East Asia Atmospheric River catalog: Annual Cycle, Transition Mechanism, and Precipitation

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Abstract
An all-season East Asia Atmospheric River (EA AR) catalog is constructed based on PanLu2.0. The annual cycle of EA AR exhibits eight stages, synchronizing with the seasonal-to-subseasonal variation of precipitation and their associated atmospheric steering. Particularly, extension of the western North Pacific subtropical high (WNPSH) to south China sea, due to the springtime east-west thermal contrast, steers ARs over Southeast China (SEC), inducing spring precipitation. During the Asian summer monsoon season, the spatial variation of the AR main route echoes the northward displacement of WNPSH, coincides with the prevailing monsoonal wind onset and stepwise propagation of rain belt. The warm moisture-laden air of the wintertime ARs confronts the dry and cold air over SEC, contributing to the winter precipitation. ARs offer substantial potential predictability of (heavy) precipitation days over the midlatitude from the late spring to early summer, and over SEC and south Japan from late winter to early spring.

Plain Language Summary
We construct an East Asia Atmosphere River catalog using our newly updated algorithm. We find that EA AR exhibits an interesting eight-stage annual cycle. Each stage presents frequent AR regions coinciding with seasonal-to-subseasonal precipitation changes and underlying atmospheric circulation patterns: in the spring, the western North Pacific subtropical high steers ARs over southeast China and bring the spring precipitation; during the summer monsoon period, AR frequent regions march with the northward displacement of the western North Pacific subtropical high, together with the stepwise propagation of rain belt; while wintertime ARs convey moist and warm air that confronts the dry and cold air over southeast China, contributing to the winter precipitation. We find that ARs offer potential predictability of (heavy) precipitation days over midlatitudes, southeast China, Japan, and Korean Peninsula. We believe that this study serves as a step-forward to bridge the role of AR in precipitation to the underlying atmospheric dynamics.

1. Introduction
Atmospheric rivers (ARs) are filamentary-shaped transient corridors with intensive horizontal moisture transport in the lower troposphere (American Meteorological Society, 2017). In recent years, ARs have received increasing scientific attention, leading to various studies that advance identification algorithms (Shields et al., 2018), investigate their climatic modulation (Guirguis et al., 2018; Pasquier et al., 2019), and assess their influence in global water cycle and hydrological extremes (Kamae et al., 2017; Paltan et al., 2017).

To conduct a comprehensive study of ARs, the upmost step is to construct an AR catalog based on a robust and resistant AR identification algorithm. Dozens of AR identification algorithms are available (Shields et al., 2018), varying in their target regions, tracking variables (vertically integrated moisture transport [IVT] or vertically integrated moisture content [IWV]), intensity thresholds, and geometric criteria. Recently, various advanced algorithms are developed that target broader regions (e.g., North Pacific and globe), consider the large spatiotemporal variability of IVT/IWV

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uncertainties brought by diverse AR algorithms in the AR scientific community (Rutz et al., 2019; Shields et al., 2018).

Despite rapid development in AR identification algorithms, significant gaps remain. First, notwithstanding some progress in distinguishing TC-like features (Mundhenk et al., 2016; Pan & Lu, 2019), failures are still reported when the TC-like feature occurs as a partition of AR. Second, a robust method distinguishing TMFs from ARs is still lacking, which is critical for studies covering the tropics (Brien et al., 2020). Third, as a large-scale phenomenon, partitions of an AR are likely affected by different systems and processes (e.g., monsoon, extratropical cyclones [ECs], TC-like features, and localized perturbation) and have distinct features (e.g., varying IVT intensity and IVT coherence), especially for ARs with varying shape, orientation, and curvature. So it is necessary to parse the structure of an AR when studying its underlying mechanism and hydrological impact.

East Asia (EA) often suffers enormous socioeconomic loss due to hydrological extremes. Multiple studies (Guan & Waliser, 2015; Kamae et al., 2017; Paltan et al., 2017; Pan & Lu, 2019) corroborate the importance of ARs in the hydrological extremes over EA. Hitherto, studies targeting the EA AR are in pieces, even a climatological study is still missing. For example, Pan and Lu (2019) presented a novel AR identification algorithm, which adapts to the peculiarly complex EA climate system and revealed an AR main route accountable for the flood triggering extreme precipitation over the Yangtze River Basin (YRB). It originates from the Arabian Sea (AS), Bay of Bengal (BOB), and South China Sea (SCS) to Southeast China (SEC) and terminates in North Pacific (NP). In fact, this main route has been captured in part by other recent studies over Asia, for example, South Asia component by Yang et al. (2018) and western North Pacific (WNP) segment by Kamae, Mei, Xie, Naoi, and Ueda (2017)). A comprehensive study addressing the climatology, hydrological impact, and underlying mechanism of EA AR is urged.

