Persistent precipitation extremes in the Yangtze River Valley prolonged by opportune configuration among atmospheric teleconnections

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Abstract
This study investigates whether and how three synoptic-scale teleconnections, i.e. East Asia/Pacific teleconnection (EAP), Silk-Road teleconnection (SR) and Eurasia teleconnection (EU), induce persistent precipitation extremes (PPEs) in the Yangtze River Valley. Results show that only the EAP teleconnection has the potential of independently incurring PPEs; while the other two teleconnections' influences on PPEs need to be exerted via their liaison with the EAP pattern. Cases are accordingly grouped into two subsets, i.e. single EAP-PPEs and three teleconnection–PPEs. In both groups, the EAP teleconnection evolves following a similar pathway that poleward energy dispersion dynamically links a westward-extended subtropical high, a deepened midlatitude trough and the Okhotsk blocking. EAP-induced circulation anomalies enhance low-level convergences and upper-level divergences, convey exceptionally abundant moisture, and hence give birth to a quasi-stationary front leading to PPEs in the Yangtze River Valley. Despite similarities, PPEs last noticeably longer in the three-teleconnection context. The EU teleconnection-related downstream energy dispersion at higher latitudes favours both earlier establishment and latter decay of the Okhotsk blocking. Constructed meridional flows at mid–high latitudes continuously steer migratory disturbances southeastward into the EAP trough. The SR plays a bigger role during the latter half of PPE life span (3 days after onset) via stimulating new cyclonic disturbances that largely overlap with the EAP trough spatially. Moreover, EU- and SR-excited disturbances could effectively extract baroclinic and barotropic energy from local mean flows to replenish components of the EAP tripole pattern, which therefore survives longer and prolongs PPEs by several days.

Keywords
monsoonal stationary front, persistent precipitation extremes, Rossby wave energy dispersion and conversion, synoptic-scale atmospheric teleconnections, thermodynamic–dynamic mechanisms
1 INTRODUCTION

Precipitation extremes and floods have resulted in severe socio-economic losses worldwide (Duan et al., 2016; Dottori et al., 2018; Watts et al., 2018). Severer consequences tend to be linked to events aligning extraordinary intensity and long duration (multi-day), i.e. persistent precipitation extremes (PPE: Chen and Zhai, 2013; Ramos et al., 2017; Du et al., 2019). A case in point is the deadly event which struck Pakistan during late July in 2010, claiming a death toll of nearly 3,000 (Hong et al., 2011). In particular, in populous monsoonal regions like eastern China, damage caused by PPEs is further exacerbated by extensive spatial coverage of the monsoonal rain band and high exposure of local population and infrastructure (Sun et al., 2016; Li and Mao, 2019). However, current accuracy and forecast lead time for PPE prediction are far from satisfactory for decision-making (Joseph et al., 2013; Zhao et al., 2017a; Zhang and Meng, 2018). This is mainly due to the lack of understanding about determinants for the intensity and duration of PPEs, and consequently ill-representations of relevant physical processes in numerical models (Zhou and Zhai, 2016; Zhao et al., 2017b; Blanchet et al., 2018; Zhou et al., 2018). Hence, deeper understanding of thermodynamic–dynamic mechanisms for PPEs is fundamental to improve the prediction with respect to PPEs.

Prolonged weather extremes result dynamically from long-lived atmospheric flow patterns, whose duration spans from days to weeks (Higgins and Mo, 1997; Stadtherr et al., 2016; Mann et al., 2018; Kornhuber et al., 2019). Recurrent atmospheric teleconnections composed of adjacent cyclones/anticyclones are deemed one major source for the persistence of weather extremes (Chen and Zhai, 2015; Li et al., 2017; Steptoe et al., 2018). Monthly-/seasonal-scale indices of atmospheric teleconnections used to be employed in explaining, monitoring and predicting climate anomalies at interannual to inter-decadal time-scales (Wallace and Gutzler, 1981; Nitta and Hu, 1996; Kubota et al., 2016). Revisiting power spectral properties of well-acknowledged teleconnection modes, Feldstein (2000) unravelled the diversity in time-scale of atmospheric teleconnections, which span from synoptic to multi-decadal scales. On this basis, follow-up analysis examined implications of synoptic teleconnections on weather anomalies/extremes, with emphasis placed on the statistical relationship between occurrence of one-day extremes and active phases of teleconnections (Archambault et al., 2008; Franzke and Woollings, 2011; Li et al., 2014; Harding and Snyder, 2015; Ohba et al., 2015; Roller et al., 2016). In contrast, little attention has been devoted to influences of synoptic teleconnections on persistence (duration) and intensity of extremes. This knowledge gap stands out particularly starkly in the field of precipitation extremes in monsoonal regions, e.g. eastern China.

During boreal summer, the involvement of East Asian monsoonal circulations complicates the mechanism for precipitation extremes over eastern China, as manifested by interactions amongst key circulation systems at different latitudes and in the different tropospheric–stratospheric levels (Ding and Chan, 2005; Chen and Zhai, 2014; Stan et al., 2017). Three prevailing tropospheric teleconnection patterns, i.e. the East Asia/Pacific teleconnection (EAP: Huang and Li, 1989), the Silk-Road teleconnection (SR: Enomoto et al., 2003), and the Eurasia teleconnection (EU: Wakabayashi and Kawamura, 2004), get involved in the interaction process. The EAP teleconnection resides in the lower–mid troposphere, shown as a tripole pattern of geopotential height anomalies along East Asia (Huang, 2004). The SR teleconnection elongates zonally along the upper-level subtropical westerly jet waveguide (Su and Lu, 2014). The EU teleconnection is a prevailing mode trapped within the polar jet stream in the mid–high tropospheric levels (Nakamura and Fukamachi, 2004). These teleconnections could individually or collectively modulate circulation elements conducive to heavy rainfall. For instance, both the EAP and EU favour the formation and maintenance of the Okhotsk high, which establishes a steady circulation backdrop imperative to prolonged heavy precipitation in central–eastern China (Wang et al., 2013; Chen and Zhai, 2015), while the SR and EAP pattern could simultaneously modulate the moisture conveyor for PPEs – the western Pacific subtropical high (WPSH: Kosaka et al., 2009; 2012). Similar collective modulation of multiple teleconnections on heavy rainfall-producing agents challenges the robustness of the teleconnection–extremes relationship established by analysis focusing on a prescribed single teleconnection (Ogasawara and Kawamura, 2007; Orsolini et al., 2015; Grotjahn et al., 2016; Whan and Zwiers, 2017). Moreover, the extraordinary magnitude and duration of the teleconnection tend to be partly ascribed to interactions amongst multiple teleconnections (Ogasawara and Kawamura, 2008; Petoukhov et al., 2013; Kornhuber et al., 2017).

