Atmospheric Rivers over the Indo-Pacific and Its Associations with the Boreal Summer Intraseasonal Oscillation

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ABSTRACT: Recent works have revealed that the wintertime atmospheric river (AR) activity is closely related to the 30–60-day tropical intraseasonal variability, yet it remains unclear whether summertime AR activity is also significantly influenced by intraseasonal variability, often referred to as the boreal summer intraseasonal oscillation (BSISO). Diagnosing the 40-yr (1979–2018) ERA5 reanalysis dataset, the present study examines the climatological features of ARs over the Indo-Pacific region during June–October and its associations with the BSISO. Results suggest that the western North Pacific subtropical high (WNPSH) provides a favorable circulation background for the summertime AR activity, which conveys the moisture from the tropics to the midlatitude North Pacific along its periphery. Our analysis reveals that the BSISO has substantial impacts on the occurrence and distribution of ARs. More ARs are found over the western North Pacific (WNP) when the BSISO convective envelope propagates northward to the subtropical regions, while fewer ARs can be seen when convection is suppressed there. Specifically, in phases 7–8, the active BSISO convection over the Philippine Sea induces a low pressure anomaly and the corresponding anomalous cyclonic circulation, leading to the enhanced poleward moisture transport and more frequent AR activity over the WNP. Moreover, the WNP ARs tend to be longer and have larger sizes during these two phases. It is also found that more frequent occurrence of tropical cyclones in phases 7–8 can significantly enhance the moisture transport and AR occurrence over the WNP.

KEYWORDS: North Pacific Ocean; Tropical cyclones; Atmospheric river; Intraseasonal variability

1. Introduction

Atmospheric river (AR), which is defined as a long, narrow, transient corridor of strong horizontal water vapor transport, often conveys plumes of moisture from the tropics and causes widespread detrimental water-related impacts (e.g., heavy rainfall, snow, disastrous flooding) when it makes landfall (Gimeno et al. 2014; American Meteorological Society 2017; Dettinger et al. 2020). On average, 11 ARs occur over the globe at any given time, while 2–3 ARs among them penetrate inland (Guan and Waliser 2015). The frequent AR occurrence and the subsequent detrimental impacts imply the importance of studies on ARs.

Recently various AR identification algorithms have been developed to address specific science research questions related to ARs over the globe or in some specific regions (Shields et al. 2018; Rutz et al. 2019). Most of these works focused on boreal wintertime as ARs in general are most pronounced in the winter months during which the extratropical cyclone is most prevalent (Ralph et al. 2004; Eiras-Barca et al. 2018; Zhang et al. 2019; Guo et al. 2020). However, our knowledge of

boreal summertime ARs remains shallow, in particular in terms of their mechanisms.

The frequency of AR occurrence varies greatly by regions and seasons (Mundhenk et al. 2016 (hereafter M16); Guan and Waliser 2019). In contrast with the ARs peaking in the cooler season in the eastern Pacific, ARs are most active during the warmer season over the western Pacific region (Guan and Waliser 2015; M16; Kamae et al. 2017a; Guan and Waliser 2019). Numerous studies have demonstrated that frequently occurred AR events have great impacts on the local weather systems, and some of them can induce heavy rainfalls and flooding disasters (e.g., Guan et al. 2010; Rutz and Steenburgh 2012; Waliser and Guan 2017; Kim et al. 2021). For example, Dettinger et al. (2011) found that the ARs are responsible for 20%–50% of the water supply over the west coast of North America. Particularly, a similar AR contribution to the rainfall is also found over East Asia, where the ARs tend to account for 14%–44% of the spring-to-autumn rainfall (Kamae et al. 2017b). Moreover, a recent study further suggests that up to 68% of the extreme precipitation amount over East Asia and 52%–56% over South Asia in summer were attributed to the ARs (Liang and Yong 2021). Another recent study showed that up to approximately 70% of the rainfall in the early East Asian summer monsoon over eastern China, the Korean Peninsula, and western Japan is associated with ARs (Park et al. 2021).

Previous studies have demonstrated that the western North Pacific subtropical high (WNPSH) plays an essential role in regulating the moisture transport and AR activity over the Indo-Pacific region (e.g., Kamae et al. 2017a, 2019; Naoi et al. 2020; Pan and Lu 2020; Zhao et al. 2021). For example, Kamae et al. (2017a) showed that the anomalous WNPSH

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accompanied by the southwesterlies can induce more ARs over its northwestern flank. Moreover, our recent study revealed that the moisture transport during the 2020 baiu season, the monsoonal rainy season in Asia (Kanada et al. 2012), was generally forced by the WNPSH, which also helped the moisture uptake over the subtropical regions (Zhao et al. 2021).

Besides the WNPSH, the factors responsible for the summertime Indo-Pacific AR activity are relatively complicated, because the local atmospheric condition can be greatly influenced by many phenomena that have different spatial and temporal scales. For instance, the relationship between the summertime western North Pacific (WNP) AR activity and the preceding-winter El Niño–Southern Oscillation (ENSO) event has been demonstrated (Kamae et al. 2017a; Naoi et al. 2020). Particularly, in terms of the intraseasonal time scales, some studies showed that the tropical intraseasonal oscillation, Madden–Julian oscillation (MJO), can modulate the AR life cycle during the wintertime (e.g., Ralph et al. 2011; Guan et al. 2012; Guan and Waliser 2015; M16; Zhou et al. 2021). Therefore, it is natural to expect that the summertime ARs may also be modulated by the most dominant component of the intraseasonal variability in boreal summer over the Indo-Pacific region, the boreal summer intraseasonal oscillation (BSISO) (Kikuchi et al. 2012; Lee et al. 2013; Kikuchi 2020, 2021). The BSISO is featured by northward propagation of convection trapped in the Indian and western Pacific monsoon regions, which significantly affects the spatial distribution of climate extremes over East Asia (e.g., Hsu et al. 2016).

