regression maps between H200 and WAF and PC1/PC2 (left/right), where the ENSO signals captured by the Niño-3.4 index have been eliminated from PCs. The leading or lagging months are labelled in each panel (e.g., -2 and -1 mean that the physical

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Figure 10. Green lines in (a)–(b) show the original ASST and ASIC indices. Bars in (a) and (b) indicate the residual signals after subtracting the linear trends (black lines). (c) and (e) show the regression maps of H200 (contour, m) and WAF (vector, $\text{m}^2\cdot\text{s}^{-2}$) on the detrended indices of ASST and ASIC, and (d) is similar as (a) except for regressions onto the interannual variations (subtracting 9-year low filtering signals) of ASST. Shadings denote the correlation coefficients between H200 and the corresponding indices. Shading values of ± 0.22 , ± 0.26 , and ± 0.34 indicate the thresholds exceeding the 90%, 95%, and 99% confidence levels for a degree of freedom of 55, respectively.

Figure 11. The upper panel shows the correlation maps between PC1 and the land precipitation over Asia (a) and North America (b). The lower panel is similar to the upper panel, but for the PC2. The contours values of ± 0.24 indicate the areas exceeding the 95% confidence level. The linear trends have been removed from the PCs.

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