It is therefore imperative to revisit the influence of individual teleconnections on PPEs by eliminating potential interventions from other co-occurring teleconnections. Also worth further exploration is the issue about differential influences of individual teleconnections and configured teleconnections on duration and intensity of PPEs, as well as thermodynamic–dynamic processes governing these differences. Taking advantage of a refined teleconnection–PPE relationship in combination with excellent skills of models in predicting teleconnections, the lead time of PPE prediction could be promisingly lengthened by a few days (Johansson, 2007; Chen and Zhai, 2014). Apart from benefiting prediction, deeper mechanism understanding in light of large-scale circulations could also add value to attribution and projection efforts specific to PPEs (Shepherd, 2014; Trenberth et al., 2015; Djurdjevic et al., 2019).
which matter for designing adaptation and mitigation strategies. To shed some light on the above gaps, this study attempts to elucidate differing abilities and influence pathways of three teleconnections in triggering PPEs in the Yangtze River Valley (YRV), which severely suffers from this type of extreme (Chen and Zhai, 2013). The rest of the article is organized as follows. Section 2 will introduce datasets and diagnostic methods. The scheme to discriminate PPEs associated with a single teleconnection and combined teleconnections will be detailed in section 3. Section 4 will show circulation evolutions and resulting PPE properties (duration and intensity) commensurate with differing configurations of teleconnection patterns. Possible thermodynamic–dynamic explanations will also be proposed in this section, followed by a brief summary and discussion in section 5.

2 DATA AND METHOD

2.1 Data

Daily rain-gauge observations (over 1961–2016) at 50 stations located in the YRV (28–32°N, 115–122.5°E) are utilized to construct domain-averaged series. These records are collected from a dataset of 756 stations, which is provided by the National Meteorological Information Center of China (available on-line: http://data.cma.cn/).

Daily reanalysis data during 1961–2016, with a horizontal resolution of 2.5° longitude × 2.5° latitude and 17 vertical levels, from National Centers for Environmental Prediction and National Center for Atmospheric Research (NCEP/NCAR) is employed to diagnose dynamic and thermodynamic anomalies (Kalnay et al., 1996). Variables used include geopotential height (gpm), horizontal winds (m/s), vertical wind (Pa/s), relative humidity (%), specific humidity (kg/kg), and air temperature (K). Another dataset – daily ERA-Interim reanalysis (Dee et al., 2011) from 1981–2010 – is also used to cross-validate composited patterns based on the NCEP/NCAR reanalysis. The comparison confirms that replacing reanalysis data does not change composited circulation anomalies in any significant manner (figure not shown). With the intent to extract common circulation characteristics shared by as many PPEs as possible (especially cases before 1979), only the NCEP/NCAR-based composites are displayed.

PPEs in the YRV exhibit pronounced seasonality, with the majority observed during June–July (Chen and Zhai, 2013). Accordingly, the following analyses would concentrate on PPE cases during June–July.

2.2 Methods

This study is mainly based on a composite analysis, which is a simple and effective method of identifying synoptic-scale flow regimes and delineating their life cycle (Grotjahn and Faure, 2008). In addition to composites for all identified cases, composites for arbitrarily grouped subsets (not shown) are also conducted. The similarity between all-case composite and subset-based composite indicates sufficient robustness of the composited results, irrespective of the inclusion or exclusion of specific events.

Apart from daily weather patterns, composites of normalized circulation anomalies are also performed to offer forecasters some quantitative clues about how unusually large departures in various variables might be taken as informative precursors for predicting teleconnection-induced PPEs (Junker et al., 2008). Daily climatological mean and standard deviation (σ) of each variable are calculated over the baseline period of 1971–2000, following the method described by Grumm and Hart (2001). Moisture flux is calculated as a product of the specific humidity (q) and horizontal wind (u,v) at the specific pressure level. Normalized anomalies in total moisture flux magnitude (√(uq)² + (vq)²) are used to measure the strength of anomalous moisture transport (Figures 5 and 11) caused by teleconnections (Junker et al., 2008). Considering unequal variances of PPE-related circulation fields and climatology (Chen and Zhai, 2014), Welch’s t-test (Welch, 1947), instead of the ordinary Student’s t-test, is conducted to arrive at a stricter threshold for statistical significance.

In sections 3 and 4, correlation analysis, including both lead–lag correlation and partial correlation, are implemented. In a continuous teleconnection series, the daily index may be heavily contingent on the antecedent or subsequent few days, particularly around the peak (active) phase as concerned. Under this circumstance, the effective number of degrees of freedom pertaining to the significance test for correlation coefficients needs to be re-evaluated following the method developed by Pyper and Peterman (1998).

To quantitatively depict interactions between mean-flow and disturbances (anomalies associated with atmospheric teleconnections), two key diagnostic items, local barotropic and baroclinic energy conversion are calculated as follows:

\[
C_K = \frac{v'^2 - w'^2}{2} \left( \frac{\partial u}{\partial x} - \frac{\partial u}{\partial y} \right) - u'v' \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right), \tag{1}
\]

\[
C_P = -\frac{R f}{S_p} \left( u'T' \frac{\partial u}{\partial p} - u'T' \frac{\partial v}{\partial p} \right), \tag{2}
\]

in which variables for mean-flow and disturbances are decorated by overbars and primes respectively. In Equation (2), S represents static stability computed as \( S = \frac{R}{\rho} \left( \frac{RT}{C_p} - \frac{\partial T}{\partial p} \right) \). Variables in all equations represent their common meaning in atmospheric sciences. Locally, positive CK and CP indicate extraction of kinetic energy (KE) and available potential energy (APE) from mean flow to feed anomalies (Simmons et al., 2011).
et al., 1983; Kosaka et al., 2009). Positive and negative conversions tend to align spatially adjacent to one another. Thus, domain averaging is calculated to indicate net growth (positive) or decay (negative) of disturbances within the domain of interest. Vertically integrated (from surface to 100 hPa) CP is utilized to measure total conversion of the APE through the troposphere (Kosaka et al., 2009); while for CK, to delineate energy conversion related to polar and subtropical westerly jets in the higher tropospheric levels, only results at 200 hPa are displayed in section 4.