In another aspect, the close association between tropical cyclones (TCs) and ARs has been revealed in some previous studies. Based on a case study, Yoshida and Itoh (2012) showed that the TC can directly affect the moisture transport through its outer circulation and indirectly induce heavy rainfall in the baiu frontal zone. Cordeira et al. (2013) analyzed two ARs and found that the AR formation over the WNP region is closely linked to the poleward transport of tropical water vapor from the TCs. More recently, Yang et al. (2018) found that 24% of ARs over the Bay of Bengal occur in the presence of TCs. Pan and Lu (2019) further found that the co-occurrence of ARs and TC-like features accounts for around 8% of the total AR cases. These findings imply that the TC may also be a critical factor affecting the moisture transport and subsequently the AR occurrence. Furthermore, Yoshida et al. (2014) revealed that the favorable phases of the BSISO vary for TC genesis over the WNP in different synoptic-scale flow patterns. Thus, it is of great importance to investigate how the summertime ARs are affected by the BSISO as well as by TCs.

The goal of this study is to gain a deep and comprehensive understanding of the climatological features and underlying causes of the summertime ARs in the Indo-Pacific region. As discussed above, some summertime Indo-Pacific ARs occurred simultaneously with the TCs nearby. It should be also noted, as discussed in section 2c, that the existing AR detection algorithms may have some issues when dealing with ARs in the presence of TCs, especially on those narrow moisture band induced by the outer circulation of TCs. Some recent studies have tried to handle such kind of ARs. For example, Pan and Lu (2019) employed a TC filtering method to detect TC-related

ARs, but their algorithm tends to simply remove the entire AR feature that includes both of the TC and AR portions. Guan and Waliser (2019) introduced a new TC filtering method in their refined algorithm, which can realistically isolate the TC and AR portions. In this study, to represent the summertime ARs that are connected to or coincide with the TC, we test and modify the M16 algorithm by introducing a different TC filtering criterion, which will be given in section 2c. Then two main questions will be addressed in this study: (i) what is the spatial distribution of the boreal summer ARs over the Indo-Pacific under the influence of BSISO; and (ii) what are the possible physical mechanisms by which the BSISO affects ARs, if any?

This paper is organized as follows: section 2 describes the data and methods including the modified AR detection algorithm. Section 3 presents the climatological features of summertime Indo-Pacific ARs and its associations with the BSISO; furthermore, the underlying dynamic background for BSISO modulation on ARs is also analyzed. The role of TC on AR activity will be presented in section 4. Finally, section 5 gives the conclusions and future work.

2. Data and methods

a. Data and analysis method

To identify the ARs and to investigate its related atmospheric conditions, we used the 6-hourly ERA5 reanalysis dataset (Hersbach et al. 2020) from 1979 to 2018 with a spatial resolution of 0.25° . In addition, to apply a new TC-related criterion in the AR detection algorithm and explore the impacts of TCs, the Regional Specialized Meteorological Center (RSMC) Tokyo best track analysis data are used, which include TC name, latitude and longitude location of the TC, TC central pressure, and maximum sustained winds at 6-hourly intervals. The Student's *t* test is employed to determine the statistical significance. In this study, the boreal summer season is defined from June to October (i.e., JJASO), and our analyses were applied to 40 years from 1979 to 2018.

b. BSISO indices

The BSISO index developed by Kikuchi et al. (2012) is used to represent the state of the BSISO, which is described by the first two leading principal components (PC1 and PC2) of the outgoing longwave radiation (OLR) mode based on extended empirical orthogonal function analysis. The phase composites in this study are based on the active BSISO events, which are defined as the BSISO amplitude $\sqrt{PC1^2 + PC2^2}$ exceeding 1.0, and the eight BSISO phases are defined following Kikuchi et al. (2012).

Using the daily National Oceanic and Atmospheric Administration interpolated OLR dataset, we apply a 25–90-day Lanczos bandpass filter (Duchon 1979) to extract the intraseasonal oscillation signal. Figure 1 illustrates the composite maps of 25–90-day filtered OLR anomalies for life cycle (eight phases) of the BSISO during JJASO 1979–2018. During phases 1–4, an enhanced convection center over the equatorial Indian Ocean (IO) propagates northward and eastward toward northern IO and the Maritime Continent

FIG. 1. Composites of the 25–90-day filtered OLR anomalies (shading and contours) in eight BSISO phases during JJASO 1979–2018. The contour interval is 3 W m^{-2} , and the zero contour is omitted. The number of days in each phase composite is shown at the top right of each panel.

(Figs. 1a–d). In phase 5, a suppressed convection center appears over the equatorial IO (Fig. 1e). Meanwhile, negative OLR anomalies display a northwest–southeast-tilted pattern covering a large area extending from the northern IO to the equatorial western Pacific, indicating the enhanced convective activity over these regions. After that, the enhanced convection center over the Maritime Continent propagates northward to the South China Sea (SCS) and Philippine Sea during phases 6–8 (Figs. 1f–h).

c. Identification of ARs

The variables that are commonly used to detect the ARs are integrated water vapor (e.g., Ralph et al. 2004; Dettinger 2011) and integrated water vapor transport (IVT; e.g., M16; Guan and Waliser 2019). In this study, ARs are detected based on the IVT, which can reflect the dynamic processes of ARs by incorporating wind and moisture (Rutz et al. 2019). According to the previous studies (e.g., Kamae et al. 2017a), IVT is defined as

$$\text{IVT} = \sqrt{\left(\frac{1}{g} \int_{1000}^{300} q u dp\right)^2 + \left(\frac{1}{g} \int_{1000}^{300} q v dp\right)^2}, \quad (1)$$

where g is the acceleration due to gravity (m s^{-2}), q is the specific humidity (kg kg^{-1}), and u and v are the zonal and meridional wind components (m s^{-1}), respectively.

