Moisture Source–Receptor Network of the East Asian Summer Monsoon Land Regions and the Associated Atmospheric Steerings

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ABSTRACT: This study aims to construct a novel source–receptor (SR) network to study the atmospheric water cycle associated with the East Asian summer monsoon (EASM) circulation. Using a dynamical recycling model (DRM), 68%–74% of the wet season (April–September) precipitation in six EASM land regions is attributed. The results reveal that terrestrial sources can be equally or more competitive than oceans for several sink regions downwind in East Asia. Terrestrial sources, such as the Indian subcontinent, Indochina, Southwest China, and the eastern Tibetan Plateau, are sustained by southwesterly monsoons and contribute to appreciable fractions of precipitation in the East Asian subregions downwind. Further, southwesterly and southeasterly sources for a sink region alternately dominate the moisture supply in the early and late wet season, respectively, referred to as the “SW–SE source swing.” The SR network is found to be largely governed by the zonal oscillation of the western North Pacific subtropical high and tropical cyclones. Knowledge about the coupled circulations might promise more predictability of the strength of the affected SR pairs. Notably, enhanced moisture supplies from regions such as the Indian subcontinent and Tibetan Plateau are well correlated with an upper-level wave train from western Russia. Finally, the preceding wintertime El Niño may favor (suppress) the moisture contribution of southwesterly (southeasterly) sources in the following wet season. The findings offer insights into the EASM water cycle and the governing circulations, and also accentuate the role of upwind terrestrial sources in the downwind precipitation and freshwater resources.

KEYWORDS: Atmospheric circulation; Mass fluxes/transport; Monsoons; Moisture/moisture budget; Statistical techniques; Intraseasonal variability

1. Introduction

There has been growing interest in studying precipitation recycling and identifying moisture sources in recent decades (Simmonds et al. 1999; Dominguez et al. 2006; Nieto et al. 2008; Hu and Dominguez 2015; Pan et al. 2017; Wang et al. 2018a; Keys et al. 2014; Lu et al. 2013; Lu and Lall 2017; Najibi et al. 2017, 2019). Given the profound influence of the East Asian summer monsoon (EASM) on the livelihood, agriculture, and economy in East Asia, understanding the contributing moisture sources and their relationship with the atmospheric drivers becomes crucial for numerical simulations, water resources management, and adaptation against hydroclimatic disasters like flooding and landslides.

Dominant moisture sources for eastern China in the wet season have been highly contentious during the past few decades and for good reasons. The South China Sea and western

North Pacific were traditionally regarded as the primary sources for summer rainfall in China (Chow et al. 2008; Xu et al. 2003; Bin et al. 2013; Chen 2004; Lu and Hao 2017; Simmonds et al. 1999). On the other side, Indian Ocean sources, such as the Bay of Bengal, the Arabian Sea, and the southern Indian Ocean, were argued to be essential or even dominant (Xu et al. 2008; Qian et al. 2004; Wang et al. 2018a). In addition to marine sources, leading terrestrial sources for the middle to lower reaches of the Yangtze River basin also differ in the literature, including Indochina and the Philippines (Xu et al. 2008), the Eurasian continent (van der Ent et al. 2010; Wang and Chen 2012), China excluding the Yangtze River basin (Wang et al. 2018a), and local recycling (Wei et al. 2012). Apparently, the research community has not yet reached consensus on the dominant sources for eastern China during the wet season, likely due to different moisture tracking approaches, diverse definitions of source and sink regions, data quality, and the inherent complexity of the EASM circulation. For other East Asian regions such as the Korean Peninsula and Japan, a handful of studies revealed that the summer precipitation is likely fueled by moisture from the South China Sea, East China Sea, or western North Pacific (Lee et al. 2003; Manda et al. 2014; Sekizawa et al. 2019). In-depth research on the dominant summer moisture sources for these regions is thus required.

Since atmospheric moisture originates from either external or local sources, a wide array of approaches were adopted to evaluate the nonlocal moisture advection and local recycling. Early studies were based on heavy isotopes of oxygen and hydrogen in water samples (Salati et al. 1979; Kurita et al. 2004;

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Lee et al. 2003) or diagnoses of the atmospheric water budget and water vapor transport in an Eulerian framework (Kuo et al. 1986; Simmonds et al. 1999). The isotopic studies often suffer from data scarcity in time and space and uncertainties involved in data collection and the understanding of the isotope–environment relationships (Welker 2000; Kurita et al. 2004), while the purely diagnostic studies depend on the quality of reanalysis data and the water budget equation in Eulerian form. Another main stream relies on numerical experiments to assess contributions of external moisture advection by modifying water vapor inflows at the lateral boundary of a target region (Qian et al. 2004; Xu et al. 2003; Chow et al. 2008) or by tagging “water” in the atmospheric general circulation models (Numaguti 1999; Pan et al. 2017). Although numerical models in general provide more information about moisture sources through resolving precipitation and evaporation fluxes at each vertical level, shortcomings are also apparent. Numerical models have inherent dependence on the physical parameterizations that are sensitive in simulating the real-world situation (Dominguez et al. 2006). Specifically, the turbulence that affects the rate of vertical mixing of water vapor is known to be the greatest source of uncertainty in the model’s moisture tracking (Tuinenburg and Staal 2020). Further, it is computationally expensive to trace the origin of the atmospheric moisture within a sink region each day for a long period using numerical models.

An alternative to establishing the source–receptor (SR) network with reasonable accuracy is perhaps a simpler two-dimensional (2D) dynamic recycling model (DRM). Like other moisture tracking models such as HYSPLITS (Draxler and Hess 1998; Draxler 2003; Gustafsson et al. 2010; Lee et al. 2003), LAGRANTO (Knippertz and Wernli 2010; Wernli and Davies 1997), and FLEXPART (Stohl and James 2004, 2005), DRM tracks the wind trajectories backward in time to estimate source contributions in a semi-Lagrangian framework (Dominguez et al. 2006; Dominguez and Kumar 2008). By incorporating the semi-Lagrangian framework and including the storage term in the water budget equation, DRM can analytically derive the recycling ratio and thereby the relative contributions from local or external sources at the daily level (Martinez and Dominguez 2014; Dominguez et al. 2006). Despite its dependency on the well-mixed assumption, DRM has shown great potential in estimating source contributions with fidelity in the La Plata River basin (Martinez and Dominguez 2014), the North American monsoon region (Hu and Dominguez 2015), the Indian summer monsoon region (Pathak et al. 2017), the middle to lower reaches of the Yangtze River basin (Wang et al. 2018a), and China (Hua et al. 2017). Additionally, East Asia and the adjacent seas are evident with weakly sheared horizontal moisture fluxes alongside, with a quite frequent vertical mixing in boreal summer (see Figs. 3b and 4b in Goessling and Reick 2013). Thus, one may expect that the well-mixed condition broadly holds for the EASM domain in the warm season, which justifies the use of the 2D DRM for at least a first-order approximation on the SR network.