3 | IDENTIFICATION OF DAILY TELECONNECTION MODES AND TELECONNECTION–PPE CASES

Before identifying PPE cases associated with teleconnections, exact identification of major daily teleconnection modes and construction of teleconnection indices are pivotal. To this end, an empirical orthogonal function (EOF) analysis is applied to daily normalized geopotential height anomalies. Specifically, for each grid, (a) daily geopotential heights are firstly normalized as introduced in section 2; (b) seasonal-mean (June–July) normalized anomaly is then removed from every year over 1961–2016; (c) daily anomalies subject to the above two steps are aligned in sequence to form a series consisting of (56 × 61) 3,416 samples, with respect to which the EOF analyses are performed. Subtracting daily-varying climatology in step (a) aims to get rid of the seasonal cycle, and the follow-up removal of seasonal mean in each participating year in step (b) acts to eliminate interannual-to-interdecadal variabilities, as well as general increases (i.e. linear trends) in heights in response to global warming. Thus, only daily variability is retained for extracting daily teleconnection modes. We acknowledge that daily anomalies within a short period (several days to a week) may be not as independent as theoretically assumed, but the large number of analysed samples (3,416) makes influences from this transient dependence trivial to the EOF-based extraction of dominant modes.

Figure 1 shows respective leading EOF modes for three key domains, (20–160°E, 50–70°N) at 500 hPa for EU, (50–150°E, 30–50°N) at 200 hPa for SR, and (115–140°E, 10–75°N) at 500 hPa for EAP. These daily leading modes account for 16.9, 15.8, and 16.2% in total variance of decomposed fields, respectively. Considering the large number (hundreds) of derived modes for daily geopotential heights within each domain, these variance contributions from the first modes are large enough to underpin the dominance of these leading modes. These daily teleconnection patterns highly resemble their monthly–seasonal-scale counterparts (Huang, 2004; Wakabayashi and Kawamura, 2004), with some of their anomaly centres shifted slightly. We use three basic points (green X in Figure 1), which represent the strongest daily variability, to construct daily teleconnection indices as follows:

\[
\begin{align*}
\text{EU} &= \frac{1}{3} H_{500}(42.5°E, 60°N) - \frac{1}{3} H_{500}(100°E, 65°N) \\
&\quad + \frac{1}{3} H_{500}(140°E, 60°N), \\
\text{SR} &= \frac{1}{3} H_{200}(67.5°E, 40°N) - \frac{1}{3} H_{200}(100°E, 40°N) \\
&\quad + \frac{1}{3} H_{200}(132.5°E, 35°N),
\end{align*}
\]

\[
\begin{align*}
\text{EAP} &= \frac{1}{3} H_{500}(122.5°E, 17.5°N) - \frac{1}{3} H_{500}(127.5°E, 40°N) \\
&\quad + \frac{1}{3} H_{500}(130°E, 62.5°N),
\end{align*}
\]

in which \( H \) denotes normalized anomalies of geopotential height at corresponding levels as indicated by its lower subscript, with constituent basic points specified in parentheses. Using any grid within a distance of 5° lon/lat to the current choice as the basic point instead yields basically the same typical teleconnection regimes and PPEs associated with them. We select geopotential heights at 500 hPa, where signals featuring both the EAP and the EU could be clearly discerned, to construct indices for these two teleconnections for the convenience of investigating interactions among them. Alternatively, using 200 hPa heights for the EU pattern and 850 hPa heights for the EAP pattern did not cause measurable impacts for the following analysis.

By placing PPEs in the context of strong teleconnection regimes, a typical teleconnection–PPE event is considered when (a) the daily teleconnection index with magnitude over one standard deviation (\( \sigma \)) persists for at least three consecutive days, and either constituent centre (basic point) has a right sign consistent with prescribed phase with its magnitude above 0.75\( \sigma \) in each day, and (b) simultaneously, normalized domain-averaged precipitation in the YRV is greater than 1.0\( \sigma \) every day.

One standard deviation is a proper compromise between the continuity (duration) and the magnitude of both teleconnections and precipitation extremes. The additional requirements on daily sign and magnitude for constituent centres aim to ensure well-structured teleconnections, rather than those loosely structured ones dictated by one or two centres. At an individual station level, domain-averaged index over 1\( \sigma \) is translated into approximately 25–50 mm/day at precipitation centres in the YRV (Chen and Zhai, 2015; 2016). Although such daily intensity appears not extraordinarily unusual, accumulated precipitation over 150 mm over consecutive days make the event damaging.

Existing results have reported preferential occurrences of above-normal precipitation across the YRV during positive phases of the EAP and EU pattern, and in negative SR phases.
Spatial patterns for the first EOF modes of normalized geopotential height anomalies (a) at 500 hPa within [20–160°E, 50–70°N] for EU, (b) at 200 hPa within [50–150°E, 30–50°N] for SR, and (c) at 500 hPa within [115–140°E, 10–75°N] for EAP, respectively. Positive and negative anomalies are represented by red/solid and blue/dashed contours. Anomaly centres used to construct daily teleconnection indices are indicated by green crosses. Note that the slight mismatch between the selected anomaly centres and contour centres is ascribed to the bias caused by the interpolation scheme employed in contour-plotting.