So far, many algorithms have been used to detect the AR features over the Indo-Pacific region (e.g., Guan and Waliser 2015; M16; Pan and Lu 2019). As shown by the results from Atmospheric River Tracking Method Intercomparison Project, compared with most other methods, based on IVT anomalies, the M16 algorithm tends to produce AR features much closer to the all-method median (see Fig. 15 in Rutz et al. 2019). In addition, this algorithm has been used in some studies related to AR activity over the WNP (e.g., Kamae et al. 2017a,b; Naoi et al. 2020). Thus, we employed the M16 algorithm in this study for AR detection, and a static IVT anomaly threshold is also applied during the procedure. The original M16 algorithm tends to retain the AR-like features associated with transitioning/recurring TCs but filter out that related to the conventional TCs. However, as mentioned in the introduction, some TCs always occur together with a narrow moisture plume, which is most probably an AR (e.g., the “tail” of the comma-like feature within the black dashed box in Fig. 2e). To retain such TC-related AR features, Guan and Waliser (2019) detected the AR that has a ring-shaped axis at first,

FIG. 2. An example of the ability of the modified algorithm to identify the AR-like features at 0000 UTC 10 Jul 2015: (a) IVT (shading), (b) IVT anomalies (shading) and detected features (red line), (c) detected features after removing the round features that are generated by TCs based on the best track TC centers (green dots) and 800-km radius (blue dashed circles), (d) detected features after removing small blobs less than 500 contiguous grid points, and (e) retained AR-like features. (f), (g) Enlarged details of the ARs shown within the orange and black dashed boxes in (e), respectively. The axis used to determine the AR length is highlighted in green in (e), (f), and (g).

and then removed the circular portion of the IVT object (i.e., TC portion) and finally retained the AR portion (see their section 2.2 and Fig. S3 in the online supplemental material). In our study, we directly use the TC best track dataset to isolate the main body of TC and its “tail” (narrow moisture plume), and then retain the latter one.

The procedures for detecting ARs are as follows:

- 1) calculate IVT (Fig. 2a) and its anomalies (shading in Fig. 2b) by subtracting the daily climatology (1979–2018) to remove the effects of background seasonal cycle (e.g., Kamae et al. 2017a);
- 2) obtain the features (red lines) by removing the IVT anomalies less than minimum threshold $250 \text{ kg m}^{-1} \text{ s}^{-1}$ that is also used in the original M16 algorithm (Fig. 2b);

- 3) remove the round features that generated by TCs based on the best track TC centers (green dots) and 800-km radius (blue dashed circles; Fig. 2c);
- 4) remove the small blobs less than 500 contiguous grid points (Fig. 2d); and
- 5) remove the non-AR features (e.g., length less than 2000 km, length–width ratio less than 1.6, west–east-oriented features along the intertropical convergence zone) using the standard image processing techniques (Fig. 2e).

Steps 1, 2, 4 and 5 generally follow the original procedures introduced by M16, while the step 3 is newly added in this study for considering the TCs. The comparison between the modified and original M16 algorithms is given in the online supplemental material (section S1a) to investigate the effects of the new TC-related criterion, and sensitivity tests using different radii for this new criterion are also given in this subsection. Section S1b in the supplemental material describes the experiments for different latitude thresholds (i.e., 10°, 20°N). In the original M16 algorithm, more restrictive testing is performed in step 5 for the detected features with centroids equatorward of 20°N in order to remove the west–east-oriented features that are mostly moisture swells along the intertropical convergence zone, and we modified this latitude threshold from 20° to 10°N in this study to retain more TC-related AR features. There are two other modifications made to the M16 algorithm, and the corresponding comparisons are also provided in supporting information (see supplemental material sections S1c and S1d). Note that, compared with the original M16 method, a larger length threshold (a minimum of 70 grid points, approximately 2000 km) and a smaller size threshold (a minimum of 500 contiguous grid points) are applied in the modified algorithm, which have been adjusted based on the finer resolution ($0.25^\circ \times 0.25^\circ$) data we used.

Figure 2 illustrates an example of how the modified algorithm works. At 0000 UTC 10 July 2015, several AR-like features in the Indo-Pacific region are finally detected after the above five steps, including an AR that coincides with the TC over the SCS (Fig. 2e). Thus, it is expected that most AR-like features that resemble the AR over the SCS (see the AR feature within the black dashed box in Fig. 2e) could be well retained by the modified algorithm. Note that, in this study, the AR frequency is used to characterize the AR features, which is defined as the number of 6-hourly time steps when an AR exists divided by the total number of time steps during the analysis period on each grid point. In addition, the centroids, length, area, and intensity of ARs are used for the statistical analysis of their geometric features. The AR length is determined by calculating the sum of the distance between each two adjacent grid cells in the AR axis (Figs. 2f,g, green), which is obtained by applying the skeletonization. The intensity of AR is indicated by mean IVT anomaly within the AR feature.

In another aspect, to explore the impacts of TCs on AR activity in section 4, we determine a snapshot as a TC-active case when a TC is present at the given time within the domain that covers East Asia and the WNP region (4° – 69° N, 98° – 188° E) based on the 6-hourly TC center positions of best track data during JJASO 1979–2018. Correspondingly, TC-free case

is identified when there is no TC at all. In total, 17 249 and 7231 snapshots are identified as TC-active and TC-free cases during JJASO of 1979–2018, respectively.

d. An example of AR event in the presence of a TC within BSISO convection

Figure 3 shows a typical TC-related AR event within a BSISO convective envelope that occurred in July 2016. Over the course of this event, the BSISO convection (corresponding to phases 7–8, denoted by orange contours) was located over the WNP and a TC developed within the envelope. At the beginning, the TC (green dot) over the WNP tended to drag the water vapor around it (see the vectors), especially at its northeastern side where the WNPSH (thick black line) was located (Fig. 3a). As the TC moved northwestward, an AR (red line) formed to the east of the TC on 7 July, and it should be pointed out that the strong IVT anomalies (hence, the AR) were not connected with the core structure of the TC (Fig. 3b). After that, the AR developed and further elongated toward the central Pacific, leading to the strong poleward moisture transport even after the TC disappeared over mainland China on 10 July (Figs. 3c–f). Our further analysis shows that there was a remarkable anomalous high pressure to the northeast of the TC-induced low pressure anomalies during this process (Fig. S12). Some previous studies pointed out that the TCs can enhance the poleward moisture transport by increasing the pressure gradient and the wind speed between the WNPSH and TCs (e.g., Kawamura and Ogasawara 2006; Hirata and Kawamura 2014). As we expected, these sequential snapshots suggest that, although ARs tend to form and grow along the periphery of the WNPSH during the full period, some of them are potentially initiated or related to the TC activity.

