Simulation and Projection of Circulations Associated with Atmospheric Rivers along the North American Northeast Coast

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ABSTRACT

Torrential rainfall occurring along the North American northeast coast (NANC) in summer and autumn is accompanied by strong atmospheric rivers (ARs), which efficiently transport abundant moisture along a narrow-stretched path associated with a low pressure system. In this study, an autodetection method was used to identify ARs that reached the NANC, based on the 6-hourly data of the ERA-Interim reanalysis conducted by the European Centre for Medium-Range Weather Forecasts, in summer and autumn from 1979 to 2016. Stronger ARs tended to occur in the eastern flank of a cyclonic anomaly that covered the entire North American east coast from Florida to Newfoundland, with a positive precipitation anomaly over the NANC. The cyclonic anomalies and precipitation in autumn were stronger but less frequent than those in summer. Cyclonic anomalies were parts of westward-tilting wavelike circulation perturbations moving into North America from the extratropical North Pacific and moving continuously eastward, reaching the east coast in approximately five days. The Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM), which realistically simulates the occurrence frequency and key characteristics of ARs in current climatic conditions, was used to project the AR activity and corresponding circulations in the future warmer climate under the representative concentration pathway 8.5 scenario. The HIRAM that was driven by sea surface temperature changes projected an overall increase in the occurrence of stronger ARs in both summer and autumn and the precipitation strength in autumn along the NANC by the end of the twenty-first century. This projected enhancement was contributed to by two processes—a smaller contribution was from the weakened basin-scale North Atlantic anticyclone but with higher moisture content, and a larger contribution was from the enhancement in anomalous circulation during AR events with integrated vapor transport exceeding the 75th percentile. These results suggest that the influence of strong ARs on the NANC may increase in the warmer future due to the combination of increased water vapor in the large-scale environment (thermodynamic effect) and enhanced anomalous circulations (dynamic effect). The AR-associated circulations in autumn were also projected to have a stronger tropical connection in the warmer future.

1. Introduction

Since the detection of long and narrow moisture-rich corridors (named tropospheric rivers) was first reported by Newell et al. (1992) in the early 1990s, the advent of satellite observations and global reanalysis have made the detection of an atmospheric river (AR) laden with abundant moisture much easier and helped connect with the extreme rainfall events over land. An AR is a narrow and elongated path along which a substantial amount of

moisture is transported and is found often associated with a low-level jet stream ahead of the cold front of an extratropical cyclone with a moisture source from the extratropics and/or tropics (*Glossary of Meteorology*, published by the American Meteorological Society; http://glossary.ametsoc.org/wiki/Atmospheric_river). There are debates about the distinction between ARs, warm conveyor belts, and tropical moisture transport. Some of ARs were embedded in the warm conveyor belt and more of extratropical origin, whereas some were connected to a long moisture corridor deep into the tropics. After a series of discussion among AR experts, it was decided to retain “the extratropical dynamics connection in the definition” (p. 838), which is now included in the *Glossary of Meteorology* (Ralph et al. 2018). In addition to the tropical moisture

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transport, the important role of large-scale synoptic perturbations such as Rossby wave breaking or extratropical cyclones in the genesis and evolution of ARs was also recognized (Ramos et al. 2019).

ARs of either extratropical or tropical origin often caused heavy precipitation along coastal areas upon landfall when moisture convergence and/or topographic lifting occurred near terrain. The North American west coast is one of the regions most influenced by landfalling ARs that occur in frontal environments (Neiman et al. 2008). These elongated narrow ARs that originated in the central Pacific transported abundant moisture to the North American west coast, and were reportedly responsible for 30%–50% of all the precipitation in the area (Ralph et al. 2006; Neiman et al. 2011). Some of the ARs in the northeast Pacific originate in the tropics and are nicknamed the “Pineapple Express” (Dettinger 2004; Shields et al. 2018). Landfalling ARs were also identified in the eastern North Atlantic (Lavers et al. 2011, 2012; Lavers and Villarini 2013; Eiras-Barca et al. 2016), the southeast United States, and the East Asian coast (Kamae et al. 2017a,b). Again, these features were found often associated with heavy precipitation.

Fast-fluctuating ARs were modulated by low-frequency climate variations, such as the Madden–Julian oscillation (MJO) and El Niño–Southern Oscillation. For example, ARs tended to be more active in phase 6–7 of an MJO after the deep convection core reached the western–central equatorial Pacific (Guan et al. 2012; Mundhenk et al. 2016) and during the El Niño winter (Mundhenk et al. 2016). Extratropical teleconnection patterns such as the Arctic Oscillation, North Atlantic Oscillation, and Pacific–North American pattern also have a modulating effect on ARs over the Pacific and Atlantic Oceans (Lavers and Villarini 2013; Guan and Waliser 2015; Eiras-Barca et al. 2016). These findings suggest that large-scale perturbations of both tropical and extratropical origins could induce ARs, which efficiently transport moisture a long distance, in the southeasterly or southerly side of anomalous cyclonic circulations.