In this study, we employ the DRM to construct the SR networks for multiple land subregions in the EASM domain during the wet season, which may contribute to a holistic picture of the atmospheric water cycle involved in the EASM and

advance the understanding of the governing circulation drivers. In particular, El Niño–Southern Oscillation (ENSO) in the preceding winter has been known to influence the EASM rainfall (Wang and Li 2004; Shen and Lau 1995; Lau and Wu 2001). Its role in modulating the SR network in the EASM subregions is thus of great interest to explore. In line with the above motivations, the present study is guided by the following research questions:

- 1) What are the governing sources for the EASM land regions based on the derived SR network?
- 2) How does the SR network evolve on intraseasonal time scale? How is it during heavy rainfall days?
- 3) What are the attributable circulation drivers and how do they modulate the SR network?
- 4) How do the preceding wintertime ENSO events influence the EASM rainfall from the SR network’s perspective?

The remainder of this paper is organized as follows. The data, model setup, and study domain are described in section 2. Section 3 presents results addressing the research questions mentioned above, followed by discussions in section 4. A summary of the results is provided in the final section.

2. Data and methods

a. Data

Forty-year hourly data (1979–2018) are retrieved from the ERA5 reanalysis dataset at $0.25^\circ \times 0.25^\circ$ spatial resolution (Copernicus Climate Change Service 2017). Since the preconditioning of the EASM generally is established in late spring (Ding and Chan 2005), we choose April to September (183 days) to track the sources from premonsoon to postmonsoon periods. The input data for DRM are daily precipitation (P), evapotranspiration (ET), precipitable water (PW), and hourly effective winds. Note that PW is namely the total column water vapor available in the ERA5 reanalysis. The effective winds are calculated from the hourly eastward and northward components of vertically integrated water vapor transport (IVT) divided by hourly PW (Dominguez and Kumar 2008), which represent the movement of the moist air column.

Among these input data, ET is the most uncertain variable, being heavily determined by model parameterizations, and there is often a lack of observations for validation (Dominguez et al. 2006). To minimize the uncertainties from the input data, we adopt the cutting-edge ERA5 reanalysis dataset. Comparing to its former generation (ERA-Interim), ERA5 incorporates a much higher native resolution in space (33 km) and time (hourly) with an improved land surface scheme (HTESSEL) that offers more reliable estimates of the ET (Mao and Wang 2017; Hersbach et al. 2018; Balsamo et al. 2015). All these make ERA5 reanalysis the most suitable dataset for our model input at the moment.

Geopotential heights at 850 and 200 hPa (Z_{850} , Z_{200}) are also retrieved for diagnosis in section 3d. An anomaly is defined as the departure from the pentad-day moving mean of the calendar day climatology in 1979–2018. A positive Z_{850} anomaly is denoted as $Z_{850}A+$, and the same convention is applied to other variables hereafter. Following the operational

FIG. 1. The prescribed 30 regions in the study domain. The labels E1–E6 denote the sink regions within the EASM region (outlined in white). Source regions include Eurasia (EURA), the Middle East (ME), eastern Africa (EAF), the Arabian Sea (AS), the western and eastern Indian Ocean (WIO, EIO), the Indian subcontinent (INSC), the Bay of Bengal (BoB), the Tibetan Plateau (TP), the eastern Tibetan Plateau (ETP), central China (CC), Southwest China (SWC), Indochina (IDC), the northern and southern South China Sea (NSCS, SSCS), the Maritime Continent (MC), Australia (AUS), the Yellow Sea and East China Sea (YSECS), the Sea of Japan (SOJ), the Philippine Sea (PS), the North Pacific (NP), the western North Pacific (WNP), the tropical Pacific Ocean (TPO), and the South Pacific (SP). The Tibetan Plateau is defined as topography with altitude reaching 3 km or above.

definition by National Oceanic and Atmospheric Administration (NOAA), full-fledged ENSO events are classified based on a threshold of $\pm 0.5^\circ\text{C}$ in the oceanic Niño index for at least five consecutive months.

b. DRM

The recycling ratio R computed in the DRM is derived by Dominguez et al. (2006) as follows:

$$R(x, y, t) = 1 - \exp \left[- \int_0^\tau \frac{\text{ET}(x', y', t')}{\text{PW}(x', y', t')} d\tau' \right], \quad (1)$$

where $x' = x - ut$, $y' = y - vt$, and $\tau = t$. By definition, R estimates the fraction of atmospheric moisture at one specific point that is recycled from the evapotranspiration within the domain and is collected by an air column along its trajectory (Dominguez and Kumar 2008). By dividing the trajectory into parts whenever it enters one source region, Martinez and Dominguez (2014) demonstrated that R is the sum of relative contributions from individual source regions along the trajectory:

$$R(x, y, t) = \sum_{k=1}^{N_A} \sum_{\lambda \in A_k} \left\{ \prod_{j=1}^{\lambda-1} [1 - R_j(x, y, t, A_k)] \right\} R_\lambda(x, y, t, A_k), \quad (2)$$

where N_A is the total number of prescribed source regions, A_k is the source region k , λ numbers each part of the backward trajectory from a grid point (x, y) in the sink region, and R_λ is the recycling ratio throughout the time when the air column moves along the part λ of its trajectory. For instance, if the first

($\lambda = 1$) and third parts ($\lambda = 3$) of the trajectory are within region A_1 , while the second part ($\lambda = 2$) is in region A_2 , then based on Eq. (2), R is given by

$$R(x, y, t) = \underbrace{R_1 + (1 - R_1)(1 - R_2)R_3}_{R(x, y, t, A_1)} + \underbrace{(1 - R_1)R_2}_{R(x, y, t, A_2)}, \quad (3)$$

where $R(x, y, t, A_1)$ denotes the recycling ratio at a point (x, y) within a sink region at time t contributed by region A_1 .