3. Results

a. Climatology of ARs

Figure 4 shows the climatology of JJASO AR frequency, IVT, and 500-hPa geopotential height over the Indo-Pacific. The ARs (shading) occur most frequently over the midlatitude North Pacific, with magnitude of over 13% (white line) at the latitude between 35° and 45° N (Fig. 4), which is consistent with previous findings (e.g., Guan and Waliser 2015; M16; Kamae et al. 2017a). Note that the summertime AR frequency over the subtropical North Pacific is slightly lower than that derived from Kamae et al. 2017a (see their Fig. 2e), which might be caused by the lower anomalous IVT threshold ($140 \text{ kg m}^{-1} \text{ s}^{-1}$) they used. The AR main body region is located to the northern side of the WNPSH (5870-gpm line; thick black line in Fig. 4). The moisture is transported (see vectors in Fig. 4) from the tropics to the midlatitude North Pacific along the periphery of the WNPSH, leading to the enhanced AR activity. Note that, although 5880 gpm at 500 hPa represents the WNPSH well in snapshots (see thick black line in Fig. 3), 5870 gpm is more appropriate in the composite analysis as shown in Fig. 4, and has been used as a proxy for the position of WNPSH in some previous studies (e.g., Zhou et al. 2009). Thus, the WNPSH is denoted by the 5870-gpm line in the following

FIG. 3. Time evolution of IVT anomalies (shading and vectors), 500-hPa geopotential height (black contours), negative filtered OLR anomalies (orange contours), and AR shape (red line) at 0600 UTC during 6–11 Jul 2016 (BSISO phases 7–8) when a TC occurred (green dot). The interval of black contours is 40 gpm for 500-hPa geopotential height, and the thick black contour represents the WNPSH (5880 gpm). Vectors are only plotted for IVT magnitudes $> 200 \text{ kg m}^{-1} \text{s}^{-1}$. The contour lines of -20 and -10 W m^{-2} of OLR anomalies are plotted for showing the convective zone.

composite analysis. Meanwhile, due to the new TC-related criterion and lower latitude threshold we used (see sections S1a and S1b in the supplemental material), there is another high AR frequency center (around 5%) over the southern SCS, which does not seem to be detected based on the original M16 algorithm (Fig. S4b; see also Fig. 2e in Kamae et al. 2017a). The moisture from the tropical IO and western Pacific tends to converge over the SCS, which forms an S-shape in these regions and leads to the prominent northward moisture transport

from the tropics to about 30°N . It should be mentioned that the SCS and its adjacent area are not only the regions where the convective envelop of the BSISO in most phases is located (Fig. 1), but also the regions where the strong TC activity appears (Li and Zhou 2013).

b. Influences of BSISO on ARs

To explore the impacts of the BSISO on the Indo-Pacific ARs, Fig. 5 depicts the composites of AR frequency anomalies

FIG. 4. Climatology (1979–2018) of JJASO AR frequency (shading), IVT (vectors), and 500-hPa geopotential height (contours). The white line denotes AR frequency of 13%. Thick black lines denote the 5870- and 5880-gpm contours. Only the IVT vectors over the areas where the AR frequency is greater than 1% are shown.

FIG. 5. Composites of AR frequency anomalies (shading) and negative filtered OLR anomalies (green dashed contours) in eight BSISO phases during JJASO 1979–2018. Contour interval is 4 W m^{-2} for OLR, and the zero contour is omitted. AR frequency anomalies that are statistically significant at the 90% confidence level are dotted.

in conjunction with negative OLR anomalies in eight phases. The composites of IVT anomalies are also given in Fig. 6 to check the moisture transport under the influences of the BSISO. The spatial distribution of the ARs varies greatly under different BSISO phases. In general, phases 6–8 provide a more favorable environment for the AR activity over the WNP with larger positive AR frequency anomalies (shading in Figs. 5f–h). We found that the ARs tend to occur with higher frequency within the enhanced BSISO convection (green dashed contours in Figs. 5f–h) in these three phases. By contrast, the AR activity is greatly suppressed in the remaining five phases (Figs. 5a–e), in particular in phases 2–4 (Figs. 5b–d). Our results suggest that the AR occurrence is tightly related to the location of the enhanced BSISO convection center and its associated moisture transport.

Particularly, in phase 6, the enhanced convection is located over the regions extending from the northern IO to the equatorial western Pacific (Fig. 5f), which induces two strong anomalous cyclonic moisture transport centers over the Indian subcontinent and the Philippines (Figs. 6f), leading to the positive AR frequency anomalies in these two regions (Fig. 5f).

Meanwhile, anomalous anticyclonic moisture transport is found over the East China Sea, leading to more AR occurrence over eastern China and Sea of Japan through the anomalous southwesterly moisture transport from the SCS (Figs. 5f and 6f).