Guan and Waliser (2015) analyzed climatological distribution and occurrence frequency worldwide to identify the hotspots of landfalling ARs. In the Northern Hemisphere, the west coasts of North America and Europe were among the most active regions. The coastal areas in the northeastern corner of North America and the southern United States were also affected by active ARs, with a frequency equivalent to the frequency of the ARs along the North American and European west coasts. The role of ARs in inducing heavy precipitation in the southeastern United States was investigated by Mahoney et al. (2016). By contrast, to the best of our knowledge, the AR activity along the North American

northeast coast (NANC) has not been systematically explored despite the fact that the increased precipitation trend since 1979 has been documented in several studies (Griffiths and Bradley 2007; Brown et al. 2010; Walsh et al. 2014; Frei et al. 2015; Huang et al. 2017). A recent study by Howarth et al. (2019) on extreme precipitation in the northeastern United States reported an increasing trend in the frequency of rainfall events exceeding 50 mm in spring, summer, and autumn, with the most robust trend observed in autumn. They further identified 24 extreme events that exceeded 150 mm, finding that all of those events occurred in summer and autumn. Evidently, summer and autumn were the seasons when extreme events were the most active, but how these events were associated with ARs and the characteristics of ARs have yet to be explored. Considering the strong link between ARs and extreme rainfall in other regions, ARs making landfall in the NANC are expected to be most active in summer and autumn when extreme precipitation is most likely to occur.

How the influence of ARs on the NANC will change in the warmer future is another critical issue that has yet to be explored. Considering that a significant increase in moisture content is expected under warming scenarios, enhanced activity and strength of ARs can be expected. Several studies have confirmed this expectation (Espinoza et al. 2018; Gao et al. 2015, 2016; Hagos et al. 2016; Shields and Kiehl 2016a,b). Espinoza et al. (2018) estimated the future changes in ARs, projected by 21 models in phase 5 of the Coupled Model Intercomparison Project (CMIP5) under RCP8.5, and concluded that ARs will occur less frequently, but become wider and longer in spatial scale and stronger in vapor transport. Payne and Magnusdottir (2015) examined 28 CMIP5 models and found that landfalling ARs along the North American west coast will become more active by the end of the twenty-first century with the thermodynamic effect (i.e., increase in moisture) as the dominating factor in most areas except in the regions that are equatorward of the peak AR distribution. In the equatorward regions, the dynamic effect will be the dominating factor. Similarly, Warner et al. (2015) reported enhanced integrated vapor transport (IVT) that was dominated by an increase in water vapor instead of wind speed. They also identified a 290% increase in the number of days with IVT exceeding the historical 99th percentile threshold and with a 15%–39% increase in precipitation on extreme IVT days.

The purpose of this study is to document the occurrence frequency and spatial distribution of ARs that influenced the NANC and to determine the major characteristics of corresponding circulations in summer [June–August (JJA)] and autumn [September–November (SON)] when extreme

precipitation events occurred most frequently. The target region is highly populated and comprises major economic and political metropolitan cities such as New York and Washington, D.C., with important international influence. Considering the increasing influence of global warming and the already occurring trend pertaining to both temperature and precipitation, an exploration on how AR activity and corresponding circulation might change under a warming scenario is valuable. As reported previously, global warming can lead to changes in both thermodynamic (e.g., moisture content) and dynamic (e.g., circulation) states. Therefore, it is necessary to determine the factors that contribute to changes in AR activity and strength, if any.

To achieve the aforementioned goals, we conducted two long-term climate simulations by using the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM) with a 25-km resolution under both current (1979–2008) and future (2075–2100) climatic conditions to evaluate HIRAM's ability in simulating NANC ARs and to use the model for projecting potential changes that might occur by 2075–2100 under the RCP8.5 scenario (Meinshausen et al. 2011; <http://www.pik-potsdam.de/~mmalte/rcps/index.htm>). In contrast to previous studies diagnosing the simulation and projection results of CMIP5 models that usually have a coarse resolution of about 100 km, the use of a high-resolution model is expected to better resolve the narrow elongated path of moisture in ARs and to provide more realistic simulation and more reliable projection of future changes (Hagos et al. 2015; Shields and Kiehl 2016a).

The arrangement of the article is as follows. Section 2 describes the autodetection method and reanalysis datasets used in this study and the HIRAM. Section 3 presents the AR activity and corresponding circulation identified through reanalysis. The results of model simulation and projected changes are discussed in section 4. Last, a summary and discussion are presented in section 5.

2. Data, AR detection, and model

In this study, the characteristics of ARs in JJA and SON from 1979 to 2016 were explored. Data used in this study were obtained from the ERA-Interim reanalysis [European Centre for Medium-Range Weather Forecasts (ECMWF), 6-hourly, resolution: 0.75°; Dee et al. 2011] and the Global Unified Gauge-Based Analysis of Daily Precipitation (Climate Prediction Center, daily, resolution: 0.5°, land only, <https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html>).

Several AR autodetection schemes have been proposed. It has been reported that different algorithms may yield different results in AR frequency and track.