In addition, the residence time of atmospheric moisture is 12–14 days over East Asia and the Indian basin (see Fig. 2c in van der Ent and Tuinenburg 2017), comparing to a global average of 8–10 days (Gimeno et al. 2020). As such, a 14-day maximum tracing period is imposed to avoid oversampling of the recycling ratio while maintaining the majority of precipitation being traced. The moisture tracking algorithm stops once the trajectory reaches the boundary of the study domain.

c. Study domain

A total of 30 regions within a study domain of 20°S – 65°N , 30° – 190°E are prescribed in Fig. 1. Note that each region is given an acronym hereafter for more accurate delivery of the results in the paper. (Readers may also refer to Table A1 in the appendix for a list of acronyms.) The EASM domain of 20° – 45°N , 110° – 140°E , as defined by Ding and Chan (2005), is set as the sink domain in the model. It is worth mentioning that the EASM influences both the land and oceans, yet this study mainly focuses on the land receptors where approximately one-third of the world population lives. Based on our preliminary

FIG. 2. Wet season climatology (April–September) of the ratio contribution (%) in regions (a)–(f) E1–E6. The relevant sink region and the Tibetan Plateau (≥ 3 km above sea level) are outlined in purple and green, respectively.

results, subregions like eastern China, the Korean Peninsula, and southern Japan receive moisture from different sets of sources. Hence, we divide the EASM domain into six subregions and treat each as an individual sink region in the DRM. They include the South China mainland and Taiwan (E1), the middle to lower reaches of the Yangtze River basin (E2), southern Japan (E3), the middle to lower reaches of the Yellow River basin (E4), the Korean Peninsula (E5), and North China (E6). The desired SR network serves to unravel the amounts of moisture of the precipitation in the sink regions recycled from both local and external sources.

To properly assess the contribution of a source region A_k to each grid of a sink region A_i , the recycled precipitation P_m and the total precipitation $\bar{P}$ are weighted by area as follows:

$$\bar{P}_m(A_k, A_i, t) = \frac{\sum_{(x,y) \in A_i} R(x, y, t, A_k) \times P(x, y, t) \times \delta A(x, y)}{\sum_{(x,y) \in A_i} \delta A(x, y)}, \quad (4)$$

and

$$\bar{P}(A_i, t) = \frac{\sum_{(x,y) \in A_i} P(x, y, t) \times \delta A(x, y)}{\sum_{(x,y) \in A_i} \delta A(x, y)}, \quad (5)$$

where δA denotes the grid area. The regional recycling ratio $\bar{R}$ of precipitation in the sink region A_i contributed by the source region A_k within a period T is then obtained by

$$\bar{R}(A_k, A_i) = \frac{\int_0^T \bar{P}_m(A_k, A_i, t) dt}{\int_0^T \bar{P}(A_i, t) dt}. \quad (6)$$

Note that $\bar{R}$ is set to zero when there is no rainfall anywhere in the region within the period T . For simplicity, the amount contribution and ratio contribution hereafter refer to the terms $\bar{P}_m$ and $\bar{R}$ defined above, respectively.

FIG. 4. Monthly climatology of the ratio contribution (%) from sources to the (a)–(f) E1–E6 regions, respectively. Only the sources with ratio contributions greater than 5% are labeled.

aggregate the ratio contributions by the prescribed source regions (Fig. 1). Specifically, the wet season precipitation in E1 primarily relies on southwesterly sources such as BoB (11%) and IDC (10%) (Fig. 3a; see the appendix for expansions of region names). In contrast, contributions of southeasterly sources (e.g., NSCS and PS) are rather secondary; each contributes only 5% of the precipitation. In addition, E2 heavily depends on southwesterly land sources, such as INSC (11%) and SWC (11%), while marine sources BoB (7%) and AS (6%) only rank fourth and fifth (Fig. 3b). Pertaining to E3, Pacific sources like PS (10%), YSECS (6%), and WNP (5%) are the primary marine contributors (Fig. 3c). Startlingly, remote sources like SWC (5%), INSC (5%), and E2 (4%) are also make noticeable contributions to sustain the precipitation in E3. The above results reveal the dominant role of southwesterly summer monsoons in sustaining long-range moisture transports from sources in the southwest.

Regarding the northern subregions (i.e., E4–E6), contributions from marine sources further lessen as terrestrial sources become more prevalent (Figs. 3d–f). Since EURA is the leading source shared by E5 (8%) and E6 (30%), it reveals the importance of northern Eurasia in supplying moisture to the northern EASM domain. Additionally, moisture contributions from local recycling and external terrestrial areas (e.g., SWC, CC, and ETP) are also emphasized but were often overlooked in the past.

In view of the unexpectedly competitive land sources, anthropogenic activities that affect upwind evapotranspiration (e.g., deforestation or overirrigation) over these contributing land sources could exert nontrivial impacts on the downwind precipitation in East Asian countries.

b. Intraseasonal variation of the SR network: The “SW–SE source swing”

In light of the presence of a subtropical rain belt propagating stepwise from south to north within the EASM season (Wang and LinHo 2002; Ding and Chan 2005), it remains unclear whether and how the state of the atmospheric water cycle undergoes changes within the season. To answer this question, we examine the evolution of the SR network in different months of the season. The results uncover an intraseasonal shift in dominant sources from southwesterly to southeasterly sectors for several subregions, which is hereafter referred to as the “SW–SE source swing.” Taking E1 as an example, it heavily depends on the moisture recycled from the southwesterly sources, including IDC, BoB, and INSC in April and May; each contributes at least 10% of the precipitation in each of the months (Fig. 4a). Later from June to July, WIO and AS become germane to the moisture supply. The sudden increase in their contributions is likely due to the typical onset of the Indian summer monsoon during this time (Chang and Chen

FIG. 5. Monthly climatology of the ratio contribution (%) of sources in categories of (a) the Pacific Ocean and the Indian Ocean; (b) Eurasia, South Asia, Southeast Asia, East Asia and the other land regions; and (c) ocean and land. Only the ratio contributions greater than 5% are labeled.

1995). Starting from August, southeasterly sources (e.g., NSCS, PS, and WNP) rise as the leading sources, along with the shrinking contributions of the southwesterly sources. We thereby document such iconic transition in dominant sources as the SW–SE source swing.