So in the following section, attention will be devoted to PPE cases in these favourable phases, referred to as EAP-PPE, EU-PPE and SR-PPE, respectively. Following the scheme delimited above, we identified 25 EAP-PPE, 14 SR-PPE and 15 EU-PPE cases in total. Based on such a uni-teleconnection identification scheme, entanglements among multiple teleconnections seem pervasive, as illustrated by Figure 2. For instance, among EAP-PPE cases, albeit the EAP pattern being strongest as expected, the other two patterns also coexist and show reasonably large magnitude. Of note, the marked lag of the SR development behind significant intensification of precipitation (Figure 2c) denies the expected causal contributions from the SR teleconnection. Further closer scrutiny of occurrence timing of the above teleconnection-related PPEs does find temporal overlaps among them. Hence, this single teleconnection-constrained identification fails the purpose of unravelling influences of the specific teleconnection pattern on PPEs.

So, the removal of other concurrent teleconnections, their vital phases at least, is the prerequisite toward pinpointing influences of single teleconnection patterns on PPEs. Accordingly, vital phases of other teleconnections, herein referring to their rapid developing phase, peak phase and early decaying phase, should be all suppressed to a negligibly low magnitude, considering potential lead/lag interactions among teleconnections. We use “significant autocorrelation interval” to frame the period from rapidly developing to early decaying stages (Yasui and Watanabe, 2010; Franzke and Woollings, 2011). Centred on strong regimes detected by criterion (a), a temporal series for this teleconnection is constructed by bonding the preceding 15 days and subsequent 15 days. Judged by the 0.05 significance level, the significant autocorrelation...
interval is about 4~6 days for EAP, 5~8 days for EU, and 4~5 days for SR, depending on specific cases. Taking this interval into consideration, a single teleconnection–PPE event then follows three constraints:

(i) it belongs to a certain teleconnection \( i \)-PPE event \( (i = \text{EAP}, \text{EU}, \text{SR}) \) as defined above, and the event regime is denoted by \( \Lambda \).

(ii) the start and end dates of the strong regime (over \( 1\sigma \) for at least 3 days) of other two teleconnections \( j \) \( (j = 1, 2) \) are labelled as start\( j \) and end\( j \), and its significant autocorrelation interval is represented by interval\( j \), and

(iii) either day during regime \( \Lambda \) is not included within \( \text{start}\ (j)-\text{interval}\ (j), \text{end}\ (j) + \text{interval}\ (j) \) \( (j = 1, 2) \), and during regime \( \Lambda \) the magnitude of any other teleconnection\( j \) index is below \( 0.5\sigma \) every day.

This event is termed as “single \( i \)-PPE” \( (i = \text{EAP}, \text{EU}, \text{SR}) \); otherwise, the event is considered as a multiple (two or three) teleconnection–PPE event. Through the above procedures, 12 single EAP-PPE cases are sifted out (Table 1), which see trivial influences from the other two teleconnections (Figure 3a). Only one single SR-PPE case is identified, but a typhoon plays an important role in it. Similarly for the EU pattern, only two single teleconnection cases are obtained, all of which are also synchronized with tropical cyclones around the South China Sea. Typhoon-induced PPEs

FIGURE 2  Composited indices of teleconnections (left \( y \)-axis) and precipitation (right \( y \)-axis) in (a) EAP-PPEs, (b) EU-PPEs and (c) SR-PPEs. Filled white hatches indicate the significance at the 0.05 level for the composite, and error bars frame the 5–95% confidence interval. The bold part of the daily precipitation curves highlights those days whose composited precipitation anomalies are above 1 standard deviation (std) and significant at the 0.05 level at least. Black dashed lines label \( \pm 1 \) std for teleconnection indices and \( \pm 2 \) stds for daily precipitation. The symbols of “-” and “+” in \( x \)-axis represent days prior to and after the onset of PPEs, respectively.
TABLE 1  The 12 typical single EAP-PPE cases in the Yangtze River Valley during 1961–2016

<table>
<thead>
<tr>
<th>Year</th>
<th>Start date (day-month)</th>
<th>End date (day-month)</th>
<th>Duration (days)</th>
</tr>
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<tbody>
<tr>
<td>1967</td>
<td>17 Jun 19 Jun</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1968</td>
<td>8 Jul 10 Jul</td>
<td>3</td>
<td></td>
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<td>1969</td>
<td>5 Jul 7 Jul</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1969</td>
<td>11 Jul 15 Jul</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1973</td>
<td>18 Jun 21 Jun</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>1983</td>
<td>27 Jun 29 Jun</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>18 Jun 24 Jun</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>30 Jun 3 Jul</td>
<td>4</td>
<td></td>
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<td>1999</td>
<td>16 Jul 18 Jul</td>
<td>3</td>
<td></td>
</tr>
<tr>
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<td>18 Jul 20 Jul</td>
<td>3</td>
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<tr>
<td>2014</td>
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<td>4</td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>12 Jun 16 Jun</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Note: Detailed identification scheme for single EAP-PPEs: please refer to section 3.

TABLE 2  The 13 typical three teleconnections–PPE cases in the Yangtze River Valley during 1961–2016

<table>
<thead>
<tr>
<th>Year</th>
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<th>End date (day-month)</th>
<th>Duration (days)</th>
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<tr>
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<td>22 Jul 30 Jul</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Note: Detailed identification scheme for three teleconnections-PPEs: please refer to section 3.

are beyond the main scope of the current study, considering the complexity of typhoon routes and forming mechanisms. Notably, in any combined EAP-EU PPE and EAP-SR PPE case, significant signals (from rapid development to early decay phase) of the third teleconnection are still discernible. In this context, for multiple teleconnection–PPE cases, we will focus on 13 PPEs under the combined influences of three teleconnections (see Table 2). No sign of influences from tropical cyclones could be detected in identified single EAP-PPEs and three teleconnection–PPEs, due mainly to the dominance of EAP-related anomalous anticyclones at lower latitudes. This can be confirmed by referring to the

FIGURE 3  The same as Figure 2, but for (a) single EAP-PPEs and (b) three teleconnection–PPEs
As indicated by Figure 3b, in combination cases, all three teleconnections show strong and significant signals typical of their respective phases. The development and peak of the EU pattern seem to lead the other two teleconnections by several days, irrespective of identification schemes (Figures 2a and 3b). Particularly when coexisting with the other two teleconnections, the EAP pattern exhibits itself much more strongly and lasts longer. Different configurations of teleconnections do not bring about discernible differences in the peak intensity of PPEs (Figure 4), nor in their spatial coverage (Figure 4a,c). Rather, precipitation extremes associated with combined teleconnections start slightly earlier and cease much later, so they have a markedly longer life span, which causes greater accumulated precipitation totals (over 200 mm from each event on average, Figure 4d).