For a review, refer to the studies by Shields et al. (2018) and Rutz et al. (2019) and the information in Atmospheric River Tracking Method Intercomparison Project (ARTMIP: <http://www.cgd.ucar.edu/projects/artmip/>). The focus of current study was to examine the characteristics of the large-scale circulation in which the NANC ARs were embedded, to evaluate the simulation skill of HIRAM, and to project potential changes under warming scenario. To minimize the effort in AR detection, this study utilized the AR detection tool (ARDT), which includes 13 processing steps, proposed by Wick et al. (2013, Fig. 3 in the paper). Instead of using integrated water vapor, our study used vertically (1000–10 hPa) integrated vapor transport (IVT) as the parameter in detection. The use of IVT, instead of integrated water vapor (IWV) as in Wick et al. (2013), can better represent the moisture transport nature of ARs by making use of velocity fields in reanalyses and model outputs, while IWV is useful when dealing with satellite-retrieved water vapor alone. To detect whether an AR point exists, a screening of IVT value at each grid point was conducted from 1450 to 250 kg m⁻¹ s⁻¹ for every 200 kg m⁻¹ s⁻¹. The adoption of 250 kg m⁻¹ s⁻¹ as the minimum criterion followed the study by Rutz et al. (2014) and the recently proposed scaling system to characterize the strength of ARs (Ralph et al. 2019). An AR must fulfill the following conditions: a contiguous length of AR points for at least 2000 km and a width narrower than 1000 km. An AR detected following the procedure is shown in Fig. 1 as an example. This particular event was characterized by an extratropical storm with an IVT path extending southward to the northern Caribbean Sea. Corresponding IWV and satellite image are also shown for comparison.

The HIRAM was developed based on AM2 (Anderson et al. 2004) with the following modifications: 1) finer horizontal and vertical resolutions; 2) an advanced finite-volume core executing a cubed-sphere grid topology (Putman and Lin 2007) with a quasi-uniform horizontal grid spacing; 3) a simplified moist convective process based on the parameterization of shallow convection by Bretherton et al. (2004); and 4) a simpler diagnostic scheme parameterizing large-scale (stratiform) cloudiness that assumes a subgrid-scale distribution of total water. These physics-based modifications were done to limit the parameterized convection. Thus, the explicit convection can substantially contribute to the vertical transport of moisture and energy in the tropics. The parameterized convection helps the model to resolve subgrid convection instead of supplanting it entirely. This modification benefits the model simulation in finer resolution with more realistic features (Pauluis and Garner 2006). See Zhao et al. (2009) for more details about the modifications. The C384 version with spatial resolution of

FIG. 1. A detected AR event occurring on 4 Nov 1981: (a) corresponding IWV (cm), (b) IVT ($\text{kg m}^{-1} \text{s}^{-1}$) with AR points shown in dots, and (c) corresponding *GOES-5* satellite image.

about 25 km and 32 vertical levels was used for simulation and projection.

The HiRAM has proved capable of realistically simulating rainfall distribution, snowfall in high mountains, extreme precipitation, and tropical cyclone activity partly because of its high resolution (Lau and Ploshay 2009; Freychet et al. 2017a,b; Tsou et al. 2016; Chen et al. 2019). The model was used to conduct two time-slice experiments, which were driven by prescribed sea surface temperature (SST), in a manner similar to that in the study of Kusunoki and Mizuta (2013). In the current climate experiment (referred to as *present_exp*), the HiRAM was forced by the observed monthly Hadley Center Sea Ice and Sea Surface Temperature (Rayner et al. 2003) and the historical greenhouse gas concentration (Donner et al. 2011). In the global warming simulations (*warming_exp*), the concentrations of greenhouse gases such as CO_2 , CH_4 , and N_2O and halocarbons [chlorofluorocarbon (CFC)-11, CFC-12, CFC-113, and HCFC-22] under the RCP8.5 scenario with the ensemble-mean SST change averaged from the 28 CMIP5 models (Mizuta et al. 2014) were applied to force the HiRAM. The simulation periods for the *present_exp* and *warming_exp* were 1979–2008 and 2075–2100, respectively. The SST changes in each CMIP5 model were defined as the differences in the

long-term mean and linear trend at each grid point between 1979–2008 and 2075–2100. SST changes in the 28 models were then averaged to produce ensemble means. These means were added to the observed SST during 1979–2008 (Kusunoki 2018) to produce the SST for the *warming_exp*. The observed interannual variability of SST was therefore retained in the *warming_exp*.

This approach is similar to those in pseudo-global warming experiments (e.g., Sato et al. 2007) that explored how the observed phenomena (in this case, under the influence of the same interannual variation of SST) would change under global warming scenarios. The approach has provided valuable information pertaining to potential changes in the future (Kitoh and Endo 2016; Kusunoki 2018). Because the HiRAM can simulate the major characteristics of the observed weather and climate phenomena in the SST-driven simulations (as shown later in this paper), it is reasonable to explore how the observed phenomena will be modified under the influence of future SST changes. This approach does not yield exact information pertaining to future changes, especially without considering the atmosphere–ocean interaction. However, it is a powerful approach for future projection at the present stage considering the large uncertainty in future projections due to model

FIG. 2. Averaged number of days when an AR passing over each grid point in (a) JJA and (b) SON. (c),(d) As in (a),(b), but only for those ARs landfalling on the NANC (marked area). Unit: days month⁻¹.

imperfection, difficulty in natural variability simulation, and divergent emission scenarios.