Intriguingly, we also observe similar source transitions in the SR networks of E2–E5, although they involve slightly different sets of sources (Figs. 4b–e). The observed swings of moisture sources suggest that the SR networks of the subregions are far more dynamic than we thought before. The findings may also shed light on the contradicting arguments about the dominant summer sources mentioned in the introduction, as the strength of which can significantly vary within the season. Further analysis suggests that the SW–SE source swing is mainly caused by the frequent tropical cyclone landfalls in the late summer (results not shown), which bring moisture from the Pacific Ocean and in the interim weaken the summer monsoons.

On the contrary, E6 has the most stagnant SR network with relatively stable moisture supplies from inland and mountainous regions throughout the season (Fig. 4f). Several factors could be attributable to the stagnant network: the absence of tropical cyclones, the blocking of monsoons by the Tibetan Plateau, and the prevailing westerly jets and extratropical cyclones at midlatitudes. Local recycling tends to be more prominent during the late summer in E1 and E2 (Figs. 4a,b), whereas it prevails throughout the entire season in E4 and

E6 (Figs. 4d,f). Moisture allocation among subregions is slightly favored in the middle of the wet season, exemplified by the moisture supply from E2 to E3 and from E4 to E5 (Figs. 4c,e).

By grouping the sources according to their basins and subcontinents, the SW–SE source swing becomes even more salient. In general, contributions of the Indian Ocean and the Pacific Ocean tend to be out of phase over time for most of the subregions. For instance, the Indian Ocean can supply up to 35% of the precipitation in E1 in the first half of the season (Fig. 5a). However, its contribution plunges dramatically when the moisture supply from the Pacific Ocean surges to 39% afterward. We also note similar swings of sources among different continental sources, in which the moisture supplies of South and Southeast Asia (East Asia) weaken (enhance) over time (Fig. 5b). These results again depict the proposed SW–SE source swing in the SR network. Regarding land versus oceanic sources, the presence of this SW–SE source swing can also modify the ratio of land to ocean contributions on the intra-seasonal time scale, manifested by more moisture supply from land (oceans) during the first (second) half of the wet season (Fig. 5c).

c. The SR network during heavy rainfall days

Upon the climatological understanding of the SR network, we proceed to investigate possible changes in the network

TABLE 1. Sources ranked by $W\bar{R}$ during the top 15% rainy days in each subregion. Only the primary (bold text) and secondary (plain text) sources are shown; $\bar{R}_{\text{WSC}}$ refers to wet season climatology $\bar{R}$. Value is not shown if $\bar{R}_{\text{WSC}} - \bar{R} < 0.1$. The number in the parentheses denotes the change in the rank of $\bar{R}$ compared to $\bar{R}_{\text{WSC}}$. All r_p values are statistically significant at the 0.05 level.

Source	$\bar{R}$ (%)	$\bar{R} - \bar{R}_{\text{WSC}}$ (%)	Rank of $\bar{R}$ compared to that of $\bar{R}_{\text{WSC}}$	r_p	$W\bar{R}$ (%)
E1					
BoB	12.12	+1.09	1 (0)	0.81	9.82
IDC	9.68	−0.21	2 (0)	0.69	6.68
INSC	7.62	+1.64	3 (1)	0.71	5.41
PS	6.05	+0.13	5 (1)	0.83	5.02
AS	6.34	+0.65	4 (3)	0.66	4.18
WIO	5.88	−0.37	6 (−3)	0.64	3.76
NSCS	4.48	−1.45	8 (−3)	0.78	3.49
SWC	4.94	+0.65	7 (2)	0.56	2.77
E2					
INSC	12.3	+1.76	1 (1)	0.78	9.59
SWC	11.37	+0.68	2 (−1)	0.74	8.41
BoB	7.69	+0.88	3 (1)	0.74	5.69
AS	7.42	+1.02	4 (1)	0.71	5.27
IDC	7.08	+0.17	5 (−2)	0.57	4.04
E3					
PS	11.14	+1.43	1 (0)	0.87	9.69
WNP	5.06	+0.25	5 (0)	0.77	3.9
YSECS	5.73	—	3 (−1)	0.65	3.72
INSC	5.71	+0.72	4 (0)	0.61	3.48
SWC	5.74	+0.51	2 (1)	0.56	3.21
E2	4.52	—	6 (0)	0.63	2.85
BoB	4.02	+0.19	8 (0)	0.54	2.17
E4					
SWC	10.79	+1.59	1 (1)	0.79	8.52
ETP	9.6	+0.21	2 (−1)	0.65	6.24
INSC	7.68	+0.65	3 (1)	0.78	5.99
CC	7.21	−0.9	4 (−1)	0.57	4.11
TP	4.56	−0.5	6 (1)	0.59	2.69
PS	3.49	+0.49	8 (1)	0.74	2.58
EURA	3.61	−2.27	7 (−1)	0.63	2.27
E4	4.97	−1.24	5 (0)	0.42	2.09
E5					
PS	7.62	+1.73	1 (2)	0.84	6.4
SWC	7.11	+0.95	2 (0)	0.69	4.91
INSC	5.17	+0.47	4 (2)	0.69	3.57
YSECS	5.05	+0.42	5 (2)	0.62	3.13
EURA	4.64	−3.77	7 (−6)	0.63	2.92
ETP	5.2	+0.4	3 (2)	0.55	2.86
E4	4.79	−0.23	6 (−2)	0.53	2.54
CC	4.44	—	8 (0)	0.55	2.44
E2	3.81	+0.13	9 (0)	0.58	2.21
WNP	3.15	+0.68	10 (3)	0.66	2.08
BoB	2.3	+0.18	13 (1)	0.51	1.17
IDC	2.77	+0.25	11 (1)	0.42	1.16
E6					
EURA	24.18	−6.07	1 (0)	0.91	22
CC	9.06	+1.34	2 (1)	0.8	7.25
ETP	9.04	+1.72	3 (1)	0.69	6.24
TP	7.46	+0.99	5 (0)	0.74	5.52
E6	7.75	−1.64	4 (−2)	0.62	4.81

during heavy rainfall days. For this purpose, we select the top 15% strongest rainy days for each subregion. Several indicators are harnessed to assess the changes in the network: $\bar{R}$, the difference of $\bar{R}$ against its wet season climatology (WSC; $\bar{R} - \bar{R}_{\text{WSC}}$), the rank of $\bar{R}$ compared to that of $\bar{R}_{\text{WSC}}$, and the

partial correlation (r_p) with the rainfall (Table 1). The reason for employing r_p is to remove the collinearity among sources, so as to depict their linear associations with the rainfall unbiasedly. To identify the critical sources considering both the contribution and the correlation, we rank all the sources based

on the ratio contribution weighted by $r_p(W\bar{R})$. By using a “one-half criterion,” primary sources are classified as those with $W\bar{R}$ greater than half of the largest $W\bar{R}$ in the network. Likewise, we classify the secondary sources as those with $W\bar{R}$ greater than half of the $W\bar{R}$ value of the top one secondary source.