There is no need to repeat the importance of enhanced moisture transport (e.g., ARs) to regional hydrology as evident by numerous studies in various regions around the world (Cheng et al., 2019; Gorodetskaya et al., 2014; Lu et al., 2013; Lu & Hao, 2017; Lu & Lall, 2017; Najibi et al., 2017, 2019). Many studies evaluate the contribution of ARs to hydrological events by calculating the fraction of AR-related events (e.g., Nayak & Villarini, 2017; Paltan et al., 2017), but the analysis suffers from its sensitivity to the definitions of AR and AR-related event. For instance, the fraction will very likely increase, if one defines an AR and a hydrological event in the vicinity as related, rather than restricting them to be co-located, or when more ARs are identified when lower threshold is applied. To say the least, high AR-related fraction does not translate to high predictability. Although potential predictability of precipitation informed by ARs has been a great interest of the AR community, very few have done beyond the veneer exemplified above (Chen et al., 2018).

In line with the aforementioned limitations, we first update our algorithm (PanLu2.0) from PanLu1.0 (Pan & Lu, 2019). A 40-year EA AR catalog is thus constructed. In section 3, the eight-stage annual cycle of EA AR is presented with the diagnosis of diverse climatic modulation and rainfall pattern among different stages. The potential predictability of precipitation days (PD) and heavy precipitation days (HPD) informed by AR is assessed in section 4, with the diagnosis of antecedent circulation pattern.

2. PanLu2.0 and EA AR Catalog

2.1. Data

All meteorological variables are retrieved from ERA5 reanalysis (Hersbach et al., 2019) from 1979 to 2018, with a 0.25° × 0.25° and 6-hourly resolution. The definition of vertically integrated zonal, meridional, and total water vapor transport (IVT, , IVT, , and IVT) and IVT direction (θ) follow those in Pan and Lu (2019), with a finer vertical resolution (137 model levels in ERA5). The 850 mb zonal and meridional winds (UV850), 850 mb geopotential height (Z850), and precipitation are used to investigate the associated circulation and precipitation predictability. The anomalies (e.g., Z850A and UV850A) are computed as the departure from the 5-day-moving-mean climatology in 1979–2018.

2.2. PanLu2.0

PanLu2.0 is updated from PanLu1.0 that is originally developed in Pan and Lu (2019). Two major improvements are presented here, with the other four minor improvements included in the supporting information. In order to differentiate TMFs (located in the tropics and without substantial poleward moisture transport)
from AR, some attempts were made by using either IVT direction or AR location (Guan & Waliser, 2015; Mundhenk et al., 2016). Unfortunately, if referring to the IVT direction only (Guan & Waliser, 2015), some midlatitude ARs are mistakenly removed when their moisture transports are mainly zonal. On the other hand, if referring to the AR location only (Mundhenk et al., 2016), ARs originated from south Asian summer monsoon (SASM) region and with substantial poleward moisture transport (Pan & Lu, 2019) will be discarded mistakenly. Besides, seasonal movement of ITCZ is not considered in that AR location criterion. In light of these, PanLu2.0 implements a two-step criterion to distinguish TMFs from AR. First is to eliminate pathways located in the tropics in spite of the movement of ITCZ (i.e., \( P_{\text{tropics}} \geq 95\% \); the \( P_{\text{tropics}} \) is the percentage of tropical grids [20°S–20°N] in the AR pathway), to remove enhanced moisture transports that have marginal extratropical components despite of their IVT directions. Next, we further filter the remaining pathways to remove those mainly living in the tropics (50 % < \( P_{\text{tropics}} \leq 95\% \)) with limited poleward component (≥50% of their grids with absolute values of IVT direction (\( \theta \)) smaller than 15°, i.e., \( \text{perl}(\theta < 15^\circ) > 50\% \)). Our results show that the second step successfully preserves the extratropical moisture transports induced by SASM and eliminates the TMFs around 20°N in the central Pacific. A comprehensive sensitivity test of the second step is provided in the supporting information.