3. Characteristics of ARs

a. Spatial and probability distribution

The occurrence distributions of ARs near the NANC in JJA and SON are presented in Figs. 2a and 2b. This

figure shows the number of days per month when ARs passed over each grid point inside the presented region in 1979–2016. ARs were more active offshore than in the coastal areas, and the occurrence in JJA was up to twice as frequent as that in SON. Landfalling ARs on the NANC were identified if five or more AR points were found over the land area inside the marked region presented in Figs. 2c and 2d. Landfalling ARs evidently

FIG. 3. Occurrence days of different IVT strengths (unit: $\text{kg m}^{-1} \text{s}^{-1}$) averaged over a landfalling AR in the NANC during JJA and SON. An AR was identified as a landfalling AR when had at least five landfall points in the NANC. Vertical lines denote the 75th percentile. There were 793 and 575 days for JJA and SON, respectively.

tended to occur closer to the coast compared with the ARs presented in Figs. 2a and 2b, and they were also more frequent in JJA. The number of occurrence days for different IVT strengths in the marked area is shown in Fig. 3. Landfalling ARs with strengths lower than the 75th percentile (vertical yellow and red lines marked in Fig. 3) were significantly less frequent in SON than in JJA. However, the ARs with strength exceeding $900 \text{ kg m}^{-1} \text{s}^{-1}$ occurred more frequently in SON than in JJA. The 75th percentile threshold was approximately 10% larger in SON than in JJA. It follows that while landfalling ARs occurred less frequently in SON, stronger ones were more active than in JJA. To examine the characteristics of landfalling ARs, we selected the AR events with strengths exceeding the 75th percentile (hereafter referred to as AR_{75}) for further investigation. The results were essentially similar to those based on all ARs but with stronger amplitudes in all aspects (not shown). Different thresholds such as the 80th and 90th percentiles were also chosen to examine the sensitivity of our results to the thresholds. The results presented here are essentially the same in three tested thresholds. We chose the 75th percentile threshold for further diagnostics (e.g., composite) because of larger number of AR_{75} events.

It was reported that the IVT detection method based on a fixed threshold such as $250 \text{ kg m}^{-1} \text{s}^{-1}$ tended to

overestimate and underestimate (depending on regions) compared to the IWV detection method (Viale et al. 2018). The dependence of IVT on both wind speed and moisture might detect events with strong flow but less moisture content. In this study, only strong AR events with IVT exceeding 75th percentile were chosen for further diagnostics. The associated IWV was checked for each event. It was found that all the AR_{75} events in JJA (SON) were associated with IWV between 3.3 (3.1) and 5.7 (5.9) cm. The corresponding mean and standard deviation of IWV were 4.6 (4.3) and 0.46 (0.62) cm in JJA (SON). The AR_{75} events analyzed in this study were evidently moisture-laden events with moisture content well exceeding the 2.0-cm criterion, which is often adopted in the IWV detection method.

b. Circulation, moisture flux, and precipitation associated with AR_{75} events

As presented in Fig. 4, the circulation associated with the onset of AR_{75} events in both JJA and SON was characterized by a cyclonic anomaly embedded in a wavelike circulation pattern that tilted westward with height. The northeastward moisture transport in the southeastern flank of the cyclonic circulation evidently led to a positive precipitation anomaly along the NANC. Notably, the positive precipitation anomaly along the NANC coincided with the convergence of moisture flux presented in Figs. 4c and 4d, whereas the negative precipitation anomaly was identified in the divergent area of the southward continental moisture flux. This contrast was particularly evident in SON. The perturbations in SON were stronger in many aspects than those in JJA. For example, the wavelike circulation perturbations in SON exhibited larger amplitudes (note the different scales and unit vectors for color schemes and winds, respectively) and spanned a larger spatial extent that covered the entire eastern North America and extratropical North Atlantic. Precipitation along the northeastern coast was also much heavier in SON under the influence of stronger moisture transport to the area. The cyclonic circulation in SON exhibited a larger meridional scale covering the entire North American east coast from 20° to 60°N . The moisture transport from the Caribbean Sea and the subtropical western North Atlantic to the NANC appeared to be much stronger in SON than in JJA. Moreover, the northeastward moisture transport was directed toward the coastal areas, which caused AR_{75} landfall along the NANC, thus explaining why the AR_{75} in SON had a higher influence on precipitation.