Considering the rank of $\bar{R}$ compared to $\bar{R}_{\text{WSC}}$, one can immediately get the picture that sources (both primary and secondary) during heavy rainfall days mostly follow their rankings in climatology for all subregions except E5 (Table 1). That could be explained by the finding that E5 has a nearly equal dependence on a variety of sources (Fig. 3e, Table 1), such that one source can easily dominate over the others.

Most of the primary sources tend to contribute slightly more moisture than their climatological values. These suggest that primary sources dictate in supplying the heavy rainfall in those subregions. Yet, the weakening of primary sources could also occur, such as the IDC–E1 (−0.21%) and EURA–E6 (−6.07%) pairs. We reckon that these weakened primary sources are more responsible for mild-to-moderate rainfall.

The SW–SE source swing may also link to heavy rainfall days. Taking the E1 network for instance, the moisture supplies from BoB, IDC, and INSC dominate from April to June, which are then replaced by AS in the midsummer and last by PS in the late summer (see Fig. S2a in the online supplemental material). Similar intraseasonal transitions are also recognized in the networks of E2, E3, and E5 (Figs. S2b,c,e). Hence, we argue that the SW–SE source swing governs the SR network both climatologically and on heavy rainfall days for these subregions.

Higher correlations of the heavy rainfall amount with the primary sources (0.76 on average) than that with the secondary ones (0.61 on average) are observed. That said, exceptionally high correlations ($r_p > 0.7$) are found between secondary SR pairs, including the pairs NSCS–E1, WNP–E3, PS–E4, and TP–E6. Assume that precipitation does not directly affect or control the contributions from its sources, accurate simulations on the moisture transport and evapotranspiration from these highly correlated sources are crucial for improving weather prediction in East Asia during the monsoon season.

It has come to our attention that the moisture reallocation among subregions has nontrivial stakes in the contribution to heavy rainfall. For E3 and E5 located in the northeast of the EASM domain, they receive nonnegligible moisture recycled from the middle to lower reaches of the Yangtze (i.e., E2) or Yellow River basins (i.e., E4) (Table 1). In other words, urbanization, irrigation schemes, vegetation coverage, and water management in these river basins have potential impacts on the heavy rainfall in southern Japan and the Korean Peninsula during the wet season.

d. Attributable circulation drivers and climate variability for the SR network during heavy rainfall days

1) ZONAL OSCILLATION OF THE WNPSH AND TROPICAL CYCLONES

With the knowledge of the SR network during heavy rainfall days (section 3c), the next aim is to identify the circulation drivers that are responsible for the network. In this section, we

perform lead–lag correlation analyses using Spearman’s rho on the top five SR pairs for each subregion with field variables. Note that the correlation at lead 7 denotes the correlation of a source’s contribution with the field variables 7 days ahead of it. Readers may find the correlation maps regarding E4–E6 in the supplemental material (Figs. S3–S5).

The correlation analysis indicates that the zonal oscillation of the WNPSH is crucial for most SR pairs by steering the moisture trajectories. For example, the anticyclonic IVTA and the Z850A+ fields over the South China Sea are the striking features associated with the sources of E1 (Figs. 6a1–c1). As influenced by such circulation, warm and moisture-laden air flows are steered from the Indian Ocean and South Asian sectors across the Indochina and the Yun-Gui Plateau, and eventually sustain the heavy rainfall in E1. By aggregating the correlation fields from lead 7 to lead 1, the Z850A+ field propagates northwestward from the southern PS to NSCS during the week before the day of heavy rainfall (Figs. 6a2–c2). This phenomenon generally resembles the positive WNPSH phase (referred to as WNPSH+) originating from its zonal oscillation (Cheng et al. 2019).

Conversely, a strengthened contribution from the PS is moderately associated ($r \sim 0.5$) with a Z850A− field over NSCS (Fig. 6d1). In this case, the IVTA field becomes cyclonic, and moisture fluxes to E1 are mainly from the southeast, while the southwesterly background monsoons are weakened. Likewise, the large-scale Z850A− field again features a northwestward propagation during the preceding week (Fig. 6d2). Further analysis reveals that such strong signals stem from both the negative WNPSH phase (referred to as WNPSH−) and tropical cyclones in the western Pacific basin (results not shown).

Similar features are also observed in the correlation maps of other subregions. Generally speaking, the WNPSH+ significantly correlates with southwesterly sources like SWC, BoB, and INSC that provide appreciable moisture supply to multiple subregions (e.g., Figs. 7b,c and 8d,e; see also Fig. S3a). In contrast, the WNPSH− or tropical cyclones tend to be associated with heightened contributions from Pacific sources (e.g., PS, WNP, and YSECS) to heavy rainfall in E1, E3, and E5 (Figs. 6d and 8a–c; see also Figs. S4a,d). Integrating with the earlier findings, we reckon that the completely reversed modulations between WNPSH+ and WNPSH−/tropical cyclones are likely the key to the intraseasonal SW–SE source swing in the SR network (section 3b).

2) COUPLED CIRCULATIONS

The atmospheric steerings that regulate the SR network are often in the form of coupled circulations. The most common form is perhaps the synoptic-scale pressure dipole, which consists of a subtropical/tropical circulation (a WNPSH phase or tropical cyclone) and a counterpart circulation at midlatitudes. Such a dipole offers the vital pressure gradient to bridge the geostrophic moisture transport. In the context of the heavy rainfall in E1, contributions from BoB and IDC both correlate with a northeastward-tilted pressure dipole (here called “NE-type dipole”) consisting of the WNPSH+ and a deep trough to the southwest of Japan (Figs. 6a,b). The dipole is imperceptible during the heavy rainfall days in other subregions, revealing its

E1

FIG. 6. One-point correlation maps (Spearman's rho) of the amount contribution anomalies of (a) BoB, (b) IDC, (c) INSC, (d) PS, and (e) AS for the E1 subregion with different meteorological variables at time lags with respect to the heavy rainfall days. (left) The time lag when the strongest correlation with Z850A (shaded), Z200A (contour; interval: 0.05 starting from ± 0.1), and IVTA (vector) are seen. (right) The lead-lag correlations for Z850A (solid) and Z200A (dashed) at lead times from 1 to 7 days, with correlations of 0.15 (contour) and 0.3 (shaded) shown only. All correlations shown are statistically significant at the 0.05 level. The relevant sink region and the Tibetan Plateau (≥ 3 km above sea level) are outlined in purple and green, respectively.