Our second major improvement responds to the call by the third ARTMIP workshop (Brien et al., 2020) to identify different “flavors” of ARs that are controlled by diverse physical mechanisms and weather systems, such as subtropical high, subpolar low, TC-like features, ECs, monsoon, and localized perturbation (Hu et al., 2017; Kamae, Mei, Xie, Naoi, & Ueda, 2017; Xiong et al., 2019; Zhang et al., 2018). Our experience strongly suggest that one AR event might possess multiple “flavors” carried by different AR segments, that is, one AR event might encounter a number of systems that modify its segmental geometric and dynamic features. Therefore, we employ a series of procedures to parse the structure of ARs. First, a novel AR metric (\( \text{IDR}_o \)) is harnessed to quantify the localized IVT coherence. For each grid on the AR pathway, the \( \text{IDR}_o \) is defined as the interdecile range (IDR) of the IVT directions (\( \theta \)) of its continuous neighborhood grids within 500 km, where IDR is the difference between the 90th and 10th quantiles. A grid with large/small \( \text{IDR}_o \) indicates that it has a discordant/coherent neighborhood. Second, in order to identify AR segments that are possible manifestations of different processes, we engage an image segmentation algorithm (Felzenszwalb & Huttenlocher, 2004) to divide an AR pathway into several segments by regarding the \( \text{IDR}_o \) as the image pixel value. Noted that we coarsen the \( \text{IDR}_o \) field to 1° × 1° resolution to reduce the computational cost.

Different segments’ “flavors” can be better distinguished by referring to their IVT intensity and \( \text{IDR}_o \). Segments that correspond to TC-like features (marked by red circles in Figures 1a and 1b) are often very discordant (rotation) and associated with strong moisture flux, that is, 50th quantile of \( \text{IDR}_o \) is greater than 90° (\( Q_{50\text{IDR}_o} > 90^\circ \)) and mean IVT intensity is greater than 750 kg m\(^{-1}\) s\(^{-1}\) (\( \text{IVT}_{\text{mean}} > 750 \text{ kg m}^{-1}\text{s}^{-1} \)). Previous trajectory-based algorithms (Pan & Lu, 2019), often overlook the TC-like features that locate in the boundary or only occupy a small portion of the AR pathway, because the AR trajectory (green curves in Figure 1) usually lies near the center of AR pathway. By referring to the \( \text{IVT}_{\text{mean}} \) and \( Q_{50\text{IDR}_o} \), this kind of TC-like features can be recognized more effectively. Moreover, discordant segments (\( Q_{50\text{IDR}_o} > 90^\circ \)) that locate in the midlatitude or even north often reflect midlatitude cyclones (marked by blue circle in Figure 1c), but the associated moisture flux is modest (\( \text{IVT}_{\text{mean}} \leq 750 \text{ kg m}^{-1}\text{s}^{-1} \)). If such discordant and modest segments occur over SASM region, it may indicate the occurrence of vortex which is often related to the onset of SASM (Wang, 2006) (marked by green circle in Figure 1b). We also find that the EC flavored segments translate their large-scale spiral features to slightly discordant IVT direction (e.g., \( Q_{50\text{IDR}_o} < 90^\circ \) and \( Q_{90\text{IDR}_o} > 60^\circ \)) (marked by pink ellipses in Figure 1d). In our EA AR catalog (section 2.3), majority of the segments (79.3%) are coherent (i.e., \( Q_{90\text{IDR}_o} < 60^\circ \)) as expected, as they correspond to well-organized long-haul moisture transports. When an AR is composed of coherent segments only (Figures 1e and 1f), it conforms to the general definition of AR (i.e., long and narrow corridors with enhanced moisture transport) and is often governed by large-scale steering systems and closely related to the occurrence of hydrometeorological extreme. As illustrated by Lu et al. (2013), persistent large-scale circulation systems are more likely to govern long-distance intensive moisture transport and offer considerable predictability to persistent extreme precipitation events. Such close relationship is also exemplified in Dai et al. (2020), Lu et al. (2013), and Lu et al. (2016). We believe that distinguishing these systems and thus understanding the underlying physical mechanism are tantamount to the identification of AR. Therefore, we mark these features in the
AR catalog instead of discarding them directly to provide future utilities for others. Likely, AR scientific community might consider this as a possible starting point to explore the interaction between AR and different systems (e.g., TCs and ECs) and their combined hydrological impacts.