An examination of the circulations from day -5 to day 5 over a domain encompassing the extratropical North Pacific, North America, and North Atlantic

FIG. 4. Composites of anomalies associated with the AR_{75} that had at least five landfalling points in the NANC during (a),(c),(e) JJA and (b),(d),(f) SON on day 0 when landfalling occurred: (a),(b) 500-hPa wind (vector; unit: $m s^{-1}$) and height (color shading; unit: m), (c),(d) 850-hPa moisture flux (vector; unit: $kg m^{-1} s^{-1}$) and IVT (color shading; unit: $kg m^{-1} s^{-1}$), and (e),(f) precipitation ($mm day^{-1}$) and sea level pressure (contour interval: 1 hPa). Anomaly was calculated as the deviation from long-term climatological mean. Precipitation data were only available over land. Solid and dashed contours denote positive and negative anomalies, respectively. Note the different scales for vector and shading. Only those values and vectors statistically significant at 0.05 level are shown.

revealed that the AR_{75} events in both seasons were associated with wavelike circulation perturbations (of a zonal scale equivalent to zonal wavenumber 5–6) in the middle–upper troposphere, which can be traced westward to the extratropical North Pacific. Examples displaying the day -2 and day 0 circulation composites at 500 hPa, 850 hPa, and on the surface in SON are presented in Fig. 5. When the upper-level cyclonic circulation moved near the North American east coast, low-level cyclonic perturbations began to develop and induced northeastward moisture transport and precipitation over eastern North America. While individual cells of the wavelike circulation pattern moved relatively slowly (e.g., less than 20° in longitude) from day -2 to day 0, the maximum amplitude shifted from the North American west coast to the east coast in two days. The

faster propagation in the amplitude envelope was consistent with the downstream development concept of baroclinic waves (Chang 1993; Hakim 2003). This result suggested that the occurrence of AR_{75} event circulations was not due to the eastward translation of a synoptic system moving from the west but was induced by the local amplification of synoptic scale perturbations triggered by the downstream energy propagation from the west. Similar to other circulation features, the wavelike circulation perturbation was stronger in SON than in JJA (not shown). This result suggests the triggering effect of upstream wavelike perturbations on the occurrence of AR_{75} in northeastern North America and suggests that stronger upstream wave activity will lead to more active and stronger AR_{75} . In view of the upper-level perturbation that led the phase in the AR_{75} prevailing in

FIG. 5. As in Fig. 4, but for (a),(c),(e) day -2 and (b),(d),(f) day 0 and in a domain encompassing the extratropical North Atlantic, North America, and North Atlantic. Only those values statistically significant at 0.05 level are shown.

the lower troposphere and the large moisture transport from low latitudes, the vertical coupling between the lower and upper tropospheric circulations and the extratropical–tropical interaction were seemingly the crucial physical processes that supported the AR₇₅ activity.

East–west vertical cross sections of the geopotential height and moisture flux averaged over 30° – 45° N are presented in Figs. 6a and 6b. The negative geopotential height anomaly in SON was characterized by a deep westward-tilting vertical structure with the maximum anomaly in the middle troposphere that extends to the upper troposphere (Fig. 6b). By contrast, the counterpart in JJA was a weaker and shallower system with a

near-surface maximum that decayed more abruptly with height (Fig. 6a; note the different scales for color shading). Anomalous moisture flux was mainly located over the eastern part of low-level negative height anomaly, for example, the anomalous southerlies in the eastern flank of the cyclonic circulation where the east–west height gradient was the largest. The anomalously positive moisture flux extended considerably upward to almost 500 hPa in SON but was confined to mostly below 700 hPa in JJA. The amount of vertically integrated water vapor was therefore much higher in SON, which was consistent with the higher precipitation and stronger circulation seen in previous figures. Characteristics such as higher and deeper moisture transport in the south of

FIG. 6. Vertical cross sections of moisture flux (contour) and height (color shading) anomalies averaged over (a),(b) 30°–45°N and (c),(d) 60°–70°W during (a),(c) JJA and (b),(d) SON. Units are $10^{-3} \text{ kg m kg}^{-1} \text{ s}^{-1}$ and m for moisture flux and height, respectively. Only those values statistically significant at 0.05 level are shown.

the negative height anomaly (e.g., anomalous westerly in the southern flank of the cyclonic circulation) were also evident in the north–south cross sections averaged over 60°–70°W (Figs. 6c,d). The confinement of the

negative height anomaly in the lower troposphere (i.e., the sign reversal around 500 hPa) in SON observed in Fig. 6d was a reflection of the enhanced westward-tilting vertical structure because of increased baroclinicity in

the cooler season. By contrast, the vertical structure in JJA exhibited a deeper structure that tilted slightly northward with height. However, the moisture transport in JJA was highly confined to the lower troposphere (Fig. 6c).

In summary, in addition to the association with the moisture flux from the tropical/subtropical North Atlantic, the NANC AR₇₅ was also associated with the cyclone and the wavelike perturbation originating from the North American continent and the extratropical North Pacific. The continental connection made the NANC AR₇₅ having a stronger extratropical and continental origin compared with AR in other regions. For example, while the AR making landfall in the North American west coast was also often associated with the extratropical front, the moisture supply was from the oceanic tropics and/or extratropics (Neiman et al. 2008; Guan et al. 2012; Gimeno et al. 2014; Guan and Waliser 2015; Jackson et al. 2016). The moisture supply of the AR in southeast United States, which could be associated with frontal systems and/or tropical cyclones, mostly originated in tropical oceans such as the Caribbean Sea, the Gulf of Mexico, and the North Atlantic Ocean (Mahoney et al. 2016). The North Atlantic AR that made landfall in Europe was also found associated with the extratropical cyclone and front over the North Atlantic with certain connection to the low latitudes (Lavers et al. 2011, 2012; Lavers and Villarini 2013; Eiras-Barca et al. 2016). The ARs in these three regions were of oceanic origin and were likely to have a stronger connection with the tropics compared with the NANC ones.