So the following analysis will pay major attention to answering why the combination of three teleconnections markedly prolongs the duration of PPEs in the YRV.

### RESULTS

#### 4.1 Single EAP-PPEs

The EAP teleconnection can independently evolve without participation of other teleconnections. In the lower troposphere, such dynamic evolvement originates from a northwest-migrating high-pressure system at lower latitudes, i.e., an anomalous anticyclonic cell (Figure 5). Diabatic heating anomalies near the Philippines related to the anomalous anticyclone’s modulation on convective activities there trigger poleward-penetrating wave activity fluxes (Nitta and Hu, 1996; Kosaka and Nakamura, 2010), which facilitate the formation, westward movement and intensification of a mid-latitude cyclonic cell (low-pressure system). During day $-1$ to day 1, as these wave activity fluxes (WAFs) penetrate further north, positive height anomalies at higher latitudes grow in intensity, forming a well-structured tripoles pattern over East Asia. Accompanying migration of the low-latitude anticyclone, a branch of anomalous southwesterlies on its north flank strengthens gradually as it marches northward...
FIGURE 5  Composited 850 hPa normalized height anomalies (contours, every 0.5 standard deviation) in single EAP-PPE cases. The vectors indicate wave activity flux (unit: m²/s²) defined by Takaya and Nakamura (2001). Shadings show significant normalized anomalies of moisture transport magnitude over 0.5 std (see methods). The number $d$ at the upper-left corner in each panel refers to the $d$th day prior (negative) to and after (positive) the onset of PPEs. Stippled regions indicate the significance (at the 0.05 level) of composited geopotential height anomalies there.
FIGURE 6 (a,b) Latitude–time cross-section (averaged over 115°E–122.5°E) of composited 850 hPa wind anomalies (vectors) and divergences of anomalous winds. Grey and black vectors indicate the insignificant and significant wind anomalies at the 0.05 level, respectively. Only convergences stronger than $-0.5 \times 10^{-6}/s$ are displayed. The symbols of “-” and “+” in x-axis represent days prior to and after the onset of PPEs, respectively (Figure 6), and brings exceptionally abundant moisture (over $3\sigma$ above normal, shadings in Figure 5) toward the YRV, while the maturing (deepening) midlatitude cyclone steers gradually enhanced northerlies toward the immediate north of the YRV (Figure 6). These anomalous winds shape a belt of convergence, which accordingly advances northward and peaks during day $-1$ to day 2 over the YRV, as an initial trigger for ascending motion (Figure 6). As the sole source for meridional dispersion of wave energy, the lower-latitude anticyclonic cell's decline in magnitude and spatial coverage from day 3 (Figure 5) lead to an instantaneous fall-apart of the tripole pattern, along with attendant attenuation of convergences (Figure 6) and moisture transport (Figure 5).

Evolutionary features of the EAP teleconnection in the middle tropospheric level basically mirror those in the lower levels (Figure 7a–e). These EAP-induced geopotential anomalies prompt westward extension of the western Pacific subtropical high (WPSH) and deepening of a midlatitude trough, as well as the establishment of the Okhotsk ridge/blocking high. As this tripole pattern maintains itself, the WPSH-steered southwesterlies pile up a thick layer of moist/warm air in the low–mid troposphere (red contour in Figure 8a–e), which sets up a highly unstable environment conducive to development of ascending motion, while descending dry/cold air invades southward along the rear of the midlatitude trough. The confrontation between these air masses of opposite natures substantially sharpens the meridional gradient of equivalent potential temperature (shadings in Figure 8b,c), facilitating the formation of a typical Mei-Yu front there (Ding and Chan, 2005). Sandwiched between the WPSH and the Okhotsk high, this front is forced to stay nearly put around the YRV (Figure 8b–d, also see Wu (2017)). In this context, continuous elevation of abundant moisture by this quasi-stationary front leads to PPEs in the YRV. Apart from lower-level convergences, upper-level divergences serve as another prerequisite for the persistence of extreme precipitation. The reversed EAP-related energy dispersion in the upper troposphere (for mechanisms, see Kosaka and Nakamura (2010) and Wu et al. (2016)) shapes a jet core to the east of the YRV (Figure 9). The resultant acceleration effect in the southern entrance of the westerly jet produces favourable upper-level divergences well atop the YRV (Figure 10a, blue curve).

Since day 3, due to the absence of supplementary inputs of energy from lower latitudes, the midlatitude trough and the Okhotsk high weaken rapidly, followed by the dissipation of the stationary front and termination of PPEs. During the entire life span of the single EAP teleconnection, upstream flows are characterized by a quasi-zonal pattern at mid–high latitudes (Figures 7a–e and 9a–e), with inactive eddy activities found within the domain of 30–120°E. Hence, there are obscure dynamic connections between these upstream elements and the downstream EAP components, as inferred by vague and irregular WAFs. At midlatitudes, no continuous energy dispersion from upstream along the subtropical jet underpins the appearance of the SR pattern (Figure 9a–e).

4.2 Three teleconnection–PPEs

With intervention of the other two teleconnections, the low-level EAP teleconnection experiences evolutionary processes similar to those in the single EAP-PPE group, including westward migration of the anticyclone–cyclone pair at lower–mid latitudes and dynamical linkages amongst three anomalous centres via the poleward-propagating WAFs. Such similarity accentuates the fact that intrinsic mechanisms generating the EAP pattern are not dictated by the other two teleconnections.