E2

FIG. 7. As in Fig. 6, but for the top five sources for E2 during its heavy rainfall days.

E3

FIG. 8. As in Fig. 6, but for the top five sources for E3 during its heavy rainfall days.

exclusive role in modulating the IDC–E1 and BoB–E1 pairs. The NE-type dipole with signs reversed is, however, more often seen when the WNPSH– or tropical cyclone couples with a blocking high anomaly over southwest Japan (e.g., Figs. 6d and

8a,b), by which contributions from Pacific sources (e.g., PS and WNP) are fortified. Another type of dipole features a northwestward-tilted pattern (“NW-type dipole”), exemplified by the WNPSH+ coupled with a trough to the east of the

Tibetan Plateau. The orientation of this dipole generally steers moisture from remote land regions in the southwest, such as INSC, SWC, and ETP (e.g., Figs. 7b and 8d,e; see also Figs. S3a–c). As such, knowledge about the orientation and the position of the pressure dipole further informs strengthened or weakened SR pairs.

In addition to the pressure dipoles, an anomalous anticyclone over South Asia is crucial for cross-basin long-haul moisture transport. Specifically, contributions from INSC to E1 and E2 are sustained when the anticyclone hovers over the central Indian peninsula (Figs. 6c and 7a). However, the anticyclone can also block the long-range moisture route if it stays right next to the Himalayan mountain range; in this case, a short-range route from IDC to E1 and E2 is favored (Figs. 6b and 7e). Besides that, the AS–E1 and AS–E2 pairs are associated with a series of coupled circulations at different lead times. In the past one week before the heavy rainfall, the long-range route is maintained by both a large-scale pressure depression to the north of the Arabian Sea and the aligned NW-type dipole over the East Asian sector (Figs. 6e1 and 7d1). After the decay of the South Asian depression, the WNPSH+ strengthens as it encompasses Southeast Asia (Figs. 6e2 and 7d2). The evolution of these circulations facilitates the long-distance moisture supply from the Arabian Sea.

As a side note, whether or not a coupled circulation is engaged depends on the route channeling a specific source to a sink region. One example is the presence of the NW-type dipole in the INSC–E3 and INSC–E5 pairs, while it is absent in the INSC–E2 pair (cf. Figs. 8d and 7a; see also Fig. S4c). The former two pairs, which require an extremely long-range moisture route, would surely need well-organized circulations in governance, yet it seems superfluous for the much shorter distance between INSC and E2. Another example would be the presence of deep convection over the northern tip of the AS region correlated with the BoB–E2 pair (Fig. 7c), which is absent, however, in the correlation map of the BoB–E1 pair (Fig. 6a). Hence, one should keep in mind that the set of coupled circulations could differ from one SR pair to another despite the same source.

3) WAVE TRAINS

Perhaps the most intriguing finding lies in the influence of upper-level wave trains on the SR pairs. Examples include the INSC–E2 pair, from which the INSC's contribution prominently correlates with an upper-level wave train from western Russia to the north of E2 (Fig. 7a1). Such a wave train coherently propagates to the southeast throughout the week before the heavy rainfall days in E2, which likely triggers the lower-level depression to the east of the Tibetan Plateau through the disturbances at upper levels (Fig. 7a2). Notably, the wave train is in abreast with the aforementioned lower-level anticyclone over South Asia, and they are both arguably the key drivers to sustain the INSC–E2 pair. Similar wave trains are well correlated to the SR pairs linking the INSC, ETP, and TP with sink regions from E2 to E6 (e.g., Figs. 7a and 8d; see also Figs. S3b,e, S4c, and S5c). We also notice an interesting coupling between the upper-level wave train and the NW-type pressure dipole at lower levels (e.g., Fig. 8d), the vertical displacement of which

favors the baroclinic instability and may thereby enhance moisture transports at lower levels.

It is worth mentioning that the observed wave trains highly resemble the Russia–China (RC) wave patterns documented in Dai et al.'s (2020) study, in which the RC patterns offer promising predictability to daily summer rainfall in Southeast China. As such, we argue that the RC wave patterns might play a crucial part in the SR network through two plausible ways: one is to introduce baroclinic instability that favors frontal rains while another is to indirectly convey moisture from the Indian subcontinent and Tibetan Plateau to sustain the rainfall.

4) PRECEDING WINTERTIME ENSO EVENTS

We revisit how the preceding wintertime ENSO events would associate with the heavy EASM rainfall from the SR network's perspective. The bootstrap Kolmogorov–Smirnov test (Sekhon 2011) is used to determine whether a preceding wintertime ENSO event could significantly affect contribution by any source from a neutral case. Results show that when El Niño occurred in the preceding winter, the moisture supply from BoB and INSC to E1 is significantly enhanced (Fig. 9a). Likewise, contributions of southwesterly sources (SWC, IDC, BoB, and ETP) are significantly and consistently fortified in the SR networks of E3–E5, although the extent is mild (Figs. 9c–e). Meanwhile, Pacific sources (NSCS, PS, WNP) are notably weakened in E1's and E5's networks (Figs. 9a,e).

A follow-up question is how the heavy rainfall weather occurs in response to the El Niño occurring in the preceding winter. By comparing the composite maps under wintertime El Niño with that under the neutral state, we find a planetary-scale high pressure anomaly encompassing the Arabian Sea and the western North Pacific (Fig. 10; see also Fig. S6). In this case, enhanced moisture fluxes from BoB, INSC, and SWC would be further directed to East Asia through a stronger WNPSH+ over the Philippine Sea, whereas contributions from the Pacific Ocean are hindered. Under such a scenario that reinforces southwesterly sources, more devastating rainfall may occur in late spring and early summer in accord with the SW–SE source swing (section 3b).