4. Simulation and future projection of ARs

In view of the close association of AR₇₅ with extratropical synoptic perturbations, we first confirmed the ability of the HiRAM in simulating the strength and location of jet streams and storm tracks over North America and the North Atlantic (not shown) before analyzing the NANC AR₇₅ and associated synoptic circulation. The HiRAM realistically simulated the major characteristics of AR₇₅, which was detected in the same procedures as applied to reanalysis, such as occurrence distribution, horizontal and vertical structure of circulation, and contrast between JJA and SON. To avoid repetition, we do not present the occurrence distribution that was realistically simulated and only discuss key statistics in this paper (Table 1). The 75th percentile thresholds, which were 709.0 and 782.3 kg m⁻¹ s⁻¹ in JJA and SON based on the reanalysis, were 736.8 and 798.3 kg m⁻¹ s⁻¹ in the present_exp, respectively (Table 1, top). The number of occurrence days per year based on the reanalysis was 5.2 and 3.8 in JJA and SON, respectively, and 5.9 and 4.2 in the present_exp, respectively (Table 1,

TABLE 1. Occurrence days of landfalling AR events with an IVT strength exceeding the 75th percentile in observation, the present_exp, and the warming_exp.

	JJA	SON
IVT PR75 Threshold value (kg × m ⁻¹ s ⁻¹)		
ERA-Interim	709.0	782.3
HiRAM present	736.8	798.3
HiRAM RCP8.5	884.6	941.2
Landfalling AR events (days yr ⁻¹)		
ERA-Interim	5.2	3.8
HiRAM present	5.9	4.2
HiRAM RCP8.5 (Present threshold)	5.0 (10.7)	4.3 (7.7)

bottom). The strength (e.g., 75th percentile) and occurrence frequency of the ARs appeared to be simulated appropriately. The circulation composites of the AR events when the IVT strength exceeded the 75th percentile threshold in the present_exp are presented in Fig. 7. As in observations, the simulated northeastward moisture transport (stronger in SON and weaker in JJA) from the Caribbean Sea to Newfoundland near the North American east coast occurred in the eastern flank of the cyclonic anomaly. The larger positive and negative precipitation anomalies were associated with anomalously low and high surface pressure perturbations, respectively. The wavelike perturbations in the mid-upper troposphere were also evident atop the low-level circulation with a westward phase shift with increasing height. As in observations, the simulated upper-level wavelike perturbations originated in the extratropical North Pacific (not shown). Moreover, zonal and meridional scales and amplitudes of perturbations in all variables were simulated appropriately. The HiRAM was evidently capable of simulating AR₇₅ events and the corresponding circulations and appeared to be a suitable tool for projecting the AR activity under the influence of future SST warming.

In the warming_exp under the RCP8.5 scenario, the ARs that influenced the NANC were projected to become stronger by 2075–2100. The 75th percentile thresholds of IVT in the warming_exp were approximately 1.2 times higher than the thresholds in the present_exp (Table 1, top). The occurrence days counted based on the thresholds for the warming_exp were slightly fewer in JJA but about the same in SON (e.g., 5.0 and 4.3 days per season for JJA and SON, respectively, compared with the present_exp and observation). However, if this number was counted based on the thresholds in the present_exp, the number of occurrence days would be 1.8 and 2.3 times the current numbers in JJA and SON, respectively (numbers in parentheses in Table 1). This enhancement can also be seen in Figs. 8a

FIG. 7. As in Fig. 4, but for the present_exp. Only those values statistically significant at 0.05 level are shown.

and 8b, which displays the number of days of AR in different strengths. In contrast with the present_exp, the distribution in the warming_exp shifts toward larger IVT strength. Similar shifts in the distribution of number of points inside the target area were also identified, as shown in Figs. 8c and 8d. The distributions of the precipitation strength at the AR points inside the target region (Figs. 8e,f) suggested that stronger precipitation in SON, except those exceeding 50 mm day^{-1} , will become more frequent while weaker precipitation will occur less frequently in the warmer future. The more frequent occurrence of $30\text{--}50 \text{ mm day}^{-1}$ precipitation seen in Fig. 8f indicates an increase in total amount of precipitation larger than 30 mm day^{-1} . By contrast, the occurrence frequency of larger precipitation events in JJA will not change, while the weaker ones will be reduced. Number of grid points in the NANC were also calculated for different precipitation strength (Figs. 8g,h). The areas with medium precipitation strength (e.g., $10\text{--}30 \text{ mm day}^{-1}$) will be reduced in both JJA and

SON, but will increase for precipitation larger than 30 mm day^{-1} in SON. These results indicate that by the end of the twenty-first century, a wider region in the NANC will be more frequently affected by stronger ARs in both JJA and SON, and more AR-associated precipitation will be observed in SON.