2.3. EA AR Catalog

An all-season EA AR catalog is constructed for all the AR events pass 20°S–60°N and 100°E–150°E during 1979–2018. The catalog is composed of 212,378 AR segments, 51,788 AR slices (6-hourly snapshots) and 5,080 AR events. A whole spectrum of AR metrics can be calculated. We select some to be included in our EA AR catalog. Classic AR metrics include length, width, length-width ratio, IVT intensity, total area, area over land, IVT direction, and sum of turning angle (PanLu1.0). We would like to remind future studies that analysis on orientation should be done with caution, as we notice that the orientation (Guan & Waliser, 2019; Mundhenk et al., 2016) is ineffective to describe ARs with large curvature (e.g., Figure 1d).

Figure 1. Examples of AR segmentation with the IDRθ (shading), segmentation result (scatter), and IVT field (vector). Red circles in (a) and (b) mark the segments corresponding to TC-like features. Blue circle in (c) marks the segment related to midlatitude cyclone. Green circle in (b) marks the segment corresponding to the vortex over SASM region. Pink ellipses in (d) mark the segment related to the EC. Green curves are the AR trajectories. Panels (e) and (f) are the examples of ARs whose segments are all coherent.
and Figure S4 in Pan & Lu, 2019). Second, localized metrics are generated to probe into the structure of AR. We include IDR to describe the localized IVT coherence, turning angle series to capture the AR curvature (PanLu1.0). Third, the segmental metrics are the statistics of localized metrics for AR segments, such as quantile of IDR, IVT mean intensity (section 2.2), and sum of turning angles. In addition, event-based metrics (duration, propagation speed, propagation direction, and accumulation of IVT intensity; Chen et al., 2018) are also found helpful to study AR life cycle from genesis, propagation to termination. It is believed that such an AR catalog will assist future study of the underlying dynamic and thermodynamic processes associated with different segments or life stages of AR, as well as its hydrological impact under future climate change. Notably, the PanLu2.0 is ready for global AR detection. In September 2019, we joined the ARTMIP project (Shields et al., 2018) and contributed the AR global catalog (available at http://www.cgd.ucar.edu/projects/artmip/).

3. Eight-Stage AR Annual Cycle and Their Transitional Mechanisms

We first investigate the climatological annual cycle of EA AR. Traditional annual cycle studies, which typically rely on predefined seasons or ad hoc periods (Kamae, Mei, & Xie, 2017; Mundhenk et al., 2016), may miss the intraseasonal variation, especially those during the Asian summer monsoon (ASM) season. To address this issue, we employ a neural network-based clustering algorithm (self-organizing map [SOM]; Kohonen, 1998) to divide the annual cycle into different stages according to the spatial pattern of AR-IVT intensity on each calendar day. The 3 × 3 configuration (nine clusters) is selected and details of the implementation is in the SI. As a result, we identify eight stages in the annual cycle (Figure 2) by defining the beginning/end of a stage as the first day of at least three continuous days in the same/next SOM cluster. As the interleaved Clusters 8 and 9 (25 November–11 March) exhibit indistinguishable spatial patterns (Figure S8) and large false discovery rate (Figure S4), we consider them as one stage (Stage 8).