In addition, wintertime La Niña may also exhibit discernible impacts on the SR network in the following wet season, evident by the significantly increased moisture supply from IDC to E2 (Fig. 9b). From the composite analysis, an anomalous cyclone over the northern Philippine Sea emerges (Fig. S7a). This low-level convergence plausibly favors frontal rainfall by encouraging cold and dry air masses from northeastern Eurasia and warm and moist flows from the southwest. However, the reason why the moisture contributions from IDC to E2 significantly enhance cannot be well deciphered from the composited circulation, which may imply the effects from other factors such as temperature, soil moisture, and evapotranspiration. After all, impacts of the preceding La Niña on the circulations and the SR networks appear to be less coherent, exemplified by a weakened INSC–E5 pair due to an overall suppression of southwesterlies over East Asia (Fig. S7b), while the weakened EURA–E6 and E6–E6 pairs are concurrent with a strengthened blocking high at midlatitudes (Fig. S7c).

FIG. 9. Boxplots of the amount contribution anomalies (mm day^{-1}) during heavy rainfall days of (a)–(f) E1–E6 under the context of ENSO events in the preceding winter (i.e., DJF). The value next to the boxplot indicates the mean of the distribution, while the number to the right of each boxplot denotes the sample size. The yellow triangle denotes the outliers. Only those have a significant difference in the cumulative probability distribution with that in the neutral state at the 0.05 level are plotted (bootstrap Kolmogorov–Smirnov test, bootstrap samples = 10 000). Only the primary and secondary sources (Table 1) are considered.

4. Discussion

Some findings in this study challenge the prior understanding of the dominant sources for the EASM subregions. For the South China mainland and Taiwan (i.e., E1), we find that NSCS and PS are rather secondary sources although they were long believed to be the dominant ones (e.g., Chen 2004; Chow et al. 2008). Regarding the middle to lower reaches of the Yangtze River basin, it turns out that INSC and SWC are the leading sources, followed by IDC, BoB, and AS (Fig. 3b, Table 1). This finding is against the traditional view that the most dominant moisture suppliers are oceanic from either SCS and the western Pacific (Lau et al. 2002; Simmonds et al. 1999; Xu et al. 2003) or BoB and AS (Qian et al. 2004; Xu et al. 2008). While the Indian subcontinent was thought to be a passive moisture

sink (Sun and Wang 2015), we show that it can actually be an active source for the downwind rainfall over East Asia.

The derived SR network in the present study contributes to the emerging viewpoint that terrestrial sources are more important than oceans for the wet season rainfall in regions including the middle to lower reaches of the Yangtze and Yellow River basins, the Korean Peninsula, and North China (van der Ent et al. 2010; Wang and Chen 2012; Keys et al. 2014; Wei et al. 2012; Fremme and Sodemann 2019). Results in Wang-Erlandsson et al.'s (2018) work revealed that human land-use change in the Yangtze River basin could impact the annual precipitation downwind in the direction of Japan and the Korean Peninsula, which supports our finding of the non-negligible moisture allocation among subregions (Figs. 3c,e).

FIG. 10. The difference in the composites of Z850 (shaded) and IVT (vector) during heavy rainfall days in E1 in the wet season between the context of preceding wintertime El Niño and that of the neutral state. All shaded contours and vectors shown are statistically significant at the 0.05 level (two-sample t test).

They also mentioned that India acts as a moisture source that contributes to about 10% of the river flow change in the Yangtze River basin (Wang-Erlandsson et al. 2018), which is somewhat consistent with our derived SR network (Fig. 3b, Table 1). Recognizing the nontrivial hydrological impacts among terrestrial regions of ever-growing urbanization and global warming, international governance and cooperation in land-use change, and water management in the upwind region could be crucial for mitigating the risk of freshwater scarcity in the downwind precipitation area (Keys et al. 2017; Wang-Erlandsson et al. 2018).

On the other hand, the SR network's intraseasonal variations are not well explored and remain debatable in the literature. Wei et al. (2012) reported that primary sources for the middle to lower reaches of the Yangtze River basin were SCS and the western Pacific from April to May, then BoB from June to July, and last, all of the three sources from August to September. Our findings, by contrast, reveal the leading southwesterly and southeasterly sources in the early and late wet season, respectively (i.e., the SW–SE source swing), which is in good agreement of the observations in Wang et al. (2018a). The discrepancy with Wei et al.'s (2012) finding may stem from the MERRA reanalysis data adopted in their work, which have been known to underestimate the lifetime of atmospheric water vapor due to the overintense water cycling in the model (Trenberth et al. 2011). As a side note, Zhong et al. (2019) confirmed that competition between the southwesterly and southeasterly transports explains the interdecadal shift in summer precipitation over South China in the late 1990s. Therefore, we argue that the SW–SE source swing could be a crucial process for the EASM rainfall variability on both intraseasonal and interdecadal time scales.

Some insights can be drawn from recent studies on the SR network of eastern China using DRM (Zhong et al. 2019; Wang et al. 2018a). Wang et al. (2018a) concluded that the southern Indian Ocean's contribution is dominant over BoB and AS for the middle to lower reaches of the Yangtze River basin in boreal summer, which differs from our findings (Fig. 4b). The inconsistency may stem from the 40-day maximum tracing period in their model setup (by which their model attributed at least 90% of the precipitation), which could inevitably oversample the atmospheric moisture given the two-week average residence time. Recognizing the 2D framework of the DRM, a trade-off for an adequate tracking time between a reasonable SR network and a sufficiently high recycling ratio becomes critical. In fact, the slope of the recycling ratio starts to flatten when the tracking time is greater than 10 days (see Fig. 8a in Wang et al. 2018). As such, we suggest that for a reasonable SR network, an adequate tracking period in DRM is perhaps two weeks, by which the model can maintain a sufficiently large fraction (~70%) of the recycling ratio without oversampling. Besides that, the strength of local recycling can be sensitive to the definition of a sink region. For example, Zhong et al. (2019) concluded that local recycling (16%) was one of the main sources in South China, while the area of which covers the high-contributing Southwest China region as found in this study.

Previous studies confirmed the profound influence of the zonal oscillation of WNPSH on the EASM rainfall (Ren et al.

2013; Cheng et al. 2019; Mao et al. 2010; Chow et al. 2008; Dai et al. 2020). Beyond that, we suggest that the NW- and NE-type pressure dipoles that include the WNPSH phases could offer predictability on the affected moisture supply routes and thereby the associated SR pairs [section 3d(1)]. In fact, we are no stranger to the NW-type dipole since it is traditionally known as the Asian continental low and the oceanic WNPSH driven by the land–sea thermal contrast (Wang and LinHo 2002). The NE-type dipole may, however, not originate from the Pacific–Japan (PJ) pattern (Kubota et al. 2016). The NE-type dipole propagates to the west (e.g., Fig. 6a2) while the PJ pattern is known to feature a meridional oscillation (Nitta 1986, 1987). We believe the NE-type dipole is more related to the tripole pattern of moisture reallocation regulated by the WNPSH phases discussed in our previous study (Cheng et al. 2019). In any case, knowledge about the type of the synoptic-scale pressure dipole and other coupled circulations would provide predictability on the strength of the affected SR pair and the rainfall, as exemplified in Lu et al. (2013).