In phases 7–8, the enhanced convection propagates northward from the Maritime Continent to the Philippine Sea (Figs. 5g,h), and the Philippine Sea is dominated by strong anomalous cyclonic moisture transport (Figs. 6g,h). The strong anomalous southwesterly moisture transport over the SCS and Philippine Sea results in more frequent AR activity, while the anomalous northeasterly moisture transport over eastern China induces remarkable negative AR frequency anomalies. It is noted that there is a regional difference in AR occurrence over the North Pacific between phases 7 and 8. In phase 7, prominent anomalous poleward moisture transport appears to the east of Japan (Fig. 6g), and the AR activity over the North Pacific is less organized, covering a large area (Fig. 5g); however, in phase 8, the AR activity is more likely trapped within the south of 35°N along the northern edge of the WNPSH (Fig. 5h) accompanied by strong positive moisture transport anomalies (Fig. 6h). The AR frequency and IVT anomalies in

FIG. 6. Composites of IVT anomalies (shading and vectors) in eight BSISO phases during JJASO 1979–2018. Areas with the IVT magnitude anomalies exceeding the 90% significance levels are plotted. The green box in (h) denotes the WNP region that is used for the statistical analysis.

phases 1–4 (Figs. 5a–d and 6a–d) exhibit almost the opposite distribution with those in phases 5–8 (Figs. 5e–h and 6e–h). Negative AR frequency anomalies together with the weaker moisture transport appear over the regions where the suppressed BSISO convection (Fig. 1) is located.

To further assess the impacts of the BSISO on the geometric features of ARs, we performed the statistical analysis on those ARs whose centroids lie within the WNP (5° – 35° N, 100° – 140° E; green box in Fig. 6h). Figure 7 shows the AR frequency anomalies, the number of AR occurrences, and its geometric features (latitude of AR centroid, length, area, and intensity) over the WNP. Note that the calculation of the occurrence number and features in Figs. 7b–f is based on AR cases in all 6-hourly time steps during JJASO 1979–2018. It is found that the number of WNP AR occurrences in the BSISO state (3255, black solid bar in Fig. 7b) is more than that in the non-BSISO state (2202, black striped bar in Fig. 7b), suggesting potential impacts of the BSISO on the WNP AR occurrence. Particularly, the AR frequency anomalies and the number of AR occurrences over the WNP are at a maximum peak during phases 6–8 and a minimum peak during phases 2–4 (Figs. 7a,b).

Besides the WNP region, we also analyze the BSISO impacts on AR frequency anomalies over eastern China (20° – 35° N, 100° – 120° E; pink box in Fig. S13a) and the Korean Peninsula and Japan (30° – 45° N, 125° – 145° E; orange box in Fig. S13a), where the landfalling ARs are found to cause great hydrological and socioeconomic impacts (Kamae et al. 2017b; Kim et al. 2021; Park et al. 2021). It shows that the AR frequency anomalies over these two subregions (see the third and fourth columns in Table S1) tend to peak in phase 6 accompanied by prominent positive IVT anomalies (Fig. 6f).

In terms of the AR geometric features, our results show that the ARs tend to be longer and have larger sizes in phases 7–8, with a mean value of around 4300 km and 2.4×10^6 km², respectively (Figs. 7d,e), which corresponds to the large positive anomalous southwesterly moisture transport over the WNP during this period (Figs. 6g,h). Moreover, ARs tend to occur at the lower latitudes in these two phases (Fig. 7c). Contrarily, in phases 3–4, the ARs tend to be shorter and have smaller sizes, and their mean values are around 3100 km and 1.1×10^6 km², respectively. The differences in the mean IVT anomaly (i.e., intensity of ARs) are small among all the phases (Fig. 7f).

FIG. 7. (a) AR frequency anomalies over the WNP (5° – 35°N , 100° – 140°E) in eight BSISO phases. Error bars indicate the 90% upper and lower confidence intervals. (b) The number of AR occurrences for (left) all days in JJASO (y axis) and (right) eight BSISO phases (y axis). Numbers on top of the bars indicate the number of AR occurrences. The black solid and striped bars for all days represent the BSISO and non-BSISO state, respectively. (c)–(f) The box-and-whisker plots of latitude of AR centroids, length, area, and mean IVT anomaly of ARs. Whiskers indicate the values of 95th (upper bound) and 5th (lower bound), while the upper and lower edges of boxes indicate the 75th and 25th percentiles, respectively. The horizontal line and asterisk inside each box denote the median and mean values, respectively.

These findings suggest that the BSISO has great impacts on the location, length, and area of WNP ARs, but not their intensity. Compared with the geometric features of all-month global ARs shown in Guan and Waliser (2015; see their Fig. 6), the summertime WNP ARs based on the modified M16 algorithm tend to be shorter (median of length at $\sim 3138 \text{ km}$; Fig. 7d) with larger intensity (median of IVT anomalies at $\sim 399 \text{ kg m}^{-1} \text{ s}^{-1}$; Fig. 7f). These differences in the AR geometric features depend strongly on the different detection algorithms used. More

comparisons need to be performed with our modified method applied to the all-month global ARs.

c. Dynamic background for the BSISO modulation on ARs

As shown in the example case in Fig. 3 and the climatological large-scale atmospheric circulation in Fig. 4, it implies that the formation and evolution of ARs are strongly associated with the WNPSH. In this subsection, we will investigate the potential role of WNPSH in regulating the AR activity under the influence of BSISO.

FIG. 8. The number of AR occurrences (shading; based on $5^{\circ} \times 5^{\circ}$ box) superimposed with composites of IVT (vectors; only composite IVT magnitudes $> 250 \text{ kg m}^{-1} \text{ s}^{-1}$ are plotted) with the magnitude in color in eight BSISO phases during JJASO 1979–2018. The black lines are composites of 5870-gpm lines at 500 hPa for showing the WNPSH in eight phases.