By following the procedure described in the preceding subsection, landfalling AR events in the warming_exp with IVT amplitudes exceeding the historical 75th percentile (i.e., in the present_exp) were selected for constructing composites. The reason for choosing the historical criterion for detecting potential changes was to examine how the future ARs of similar strengths as the current ARs might be different in the future. This approach seems to be more relevant for the adaptation purpose and is often taken to report how the degree of severity of extreme events might change in the future.

The differences between the AR₇₅ event composites simulated in the present_exp and warming_exp presented in Figs. 9a and 9b revealed an overall increase

FIG. 8. Occurrence of landfalling NANC ARs vs (a)–(d) IVT and (e)–(h) precipitation strength during (left) JJA and (right) SON, and (g),(h) precipitation points inside the NANC domain. The occurrence is counted as numbers of (a),(b),(e),(f) days and (c),(d),(g),(h) points in the NANC. Only the precipitation inside the NANC domain were averaged to calculate the curves in (e) and (f). Numbers of IVT days were

in IVT in both JJA and SON. A particularly notable feature in JJA was the band of high IVT increase that extended northeastward from the North American east coast to the coast of northern Europe. This increase in the IVT band was observed in the northern and western flanks of an anomalously anticyclonic moisture flux pattern that encompassed the entire North Atlantic. The increase in IVT north of 50°N was associated with a band of anomalously westerly moisture flux in both seasons. In SON, a notable increase in IVT and a cyclonic anomaly were evident to the east of the NANC and covered a large area from 30° to 50°N in the western North Atlantic.

The composite differences in 850-hPa moisture flux and IVT presented in Figs. 9a and 9b comprised two parts—the changes in climatological means and AR₇₅ events. We computed the climatological means simulated in the present_exp and warming_exp and subtracted them from the AR₇₅ event composites in each experiment to obtain AR₇₅ event anomaly fields. Subsequently, the differences between the AR₇₅ event anomaly composites were computed. In addition, the changes in climatological means were also calculated by subtracting the mean in the present_exp from the one in the warming_exp. Through this procedure, we could clearly evaluate the relative contributions of climatological means and perturbations to the changes in AR₇₅ event circulation.

The changes in climatological means shown in Figs. 9c and 9d were characterized by the enhancement of anticyclonic moisture flux pattern. A particularly interesting feature was the westward penetration of poleward branch of moisture flux over the North American continent in JJA. A comparison reveals that the overall changes in AR₇₅ event circulation observed in Figs. 9a and 9b were similar to the changes in the climatological means. It follows that the changes in the basin-scale moisture flux pattern can be attributed to the changes in the mean fields, for example, the enhancement in the westerly IVT to the north of 50°N and in the North Atlantic anticyclonic IVT. A further comparison revealed subtle differences; specifically, the changes in the long-term means were relatively smaller near the North American east coast. Evidently, the changes near the coast were due to the changes in the AR₇₅ event anomalies as presented in Figs. 9e and 9f. The enhanced 850-hPa moisture transport and IVT were located near

and off the NANC, respectively, in both seasons. In JJA, the enhancement was due to the southwesterly moisture flux, which was embedded in a cyclonic anomaly over the east coast, along the NANC between 35° and 50°N. By contrast, in SON the enhancement was due to the appearance of an enhanced cyclonic flux anomaly off the coast that transported more moisture to the NANC. The contrast between the changes in long-term mean and AR₇₅ event anomaly indicated that the changes in the IVT near the coast was mainly due to the enhanced moisture transport embedded in the AR₇₅ events, whereas the changes in long-term mean dominated in the basin-scale IVT pattern.

One interesting contrast between JJA and SON is that while stronger IVT was projected to enhance in the future in both seasons, stronger precipitation in the NANC was projected to enhance only in SON (Fig. 8). A possible reason for the discrepancy is the following. A stronger AR does not guarantee stronger rainfall if no moisture convergence or topographic lifting occurs. The changes in moisture fluxes over the NANC in JJA (Fig. 9e), which were mostly of continental origin from the west, were relatively uniform in space and showed no signs of obvious convergence. In addition, larger IVT occurred mostly over the ocean off the NANC, instead of over the NANC. By contrast, in SON, the enhanced moisture fluxes embedded in a cyclonic circulation over the western extratropical North Atlantic were of oceanic origin and showed strong convergence over the NANC (Fig. 9f). This contrast in circulation and moisture source may explain why a more frequent occurrence of stronger precipitation in JJA was not projected despite more frequent occurrence of stronger AR.

It is interesting to note that the tropical connection of AR₇₅ events was projected to enhance. Day −2 composites shown in Figs. 9g and 9h reveal statistically significant moisture fluxes from south of 20°N before the cyclonic anomaly in AR₇₅ events reached the east coast. This enhanced tropical connection was particularly evident in SON with more moisture fluxes from the tropical eastern Pacific and the Caribbean Sea. This enhancement was consistent with the enhancement of the continental-crossing wavelike perturbation that will be discussed latter. These results indicate that in the warmer future, the perturbations associated with the NANC AR₇₅ would not only amplify in the strength but

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711 and 500 for JJA and SON, respectively, in the present_exp, and were 519 and 443 in the warming_exp. Number of IVT points were 69 793 and 51 295 for JJA and SON, respectively, in the present_exp, and 57 889 and 54 099 in the warming_exp. Units for IVT and precipitation strength are $\text{kg m}^{-1} \text{s}^{-1}$ and mm day^{-1} , respectively.