The eight stages not only well capture the subseasonal evolution of EA AR but also notably synchronize with the seasonal-to-subseasonal (S2S) variations of precipitation and circulation patterns. In Stage 1 (12 March–15 May), ARs prevail over SEC and WNP compared to the wintertime, when ARs concentrate in the south of the Aleutian low (Figure 2a vs. 2h). Springtime east-west thermal contrast over the Indochina Peninsula (IP) and the WNP to the east of the Philippines results in deep extension of the Western North Pacific Subtropical High (WNPSH) to SCS (Cheng et al., 2019; Li et al., 2018; Tian & Yasunari, 1998). The resulting intensive southwesterly over the northwestern flank of WNPSH is likely the key to the intensification of springtime ARs over the SEC and render precipitation. In Stage 2 (16 May–10 June), ARs emerge in the SCS, IP, and BOB and further intensify over northwest flank of WNPSH. The WNPSH retreats eastward but intensifies toward the northwest, leaving the SCS a void for intensive southwesterly, strengthening ARs over northwest flank of WNPSH, in line with the onset of EASM prevailing wind over SCS and presummer rainfall over south China (Ding & Chan, 2005; Ho & Wang, 2002). Compared to the northwest flank of WNPSH, the moderate AR-IVT intensity over south China may be attributable to the moderate southwesterly at the early stage of EASM and the moisture releasing due to the presummer rainfall. Stage 3 (11 June–1 July) marks the peak AR season, that is, the AR-IVT intensifies significantly almost over the entire AR main route (Pan & Lu, 2019). The further northward shift and intensification of WNPSH steers the AR main route northward to south Japan and YRB, coincide with the grand intensification of monsoon flow over the ASM region and the commencement of Meiyu/Baiu rainy season and Indian rainy season (Ding & Chan, 2005). Note that the terrestrial AR-IVT intensity (i.e., over India Peninsula, IP, Hainan island, and Taiwan) is significantly weaker than the adjacent sea, while the wind field remains barely changed, which implies substantial moisture releasing by rainfall when ARs make landfall. In Stage 4 (2 July–22 July), we observe a northward shift of the AR main route and a sudden weakening of the ARs over south China, responding to the second northward jump of WNPSH, commencing the Changma rainy season over the Korean Peninsula (KP), and possibly heralding the end of the presummer rainy season over south China (Wang, 2006). AR weakens in Stage 5 (23 July–15 August), with the main route advancing further north, marching with the northward progression of EASM flow, rain belt to northeast China and the break of Meiyu/Baiu rainy season. As Asian monsoon begins to withdraw and the monsoon rain belt disappears, extensive weakening of AR starts in Stage 6 (16 Aug–9 September) and lasts until Stage 7 (10 September–24 November), when AR enters the weakest stage in a year, and mainly locates over the NP.
Last but not least, in Stage 8 (25 November–11 March), there is modest intensification of AR over the NP, embedding in the East Asia winter monsoon (EAWM) flow, that is, the intensive northwesterly governing by the Siberian–Mongolian High and Aleutian Low (Wang, 2006). Meanwhile, the ARs over SEC are accompanied by southwesterly, later merging with the prevailing northwesterly around coastal eastern China (Figure 2i). Huang et al. (2019) and Yang et al. (2019) found that the moisture of winter extreme precipitation events is mainly supplied by the moisture flux across the southern and western boundary of east China, in line with a warm anomaly contributed by the warm advection emerging over south China before the onset of winter precipitation. All suggest the crucial role of warm moisture-laden air brought by the ARs from the southwest in the wintertime precipitation when dry and cold EAWM prevails, which is further corroborated in section 4.

4. Potential Predictability for Precipitation Day

For each stage and each grid, the Pearson’s product moment correlation \( r \) (Kornbrot, 2014; Lu et al., 2016) is calculated between binary time series of the AR days (ARD) and precipitation days (PD) or heavy precipitation days (HPD), respectively, to explore potential predictability of precipitation occurrence. At each grid, based on the 6-hourly EA AR database and precipitation record, ARD = 1, when AR appears at least two time steps (not necessarily consecutive); PD = 1 when precipitation exceeds 1 mm; and HPD = 1 when precipitation exceeds the 80th quantile (Q80) of the wet days’ (PD = 1) in the calendar month. The substantial spatial variability of the Q80 values in each month is shown in Figure S9, with the sensitivity test on the HPD threshold (w.r.t. Q80) in Figure S10.

During the first three AR warm stages (12 March–1 July), the occurrences of both PD and HPD are considerably correlated with the presence of AR over the entire EA (Figures 3a and 3b). Especially in the north of
the AR main route (30°N–40°N), the presence of AR is highly correlated with the occurrence of heavy precipitation. While only moderate correlation is found over regions directly beneath the AR main route. When AR flows over South Korean and Japan (the blue box in Figure 3c1–c3), a zonal pressure dipole is observed, and steers AR between the pressure centers into the north. The warm and moisture-laden air encounters abrupt drop of temperature, leading to condensation in areas of convergence. The presence of

Figure 3. Product moment correlation map between ARD and PD/HPD with the AR frequency and associated circulation pattern. The first/second columns are the grid-based correlation maps (shading) between ARD and PD/HPD for Stages 1–3 and 8, with AR frequency contour. All correlations are statistically significant at the 10^{-4} level. The third column is the composite maps of Z850A (contour) and UV850A (vector) when AR pathway overlaps the target regions (blue or red box), where we observe the correlation between HPD and ARD peak in the second column. The colormaps in the third column represent the frequency of ARs passing the target region.
such favorable antecedent weather condition may explain the strong correlation between the ARD and HPD over South Korean and Japan. Also, the difference between Japan, South Korean, and their marginal sea area suggests that landfalling AR is more associated with heavy precipitation.