In the three teleconnection–PPE groups, the low-latitude anticyclone cell behaves more strongly, covers a broader extent, and extends further westward, particularly during the early stages (day $-4$ to day 0 in Figure 11). These peculiarities give rise to noticeably stronger and better-organized WAFs, which further lead to earlier establishment and delayed collapse of the tripole pattern along East Asia. Also, the more
FIGURE 7  Composited 500 hPa geopotential height (contours, every 4 gpdam) and normalized height anomalies (shadings, every 0.5 standard deviation) in (a–e) single EAP-PPE cases and (f–j) three teleconnection–PPE cases. The red dashed line in (f) delineates the general direction of the EU-related trough, along which a cross-section is created as shown in Figure 13. The vectors and the number d at the upper-left corner represent the same meaning as in Figure 5. Cross-hatched shadings represent their significance at the 0.05 level. Only normalized anomalies over 1 standard deviation are shown, to highlight strong signals.
Composited latitude–height cross-section (averaged within 115–122.5°E) of equivalent potential temperature (contour, every 5 K), meridional gradient of equivalent potential temperature (shadings with deeper colour indicating sharper gradient), and wind anomalies ($v$-component, m/s; $\omega$-component, hPa/s) for (a–e) single EAP-PPEs and (f–j) three teleconnection–PPEs. The green dashed lines frame the domain of the YRV. The 355 K contour of equivalent potential temperature is highlighted by the red bold line. For composited winds, only those vectors having at least one component significant at the 0.05 level are shown.
FIGURE 9  Composited 200 hPa geopotential height (black contours, every 4 gpdam), U-wind (grey contours, every 5 m/s) and normalized height anomalies (shadings, every 0.5 standard deviation) in (a–e) single EAP-PPE cases and (f–j) three teleconnection–PPE cases. The vectors and the number d at the upper-left corner represent the same meaning as in Figure 5. Cross-hatched shadings represent their significance at the 0.05 level. Only normalized anomalies over 0.75 standard deviation are shown to highlight strong signals. The 1,212 gpdam isoline is used to characterize wavy circulation patterns at midlatitude associated with the Silk-Road teleconnection. The solid and dashed rectangle in (a) and (f) locate the region used for calculating upper-level divergences, as shown in Figure 10.
Domain-averaged divergences associated with (a) zonal winds ($\partial U/\partial X$) within [115–122.5°E, 30–35°N], and (b) meridional winds ($\partial V/\partial Y$) within [105-120°E, 20-27.5°N], for single EAP-PPEs (blue curves) and three teleconnection–PPEs (red curves). $U$ and $V$ in the above equations represent zonal and meridional components of horizontal winds. These individual components of the divergence field are shown to highlight “anomalous divergence” associated with circulation anomalies caused by teleconnections.

Figure 10

(a) Divergences within [115-122.5E,30-35N]

(b) Divergences within [105-120E,20-27.5N]

westward-extended anomalous anticyclone at earlier stages determines the earlier arrival of stronger moisture transport at the YRV (Figure 11), thereby the earlier onset of PPEs (Figure 3). These differences also manifest at 500 hPa, with the EAP pattern persisting from day −2 to day 6. In particular, at day −4, the westernmost point of the WPSH has already arrived at 120°E and started to excite strong poleward energy dispersion (Figure 7f). This is much earlier than those processes in single EAP-PPE cases (Figure 7a). About 1 week prior to the onset of PPEs, a strong ridge/blocking high, as the upstream component of the EU pattern, prevails around the Ural Mountains and emanates eastward-propagating WAFs, which foster an embryo of the Okhotsk blocking high from day −6. These EU-related elements set up a meridional circulation background at higher latitudes, as opposed to the zonal pattern shown in the single EAP-PPE group. Subsequent confluence between these eastward-propagating WAFs and those meridional ones from lower latitudes produce a much stronger and longer-lived Okhotsh high, relative to that in single EAP-PPE cases. In a similar manner, an abundant and steady supply of moist/warm air on the northern flank of the WSPH (Figure 11) strongly converges with dry/cold air from the midlatitude trough (Figure 6), giving birth to the quasi-stationary front and resultant precipitation extremes (Figure 8f–j). This quasi-stationary front is of noticeably longer duration than its counterpart in single EAP-PPEs.

At 200 hPa, in addition to eastward-travelling WAFs at higher latitudes related to the EU teleconnection, also discernible is southeastward-propagating WAFs also originating from the Ural ridge/blocking high (Figure 9f–j). These WAFs then continuously progress eastward along the westerly jet waveguide, stimulating and maintaining the negative phase of the SR pattern. The alignment of SR-related centres makes the midlatitude circulations markedly wavier than that in single EAP-PPEs (indicated by the 1,212 gpdam isoline). The southeastward-propagating WAFs from the southern part of the Ural ridge/blocking high are not totally trapped within the westerly jet; instead, some of them keep traveling further south, stimulating and enhancing positive height anomalies around the Tibetan Plateau to southern China. In response, the main entity of the upper-level South Asian High (SAH) is anchored to the east (see also Ren et al., 2015; Shi and Qian, 2016; Yang and Li, 2016), in sharp contrast to the west-centred SAH in single EAP-PPE cases. In three teleconnection–PPEs, upper-level divergences also result from the westerly acceleration in the rear of the jet core, but the acceleration effect is more conspicuous than in single EAP-PPEs (Figure 10a, red curve).
FIGURE 11  Same as Figure 5, but for three teleconnection-PPEs
4.3 Thermodynamic–dynamic causes for the difference

Essentially, it is the life span of the EAP tripole pattern that determines the duration of PPEs, irrespective of individual EAP or combined teleconnections, because it determines all ingredients imperative to the heavy rainfall-producing stationary front.