Figure 8 depicts the number of AR occurrences superimposed with the composite maps of IVT vector in eight BSISO phases. In all BSISO phases, ARs (shading) tend to spread along the periphery of the WNPSH (black line) accompanied by the strong southwesterly moisture transport (vectors; Fig. 8), which is in agreement with the evolution of the individual AR event (Fig. 3). Thus, the WNPSH can be treated as the dynamic background for the BSISO modulation on AR activity. To further elucidate how the BSISO affects the spatial distribution of ARs via modulating the large-scale circulation anomalies, we also composite the 500-hPa geopotential height and 850-hPa wind anomalies in each BSISO phase (Fig. 9). The climatological position of the WNPSH is also plotted for comparison (green dashed lines in Fig. 9). It shows that the location of the WNPSH in some BSISO phases slightly differs

from its climatological position (see the black solid and green dashed lines in Fig. 9). Under the background effect of WNPSH, the spatial distribution of the number of AR occurrences differs in each phase (Fig. 8), which is consistent with the statistical analysis on the latitude of AR centroids in Fig. 7c. Correspondingly, the moisture transport pathways vary in each phase. In phase 4, the WNPSH is located more westward, which guides the water vapor to convey from the Indo-China Peninsula to the WNP (Fig. 8d). The ARs concentrate along the northwestern flank of the WNPSH (Fig. 8d) with significant positive AR frequency anomalies over eastern China (Fig. 5d). In phases 7–8, the WNPSH is located more eastward. The moisture is transported northeastward from the SCS to the WNP, and then more ARs occur over the southwestern flank of the WNPSH (Figs. 8g,h).

FIG. 9. Composites of 500-hPa geopotential height anomalies (shading) and 850-hPa wind anomalies (vectors) in eight BSISO phases during JJASO 1979–2018. The black solid lines are composites of 5870-gpm lines at 500 hPa for showing the WNPSH, while the green dashed lines denote its climatology. Only the anomaly fields exceeding the 90% confidence level are plotted. “H” and “L” denote the anomalous high and low pressure centers, respectively.

Further analysis shows that changes in the large-scale circulation anomalies associated with the BSISO strongly affect the spatial distribution of moisture transport and AR occurrence. In phase 1, a low pressure anomaly east of Japan accompanied by an anomalous cyclonic circulation helps convey the moisture eastward to the central Pacific and enhance the AR activity (Figs. 5a, 6a, and 9a). This low pressure anomaly is displaced by a high pressure anomaly in the following phases (phases 2–4; Figs. 9b–d). Meanwhile, an anticyclonic circulation appears over the SCS and Philippine Sea (Figs. 9b–d).

Such circulation pattern in conjunction with the suppressed convection (Figs. 1b–d) leads to less AR occurrence over the WNP (Figs. 5b–d and 8b–d).

In phases 5–6, two anomalous cyclonic circulation centers are located over the northern IO and SCS (Figs. 9e,f). Meanwhile, the East China Sea is dominated by an anomalous high pressure. Specially, the 850-hPa southwesterly flow over eastern China in phase 6 helps guide the moisture to be transported more northeastward into the Yellow Sea and Sea of Japan (Figs. 6f and 9f). However, the anomalous high pressure extends more

northward and deflects the poleward moisture transport in phase 5 (Figs. 6e and 9e). In phases 7–8, an anomalous cyclonic circulation lies over the Philippine Sea (Figs. 9g,h) accompanied by an enhanced BSISO convection (Figs. 1g,h), which creates a favorable condition for northeastward transport of moisture associated with the active BSISO convection into the WNP through the southwesterly flow (Figs. 6g,h). Simultaneously, a strong low pressure anomaly appears in the central Pacific to the east of Japan in phase 8 (Fig. 9h), resulting in more frequent AR occurrence along the northern edge of the WNPSH (Figs. 5h and 8h).

4. Role of TC on AR activity

As shown in Fig. 3, it was suggested that the genesis and maintenance of some ARs are greatly affected by TCs. Meanwhile, as mentioned in the introduction, the TC activity over the WNP is substantially modulated by the BSISO (Yoshida et al. 2014). That is, the BSISO convection is likely to be accompanied by TCs. One may expect that the influences of BSISO on the AR activity would be different when it is accompanied by TCs or not.

Following the criterion described in section 2c, Table 1 summarizes the number of snapshots in the TC-active and TC-free cases in each BSISO phase and non-BSISO state during JJASO 1979–2018. There are 9611 snapshots identified as TC-active cases for all BSISO phases, accounting for 68.8% of BSISO-related snapshots, which are twice more than the TC-free cases. Meanwhile, the same ratio of the TC-active cases is also found in non-BSISO snapshots, suggesting the BSISO might not influence the mean state of the atmospheric conditions for TC genesis; however, it is not the case when we further decompose it by the BSISO phases. TCs formed more frequently from phase 5, leading to enhanced TC-active cases in the following phases (Table 1). In particular, TCs occur most frequently in phases 7 and 8 during which TCs are detected in 1553 and 1465 snapshots, accounting for 87.1% and 85.2% of the corresponding BSISO period, respectively. Compared with other phases, TC-active cases in phases 3 and 4 are less, which are detected in around 56.9% and 52.9% of the active BSISO period, respectively. This statistics analysis confirms that the BSISO phases and TC occurrence are not independent (e.g., Yoshida et al. 2014), which can also be seen from the different spatial distribution of the TC genesis locations in each BSISO phase (Fig. S13).

To further investigate the effects of BSISO-modulated TC occurrence on the AR activity, we focus on a pair of opposite BSISO phases, phase 4 and phase 8, which have suppressed and enhanced TC occurrences, respectively (Table 1 and Fig. S13). In phase 8, frequent occurrence of TCs tends to enhance the BSISO convection over the WNP (Fig. 10g), inducing an anomalous low pressure and cyclonic circulation (Fig. 10e), which further leads to the greatly enhanced poleward moisture transport (Fig. 10a) and AR activity (Fig. 10c). On the other hand, during the period without TC occurrence, the BSISO convective intensity is greatly reduced and less organized (Fig. 10h). Over the subtropical WNP region, the poleward moisture transport from tropics is suppressed (Fig. 10b),

TABLE 1. Number of snapshots (ratio) for the TC-active cases, TC-free cases, and TC genesis number in different BSISO phases and non-BSISO state during JJASO 1979–2018.