During the extended AR cold stage (Stage 8, 25 November–11 March; late winter to early spring), notable correlation (r > 0.4) under the AR main route (opposite to that of Stages 1–3) ratifies the substantial role of AR in the winter precipitation despite of the relatively low AR frequency. When AR flows over SEC (the red box of Figure 3c4), the low-level convergence (Z850A-) encourages the collision of the warm and moist southwestely with the cold and dry northeasterly, likely resulting in winter precipitation underneath. During Stage 4 (2 July–22 July), the association weakens overall: It almost disappears over SEC, some sustained in Korean Peninsula and South Japan, which is in line with the northward shift of rain belt during the Changma rainy season. The correlation continues to deteriorate during the AR hiatus (Stages 5 and 6; 23 July–9 September), implying that the revival of EASM rainfall after late July has barely any association with ARs. The correlation analysis results of Stages 4–7 are provided in the Figure S11.

The above analysis suggests that apart from directly underneath the AR pathways, rainfall may also be induced near the AR banks. In order to verify this hypothesis, we extend the correlation analysis to relate the AR coverage over the neighborhood to the PD/HPD grid. The AR coverage is calculated as the percentage of grids in the neighborhood that is overlapped by any AR pathway. The correlation deteriorates rapidly with lead time (result not shown). The presence of AR has more immediate effect on the occurrence of precipitation and heavy precipitation over regions with favorable circulation patterns that encourages convergence and/or steers northward propagation of ARs that lead to condensation.

5. Summary and Discussion

In this study, an all-season EA AR catalog is delivered based on our updated PanLu2.0. To filter the TMFs, a robust and resistant criterion is implemented, which considers both IVT direction and AR location and provides a significant step-forward for AR study especially for those covering the tropics that received limited attention previously (Brien et al., 2020; Rutz et al., 2019). In order to probe into the AR structure, a novel AR metric (IDRθ) is proposed to capture the localized IVT coherence and a segmentation algorithm is employed to divide AR into segments. Different “flavors” of AR segments corresponding to diverse weather systems (e.g., TC-like features and ECs) can be identified by the segmental metrics (i.e., IVTmean and quantile of IDRθ) and flagged in this catalog. It is believed that various metrics provided in this catalog (including localized, segment-based, slice-based, and event-based) will facilitate the further investigation of AR in terms of recognizing different “flavors” of ARs (Brien et al., 2020), their underlying dynamic and thermodynamic processes and hydrological impact.

The eight stages of EA AR annual cycle well capture its S2S evolution, associated circulation, and precipitation pattern (i.e., the oscillation of WNPSPH, northward shift of ASM prevailing wind and rain belt, and the formation of winter and spring precipitation). Explored by the Pearson's correlation analysis, we find potential predictability of PD/HPD by the occurrence of ARs over the midlatitude (30°N–40°N) during the late spring to early summer (12 March–1 July) and over SEC and south Japan from late winter to early spring (25 November–11 March), which counterintuitively suggests that the regions/seasons with lower ARs are deserved to be further studied in the future. Besides the occurrence of AR, predictability may be further improved by involving the antecedent weather conditions manifested by diverse AR segments, such as strong convergence and front. Exploring the AR-related precipitation mechanism conditional on different “flavors” of AR segments will be our next target.

In this study, we take a climatological scan of the EA AR. Whereas numerous research topics emerge, such as the interannual, interdecadal and S2S variability of ARs, and associated environmental condition, which may provide more insight of the onset and oscillation of ASM and associated rainfall prediction. The slightly discordance between the IVT and UV850 field (Figure 2i) encourages a further look into the vertical profile and the upper-level modulation of ARs. During the ASM season, we find that AR is only partially affected by the monsoon flow. Thus, it would be interesting to examine the moisture budget by considering the role of
moisture convection, condensation, and releasing in the interplay of AR, ASM, and related precipitation. It is worth mentioning that negative correlation is observed near the Hainan island in Stages 1 and 2. We surmise that it is attributable to the moisture recharge when AR flows over SCS after releasing in IP. The recharge process might be stronger than the precipitation. The influence of AR to the precipitation near Hainan island and associated underlying mechanism is of regional interest.

Data Availability Statement

We thank ECMWF for providing access to ERA5 data (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5). Python codes of PanLu2.0 are available online (https://doi.org/10.5281/zenodo.3901537).

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