Before the onset of PPEs, the most obvious circulation difference between two groups of cases lies in the rapid development of the EU pattern (Figure 12a). Resultant wavy flows continuously steer migratory disturbances originating from the EU-related trough toward East Asia, where they are then obstructed by earlier-established blocking/ridge and diverted into the midlatitude cyclone there (Figure 13b). The receipt of these upstream incoming disturbances is also evidenced by the northwest–southeast orientation of the midlatitude trough over East Asia in three teleconnection–PPEs (Figure 7f–h). By contrast, just fed by downstream disturbances (Figures 7a–e and 13a), the midlatitude trough related to the EAP teleconnection is tilted northeast–southwest in single EAP-PPEs instead. This upstream feeding effect contributes to faster development and earlier maturation of the midlatitude trough in the three teleconnection–PPE groups. When these upstream transient eddies amalgamate with the EAP-controlled westward-progressive cyclonic anomalies (day 0), a cut-off low takes shape, in tandem with an enclosed blocking high to its north (day 2, Figure 7i). This configuration of “north blocking – south cut-off low” tends to last longer than the normal omega-type blocking as shown in single EAP-PPEs (Shi et al., 2016).

Also prior to the onset of PPEs (day −3 to day −1), the SAH characteristic of the eastward-shifted core induces much stronger convergences (Figure 10b) and descending motions (Figure 8) within its column. The resultant greater increase in local pressure underneath within the domain of 105–120°E (Figure 12a) favours the westward extension of the lower-level high-pressure system, thus explaining the earlier arrival of the WPSH at 120°E (Figure 7, also refer to Tao and Wei (2006)), as well as the earlier establishment of the EAP tripole pattern.

During the first 3 days of PPEs (day 0 to day 2), heavy precipitation-producing systems, i.e. the midlatitude trough and the WPSH, do not exhibit significant difference between the two groups of cases (Figure 12b). That is why there is no significant difference in precipitation intensity between the two groups during this stage.

Apparently, a significantly stronger midlatitude trough over East Asia after day 3 is the direct driver for the longer duration of PPEs in the context of three teleconnections (Figure 12c). The maintenance of the EU-related wavy pattern at higher latitudes and resultant feeding effects from upstream travelling disturbances continue to play important roles in sustaining the midlatitude trough after day 3 (Figure 13). From a dynamic perspective, this longer-lasting midlatitude trough, on one hand, prolongs precipitation extremes after day 3 by continuously steering northerlies favourable for low-level convergences in the YRV; on the other hand, it keeps deepening the meridional pressure gradient there, which in turn sustains accelerated westerlies conveying moisture (compare Figure 6a,b after day 3). Additionally, these anomalous northerlies with strength comparable to that of anomalous southerlies play a key role in stabilizing the front in the YRV. From a thermodynamic view, this longer-surviving midlatitude trough extends the life span of the stationary front by equipping it with continuously descending and southward-invading dry/cold air, as inferred by the more southward-displaced 345 K contour of equivalent potential temperature (compare days 4–6 between the two groups, Figure 8).

In essence, the maintenance of anomalous synoptic-scale circulation agents could be explained in light of the internal energy conversion process, i.e. interactions between anomalies (disturbances) and mean (basic) flow. Obviously, the excitation and appearance of key disturbances in proper regions are the premise of disturbances–mean flow interactions. In the three teleconnection–PPEs, during day −4 to day −1, once the Okhotsk high-pressure disturbance is excited by
the downstream energy dispersion related to the EU teleconnection, it could soon gain baroclinic APE from the mean flow there (i.e. the polar jet) to sustain itself for a few days. That explains the earlier establishment of the Okhotsk high. Regardless of the single EAP case or three-teleconnection cases, during the mature phase, barotropic KE and baroclinic APE conversion play a joint role in replenishing the midlatitude cyclone (Figure 14, net positive values days 0–2, 120–150°E). As documented above, in single EAP cases, disturbances along East Asia are excited solely by poleward-penetrating WAFs from lower latitudes. So, once this wave source is too weak to emanate WAFs (after day 3), the disturbance–mean flow interaction process ceases rapidly, followed by an instantaneous fall-apart of the tripole pattern. By contrast, after day 0, the northern part of the Ural blocking high could firstly gain energy through APE conversion, and then serve as a stable wave source continuously exciting new disturbances downstream at both middle and high latitudes. The southern part of the Ural blocking high could also contribute to the SR pattern, as detailed above. In contrast, correlation coefficients indicate that both the SR and EAP could directly contribute to PPEs in a significant manner. However, additional partial correlation analysis accentuates the determinant role of the EAP amongst three teleconnections in inducing PPEs, and implies the indirect role of the SR pattern via its modulation on EAP components (Table 4).

5 | SUMMARY AND DISCUSSION

5.1 | Summary

This study attempts to disentangle differing influences of three daily-scale teleconnections, i.e. the East Asia/Pacific teleconnection (EAP), Silk-Road teleconnection (SR) and Eurasia teleconnection (EU), on persistent precipitation extremes in the Yangtze River Valley. Among three teleconnections, the EAP-related tripole pattern is the direct and ultimate driver for PPEs in the YRV, while the other
two teleconnections impose indirect impacts on PPEs, particularly on their duration, via modulating ingredients of the EAP tripole pattern. Detailed influential mechanisms are summarized as follows.

Regardless of evolving individually or co-evolving with other teleconnections, the tripole pattern of the EAP teleconnection is launched by poleward energy dispersion arising from the westward-progressive WPSH. The arrival of northward-penetrating WAFs deepens the midlatitude trough and enhances the Okhotsk high in sequence. This tripole pattern produces and then anchors a stationary front in the YRV, which strongly elevates moist/warm air continuously.

**FIGURE 14** Vertically integrated baroclinic energy conversion (shadings, every 0.5 W m^2) and 200 hPa barotropic energy conversion (contours, solid for positive and dashed for negative, with an interval of 5 m^2/s^3) for (a–e) single EAP-PPEs and (f–j) for three teleconnections-PPEs. Grey contours show climatological mean $U$ winds during June–July (every 5 m/s from 20 m/s). See Figure 5 for day used.
TABLE 3 Lead–lag correlation coefficients between teleconnection indices

<table>
<thead>
<tr>
<th>Leading days</th>
<th>Lagging days</th>
</tr>
</thead>
<tbody>
<tr>
<td>-7</td>
<td>1</td>
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<tr>
<td>-6</td>
<td>2</td>
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<tr>
<td>-5</td>
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<td>-3</td>
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<tr>
<td>-2</td>
<td>6</td>
</tr>
<tr>
<td>-1</td>
<td>7</td>
</tr>
</tbody>
</table>

Note: Grey shadings highlight correlation coefficients being significant at the 0.05 level. Negative (positive) day indicates the temporal step by which former teleconnection leads (lags) the latter teleconnection. Composited indices are constructed by connecting preceding 15 days, the onset day of PPEs, and subsequent 15 days to ensure that only highly relevant signals are involved in the series.