BSISO phase	TC-active cases	TC-free cases	TC genesis
1	1210 (74.3%)	418 (25.7%)	36
2	1027 (60.0%)	685 (40.0%)	35
3	1060 (56.9%)	804 (43.1%)	41
4	961 (52.9%)	855 (47.1%)	44
5	1083 (63.9%)	613 (36.1%)	61
6	1252 (72.0%)	488 (28.0%)	73
7	1553 (87.1%)	231 (12.9%)	87
8	1465 (85.2%)	255 (14.8%)	59
Sum	9611 (68.8%)	4349 (31.2%)	436
Non-BSISO	7638 (72.6%)	2882 (27.4%)	354

accompanied by a much weaker southwesterly flow (Fig. 10f), and then fewer ARs occur (Fig. 10d). Note that positive IVT anomalies appear along the northern periphery of the WNPSH toward the central Pacific together with the enhanced AR occurrence and convective activity (Figs. 10b,d,f,h). In phase 4, the composite maps in the TC-active and TC-free cases display generally similar patterns (Fig. S14). As seen from the difference fields, in phase 4 (Fig. 11, left panels), TC activity tends to induce similar differences in moisture transport, pressure, and OLR anomalies as phase 8 (Fig. 11, right panels) but with much smaller magnitudes, which is mainly due to the less frequent TC occurrence in phase 4 (Table 1 and Fig. S13).

Further statistical analysis shows that more ARs occur over the WNP in the phases (especially phases 6–8; Fig. 12a) during which the TC occurrence is more frequent (Table 1 and Fig. S13), and these ARs tend to be longer under the influence of TCs (Fig. 12b). In some TC-inactive phases (phases 3 and 4; Figs. S13c,d), it is found that the number of WNP AR occurrences in the TC-free cases is more than that in the TC-active cases, in particular in phase 4 (Fig. 12a). As seen from the large-scale circulation patterns, a prominent anomalous high pressure dominates the Philippine Sea accompanied by a stronger low-level southwesterly flow in the TC-free cases in phase 4 (Fig. S14f), which corresponds to the positive IVT anomalies (Fig. S14b) and enhanced convection (Fig. S14h) over eastern China, creating a favorable condition for AR occurrence over the WNP (especially to the north of 25°N; see Figs. S14d and 12a). On the other hand, in the TC-active cases, the anomalous high pressure over the Philippine Sea is weaker (Fig. S14e), while another anomalous high pressure appears to the north of the WNPSH accompanied by strong northeasterly flow anomalies, which tends to weaken the southwesterly moisture transport along the northern periphery of WNPSH (Fig. S14a), resulting in less AR occurrence (Figs. S14c and 12a).

In general, the close relationship between TCs and ARs is demonstrated in this section based on the composite analysis. It should be mentioned that, although some cases (e.g., Fig. 3) show that the anomalous moisture transport and circulation associated with TCs can systematically foster ARs along the WNPSH, potential impacts of ARs on TCs remain unclear. When the ARs and TCs coexist, their relationship can be

FIG. 10. Composites of (a),(b) IVT anomalies (shading and vectors); (c),(d) the number of AR occurrences (shading; based on a $5^\circ \times 5^\circ$ box); (e),(f) 500-hPa geopotential height anomalies (shading) and 850-hPa wind anomalies (vectors); and (g),(h) filtered OLR anomalies (shading and contours) in the (left) TC-active and (right) TC-free cases in BSISO phase 8. Only the anomaly fields exceeding the 90% confidence level are plotted in (a), (b), (e), and (f). The black lines in (e) and (f) denote the composites of WNPSH in the TC-active and TC-free cases, respectively.

FIG. 11. As in Figs. 10a, 10b, and 10e–h, but for the differences between the TC-active and TC-free cases in BSISO (left) phase 4 and (right) phase 8.

complex by mutual (nonlinear) interactions and diabatic processes. Zhang et al. (2019) demonstrated a positive feedback between the ARs and extratropical cyclones in the cool season. They found that the extratropical cyclones can intensify the ARs by inducing stronger meridional IVT driven by the cyclonic low-level wind, while the moisture from ARs can enhance the precipitation and latent heat release, which favors the deepening of the extratropical cyclones. The potential impacts of ARs on TCs and their mutual interactions are the research topics for forthcoming investigations.

5. Conclusions

Using the 40-yr (1979–2018) ERA5 reanalysis, the influence of the BSISO on ARs during boreal summer (June–October) over the Indo-Pacific region and the processes are examined. We found that the WNPSH provides an atmospheric circulation background favorable for the summertime Indo-Pacific

AR activity. It favors the moisture transport from the tropical region to midlatitude North Pacific, leading to more AR occurrence along its northern periphery. The BSISO convection and its associated large-scale circulation anomalies can cause significant changes in the moisture transport and AR activity. Generally, phases 6–8 of the BSISO are favorable for the AR occurrence over the WNP where there is enhanced BSISO convection. Particularly, in phases 7–8, when the active BSISO convection is located over the Philippine Sea, AR occurrence is greatly enhanced over the WNP accompanied by stronger moisture transport (Figs. 5, 6, and 8). The opposite features occur in BSISO phases 3–4. Moreover, it is revealed that the geometric characteristics of ARs (e.g., length and area) are strongly affected by the BSISO. The WNP ARs in phases 7–8 (3–4) tend to be longer (shorter) and have larger (smaller) sizes (Fig. 7). Further analysis also shows that more frequent occurrence of TCs during phases 7–8 can significantly increase the WNP AR activity.