5. Conclusions

This paper presents a novel perspective of the SR network derived by the physically based DRM to understand the atmospheric water cycle and the monsoon dynamics during the wet season in East Asia. Key findings are summarized as follows.

- 1) Agreeing with the merging viewpoint in the research community, terrestrial sources can be equally or more competitive than oceans for multiple EASM land regions especially the middle to lower reaches of the Yangtze and Yellow River basins, the Korean Peninsula, and North China. High-contributing terrestrial sources for several EASM land regions downwind (i.e., a one-to-many linkage) include the Indian subcontinent, Indochina, Southwest China, central China, the eastern Tibetan Plateau, and northern Eurasia. These vital terrestrial sources are sustained by the prevailing southwesterly monsoons across basins during the wet season, and were, however, often overlooked in the past and deserve further investigation for validation.
- 2) The SR network generally undergoes an intraseasonal change during the wet season. The “SW–SE source swing” is proposed to generalize the salient and systematic shift in the network. It documents the phenomenon that the southwesterly and southeasterly sources for an EASM subregion alternately dominate the moisture supply in the early and late wet season, respectively. Such a swing in dominant sources can be recognized in the SR network of the South China mainland and Taiwan, the middle to lower reaches of the Yangtze River basin, and southern Japan. The southwesterly monsoons and the late-summer tropical cyclones are likely responsible for the SW–SE source swing.
- 3) The structure of the SR network during heavy rainfall days mostly follows its climatology for nearly all subregions. Yet, climatologically primary sources are believed to trigger the heavy rainfall events given their enhanced contributions and high correlations (0.75 on average) with the rainfall.

TABLE A1. List of acronyms.

Acronym	Explanation
AS	Arabian Sea
AUS	Australia
BoB	Bay of Bengal
CC	Central China
DRM	Dynamical recycling model
E1	South China mainland and Taiwan
E2	Mid-lower reaches of the Yangtze River basin
E3	Southern Japan
E4	Mid-lower reaches of the Yellow River basin
E5	Korean Peninsula
E6	North China
ET	Evapotranspiration
EAF	Eastern Africa
EIO	Eastern Indian Ocean
ETP	Eastern Tibetan Plateau
EASM	East Asian summer monsoon
EURA	Eurasia
ENSO	El Niño–Southern Oscillation
MC	Maritime Continent
ME	Middle East
NP	North Pacific
NSCS	Northern South China Sea
IDC	Indochina
IVTA	Vertically integrated water vapor transport anomaly
INSC	Indian subcontinent
RC	Russia–China
SR	Source–receptor
SP	South Pacific
SOJ	Sea of Japan
SWC	Southwest China
SSCS	Southern South China Sea
TP	Tibetan Plateau
TPO	Tropical Pacific Ocean
P	Precipitation
PS	Philippine Sea
PW	Precipitable water
WIO	Western Indian Ocean
WNP	Western North Pacific
WSC	Wet season climatology
WNPSH	Western North Pacific subtropical high
WNPSH+	Positive WNPSH phase
WNPSH−	Negative WNPSH phase
YSECS	Yellow Sea and East China Sea
Z200A	Geopotential height anomaly at 200 hPa
Z850A	Geopotential height anomaly at 850 hPa

Hence, accurate simulations on moisture transport and evapotranspiration from these highly correlated and contributing sources are essential for weather forecasts.

- 4) The WNPSH phases and tropical cyclones are crucial in modulating the SR network for the EASM land regions. Their impacts are twofold: the WNPSH+ tends to fortify the moisture supply from the Indian basin and across the Yun-Gui Plateau, while it weakens contributions from the Pacific sources, and vice versa for the WNPSH− or tropical cyclones. Knowledge about the coupled circulations would

provide predictability on the strength of the affected sources in the SR network. Also, we find an upper-level wave train from western Russia to eastern China in the week before the heavy rainfall days. Such a wave train phenomenon is significantly correlated with the SR pairs linking the INSC, ETP, and TP with sink regions from E2 to E6. The wave train highly resembles the RC pattern documented in a recent study (Dai et al. 2020), the cause of which requires further research.

- 5) Last but not least, ENSO events in the preceding winter could lead to a lagged response of the SR network in the following wet season. In the context of the preceding wintertime El Niño, an anomalous high pressure band encompassing Indian and Pacific basins is triggered in the following warm season. Amidst the pressure band, the anomalous anticyclones over the northern Indian Ocean and the WNPSH+ over the Philippine Sea promote (weaken) moisture transport from the Bay of Bengal, Indian subcontinent, and Southwest China (Pacific sources). With the preference for the southwesterly source contribution in the SR network, this may favor devastating rainfall in late spring and early summer in accord with the SW–SE source swing.

On the interpretation of the SR network presented here, one should be reminded that water in the land regions must be supplied by oceans sometime before, as oceans are the ultimate reservoir for the water on Earth (Numaguti 1999). For this reason, land sources mostly serve as temporary water storage and intermediate suppliers for rainfall downwind. Besides, the network is solely based on the results from DRM, uncertainties of which intrinsically stem from the 2D Lagrangian framework (Tuinenburg and Staal 2020) and the well-mixed assumption (Goessling and Reick 2013; Dominguez et al. 2006). The results, to some extent, also depend on the quality of the input dataset, the maximum tracing period, and the definitions of the sink and source regions. Despite these uncertainties, the main features of the SR network for the EASM subregions should be largely unveiled for the first time. Validations of the network using 3D moisture tracing models may be necessary.

The SR network and the attributable circulations presented in this study advance the understanding of the atmospheric water cycle associated with the EASM and offer insights to model evaluation. Plus, given the impacts of the upwind terrestrial sources in the downwind precipitation and the extreme weather foreseeable under global warming (e.g., more devastating droughts), international coordination between countries in the upwind and downwind area upon the issue of land-use and water management could be crucial for natural freshwater resources in the future.

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APPENDIX

List of Acronyms

Table A1 provides expansions of acronyms.

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