TABLE 4 Correlation coefficients between teleconnections and precipitation

<table>
<thead>
<tr>
<th>Normal correlation</th>
<th>Partial correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precip.</td>
<td></td>
</tr>
<tr>
<td>EAP</td>
<td>0.83*</td>
</tr>
<tr>
<td>SR</td>
<td>−0.71*</td>
</tr>
<tr>
<td>EU</td>
<td>−0.19</td>
</tr>
<tr>
<td>EAP-SR</td>
<td>0.61*</td>
</tr>
<tr>
<td>SR-EAP</td>
<td>−0.01</td>
</tr>
</tbody>
</table>

Note: The first three columns show direct correlation coefficients between teleconnections and precipitation. The latter two columns present partial correlation coefficients. For instance, “EAP-SR” indicates the partial correlation between the EAP teleconnection and precipitation series after removing influences of the SR teleconnection. The symbol “*” in the upper-right corner indicates significance at the 0.05 level. Composited indices are constructed by connecting preceding 15 days, the onset day of PPEs, and subsequent 15 days to ensure that only highly relevant signals are involved in the series.

So, it seems that teleconnection-induced PPEs (25 used for composite) only account for 45% non-typhoon-influenced cases. Note that these 25 cases represent those in tandem with strong and well-structured teleconnection patterns. In other words, the remaining non-typhoon-influenced cases may also involve influences from teleconnections, yet not as strong and typical as those used for the composite. Lowering the intensity threshold for daily teleconnection indices to 0.8σ and 0.75σ instead, will increase the percentages to 62% and 74%, respectively. Further considering the complexity and diversity of large-scale circulations responsible for PPEs in this area (Chen and Zhai, 2014; Li and Zhou, 2015), this percentage punctuates the dominant role of these three teleconnections over other flow patterns in triggering PPEs.

5.2 Discussion

This study is important and useful only if teleconnection–PPEs account for a reasonably large portion of all PPE cases. Note that teleconnection-related PPEs as defined in this study only serve our specific purpose of disentangling roles of different teleconnections on PPEs. Pertinent definitions should not be generalized to represent PPEs essentially representative of a combination of intensity and duration of precipitation. Adopting the criteria of normalized domain-averaged precipitation over 1.0σ for at least three consecutive days, we identify 91 PPEs during 1961–2016, 36 of which were influenced by a typhoon or its remnants.

adverted from the south and triggers PPEs there. The SR and EU teleconnections, on one hand, set up a wavy circulation background favourable for confluence of upstream travelling disturbances into the midlatitude trough over East Asia; on the other hand, they directly stimulate in-phase disturbances spatially overlapping with the EAP constituents. Moreover, these stimulated disturbances, extracting energy from local mean flows, are especially important to prolong the life span of the tripole pattern and thereby sustain the quasi-stationary front. So PPEs in tandem with configured teleconnections are noticeably longer-lasting than those associated with the individual EAP teleconnection.

Key thermodynamic–dynamic processes are encapsulated in a schematic diagram in Figure 15.

Among three teleconnections, earlier development of the EU pattern renders it a promising source for extending the lead time of circulation precursors informing PPE forecasts (Kosaka et al., 2012; Lau and Kim, 2012). Actually, significant precursors associated with the EU pattern may be traced backward to 2 weeks prior to PPEs (Chen and Zhai, 2014). More encouragingly, some models show reasonable skills in predicting this blocking/ridge, with an optimal lead time of 10 days (Dole et al., 2011). Thermodynamic and dynamic forcings related to the topography of the Ural Mountain exert impacts on this key system, so exact representation of the topography around the Ural area in models holds great promise in improving forecasts for anomalous behaviour of this blocking as well as for PPEs in the YRV (Luo, 2005). Also under-explored are intraseasonal (e.g., biweekly and 30–60 days) evolutionary features of these teleconnections...
FIGURE 15  A schematic diagram for circulation anomalies, wave energy dispersion and energy conversion between mean flow and teleconnection-related disturbances. See the figure legend at the upper-left part for the meaning of each element. In particular, $\text{APE} \rightarrow \text{APE}'$ means teleconnection-related disturbances gain available potential energy from local mean flow; while $+\text{KE}' | -\text{KE}'$ means the left half of disturbances gains kinetic energy from the mean flow and the right half loses kinetic energy. WAFs represent wave activity fluxes. Contours of composited 500 hPa geopotential heights (unit: gpdam) at day 0 are overlaid spanning mid–high latitudes and their lead–lag phase relationships, as well as their implications on intraseasonal components of PPEs (Chen et al., 2017; Li and Mao, 2018; 2019). Extracted intraseasonal signals could be readily exploited by local forecasters to foretell active and quiescent phases of PPEs.

Caution is still warranted in interpreting and utilizing the relevant conclusions. In this study, we deliberately put PPEs into the context of strong teleconnection regimes, but it does not necessarily mean that PPEs will definitely occur in the YRV in company with these teleconnections. Subtle shifts in position and intensity of teleconnection components may result in substantial differences in occurrence, intensity, duration and affected areas of PPEs (Bao and Wallace, 2015; Chen and Zhai, 2015). What is more, concurrent negative/positive phases of the EU/SR teleconnections may also undermine evolution and maintenance of the EAP tripole pattern and further deprive the EAP teleconnection of its potential in causing PPEs in the YRV. So proper configuration amongst multiple teleconnections as delimited in this study, including their phases, magnitude and geographic location, should be kept in mind when leveraging them to predict PPEs.

In spite of these uncertainties, the derived conclusions hold great promise in improving the accuracy and extending the lead time of forecasts with respect to PPEs in the YRV, via both gaining local forecasters' experience of recognizing significant precursors and informing models' improvements in reproducing critical physical processes.

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