FIG. 12. (a) The number of AR occurrences over the WNP (5° – 35° N, 100° – 140° E), and (b) box-and-whisker plot of AR length for all days (JJASO) and eight BSISO phases in the TC-active (red) and TC-free (blue) cases. Numbers on top of bars in (a) indicate the ratio (%) of the number of AR occurrences in each case to the total number of AR occurrences. Left y axis in (a) is for all days while right y axis is for eight BSISO phases. The definition of the box-and-whisker plot in (b) is as in Figs. 7c–f.

Figure 13 depicts the schematic diagram illustrating the impacts of BSISO on the AR occurrence along with associated contributions from WNPSH and TC in a pair of TC-inactive and TC-active BSISO phases, phase 4 (Fig. 13a) and phase 8 (Fig. 13b), respectively, which have the opposite features. In phase 4 (Fig. 13a), a suppressed BSISO convection together with a high pressure anomaly appears over the Philippine Sea. Meanwhile, the WNPSH is located more westward. Moisture tends to be conveyed from the Indo-China Peninsula to the subtropical WNP, which enhances the AR occurrence over eastern China and suppresses the AR activity over the WNP. In phase 8 (Fig. 13b), an enhanced BSISO convection and its induced low pressure anomaly occur over the Philippine Sea accompanied by a more eastward-located WNPSH. Simultaneously, more frequent TC occurrence is found in this phase. Such a circulation pattern helps strengthen the eastward moisture transport from the moisture-rich region (e.g., IO, SCS) to the Philippine Sea and then enhance the poleward moisture transport toward the subtropical WNP, which dramatically enhances the AR occurrence over the WNP.

In this study, we saw that the joint effects of BSISO, WNPSH, and TCs exert a strong influence on the moisture transport and AR occurrence. However, the covariability between the WNPSH and TCs across scales under the influence of BSISO has not yet been well examined. As shown in previous studies, the TCs tend to move northwestward along the western edge of the WNPSH during the evolution of AR (Hirata and Kawamura 2014; Camp et al. 2019; see also the case in Fig. 3). Thus, how the TCs and WNPSH interact with each other across scales and their joint effects on the genesis and maintenance of ARs need to be investigated in future studies. In addition, the relationship between the WNPSH and BSISO has not yet been revealed. A recent research suggested that the accumulated effect of the tropical WNP intraseasonal oscillation convolutions exerts a significant impact on modulating the meridional displacement of the WNPSH since the late 1990s (Huang et al. 2020). It is speculated that the BSISO might modulate the WNPSH and subsequently affect the AR activity. However,

the interaction between the BSISO and WNPSH requires an in-depth analysis.

On the other hand, given the hydrological hazards and socioeconomic losses brought by ARs, many studies have

FIG. 13. Schematic diagram illustrating the BSISO's impact on the summertime ARs over the Indo-Pacific region, along with associated contributions from WNPSH (black solid line) and TCs (TC symbol) in the BSISO (a) phase 4 and (b) phase 8. The black dashed line represents the climatological WNPSH. Dashed ellipses indicate the pressure anomalies. "H" and "L" represent the anomalous high and low pressure centers, respectively. More TC symbols indicate more frequent TC occurrence.

focused on the variability and predictability of AR frequency at subseasonal-to-seasonal time scales using different climate modes (e.g., MJO, ENSO, quasi-biennial oscillation) as the predictability sources (Mundhenk et al. 2018; DeFlorio et al. 2018, 2019). In this study, we revealed the important roles of the BSISO and the WNPSH on summertime AR activity over the WNP region, indicating that they could be listed among the major sources of subseasonal-to-seasonal AR predictability. Moreover, the predictability and prediction skill of both the BSISO and the WNPSH have been widely investigated by previous studies (e.g., Wang et al. 2013, 2019; Zhang et al. 2020; Kikuchi 2021). It is found that the prediction skill for BSISO is in the range of around 1–5 weeks (Wang et al. 2019), while the intensity and position of the ridge line of the summer mean WNPSH exhibit a significant predictive skill with a lead time of up to three months (Zhang et al. 2020). Given the essential roles of BSISO and WNPSH in the AR frequency revealed in this study, it is supposed that our findings will facilitate the subseasonal-to-seasonal AR prediction, therefore, the related heavy rainfall (e.g., Kamae et al. 2017b; Zhao et al. 2021), which further supports the decision making to mitigate the risk and impact of ARs.

In another aspect, besides the BSISO and TCs, the sea surface temperature (SST) also has strong influences on the WNP AR activity (Kamae et al. 2017a). Kamae et al. (2017a, 2019) showed that the anomalous WNPSH can be reinforced due to the SST warming over the northern IO and SCS, which further strengthens moist southwesterlies and leads to the enhancement of AR occurrence on the northwestern flank of the WNPSH. In addition, the close relationship between the variation of the WNPSH and large-scale SST variability has also been demonstrated (e.g., Wang et al. 2013). Furthermore, the essential role of air–sea coupling in the BSISO activity has been examined in earlier studies (e.g., Gao et al. 2019). It is our aim to extend this work by including the effect of SST in the future.

Finally, some amount of moisture originates from the moisture-rich regions to feed and maintain the ARs. Recently an increasing number of studies have focused on the quantification of moisture sources within ARs based on the numerical modeling (e.g., Nusbaumer and Noone 2018; Zhao et al. 2021). Zhao et al. (2021) found that the AR along the baiu front in July 2020 was contributed by around 15% and 80% moisture from the tropics and subtropics, respectively. However, the origin of moisture within the summertime Indo-Pacific ARs still has not been examined quantitatively on climatological time scales. It is expected that future studies on the moisture source of ARs will lead to a more complete understanding of the physical mechanisms.

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Copernicus Climate Change Service (C3S) Climate Data Store (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview>). The best track data are available on the RSMC Tokyo website (<http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html>). The BSISO index is available at http://iprc.soest.hawaii.edu/users/kazuyosh/Bimodal_ISO.html. The code for the modified M16 AR detection algorithm is available on [Zenodo.org](https://doi.org/10.5281/zenodo.5151038) (<https://doi.org/10.5281/zenodo.5151038>).

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