FIG. 9. Changes in 850-hPa moisture flux and IVT by subtracting the present_exp from the warming_exp during (left) JJA and (right) SON: (a),(b) day 0 composite, (c),(d) long-term climatological means, (e),(f) day 0 anomaly (defined as the deviation from long-term climatology in individual experiments), and (g),(h) day -2 anomaly. Units are $\text{kg m kg}^{-1} \text{s}^{-1}$ and $\text{kg m}^{-1} \text{s}^{-1}$ for 850-hPa moisture flux and IVT, respectively. Only those differences statistically significant at 0.05 level are shown.

FIG. 10. Cross sections of moisture flux changes (as defined in Fig. 9) averaged over 30°–45°N: composite (contour) and anomaly (color shading). Unit: $10^{-3} \text{ kg m kg}^{-1} \text{ s}^{-1}$. Anomalies statistically significant at 0.05 (0.1) level are marked by dot (shading).

also expand further into the lower latitudes. The projected equatorward penetration is particularly intriguing because more tropical moisture can be transported poleward into the extratropical synoptic systems and potentially enhance the convection and hydrological cycle in the extratropics.

To further confirm the aforementioned results, we analyzed the changes in the vertical distribution of moisture flux. The results for the 30°–45°N latitudinal band are presented in Fig. 10. The moisture flux changes in JJA were confined mostly below 700 hPa, with the maximum occurring near the surface (Fig. 10a, contour). By contrast, the changes in SON occurred in a much thicker layer, with the maximum occurring near 900 hPa. The moisture flux over the ocean (e.g., east of 70°W) was much larger than its counterpart near the coast (e.g., west of 70°W). The changes in AR₇₅ event anomaly (Figs. 10a,b, shading) exhibited a vertical distribution similar to those in the composite differences (Figs. 10a,b, contour) in terms of both pattern and strength, thus indicating that the AR₇₅ events were the dominant factors in the moisture transport changes in the vicinity of the NANC. By contrast, the differences due to the changes in climatological mean exhibited a similar vertical structure but with much weaker amplitudes (not shown).

Moisture flux changes represent a combination of changes in moisture and circulation. We further explored the relative contributions of moisture and circulation. Figure 11 displays the climatological-mean 850-hPa moisture and winds in the present_exp and the differences between the present_exp and warming_exp. In both JJA and SON, the climatological-mean low-level circulation was characterized by the anticyclonic circulation that transported moisture northeastward to the east of the North American east coast from low latitudes to high latitudes (Figs. 11a,b). Although the basinwide anticyclonic circulation continued to prevail in the warming_exp, it was projected to become weaker as indicated by the anomalous cyclonic circulation in the central and western extratropical North Atlantic in JJA and SON, respectively, in Figs. 11c and 11d. In contrast to the weakened anticyclone, the moisture content increases in the entire domain but with larger increases in the subtropical western North Atlantic in both seasons and an increase near the North American east coast in JJA. Weakened circulation and increased moisture content were also identified in the mean climatological changes that were characterized by essentially the same spatial structures (not shown). In contrast to the changes in the basin-scale circulation, the circulation changes near the NANC were mostly due to the changes in AR₇₅

FIG. 11. 850-hPa winds and moisture during (left) JJA and (right) SON: (a),(b) long-term means in the present_exp, and (c),(d) composite and (e),(f) anomaly differences between the warming_exp and present_exp. Units are m s^{-1} and kg kg^{-1} for winds (vector) and moisture (color shading), respectively. Only those differences statistically significant at 0.1 level are shown.

event circulation anomaly, as displayed in Figs. 11e and 11f. Although moisture increase in the western flanks of the anticyclonic anomalies east of the NANC was also projected, the increase was not statistically significant at the 0.05 level. By contrast, the circulation change was mostly statistically significant. It follows that enhanced southerlies or southwesterlies resulted in enhanced IVT and ARs near the NANC in the warming_exp. In conclusion, the enhanced basinwide IVT was mostly dominated by increased moisture (i.e., the thermodynamic effect), whereas the local changes in AR_{75} event IVT near the NANC were caused mainly by the dynamic (i.e., enhanced circulation) effect. The combination of basinwide thermodynamic and local dynamic changes led to the total IVT increase in the AR_{75} events in the warmer future.

A further examination revealed that the enhancement of circulation was an overall tendency over North America and the extratropical North Atlantic. Figure 12

shows the 200-hPa geopotential height and wind anomalies in the present_exp and the projected future changes (i.e., differences between the warming_exp and present_exp). Note that the anomalies shown were the deviations from the present and future climatological fields, respectively, in individual seasons. That is, the future changes in the mean fields were excluded. Evidently, observed wavelike perturbations were well simulated by the HiRAM (Figs. 12a,b), reflecting again the adequacy of using HiRAM in this study. The projected anomaly changes exhibited similar structures as in the present climate (Figs. 12c,d) over North America and the extratropical North Atlantic. Similar circulation enhancement was found in all other levels. The in-phase relationship between the anomalies in current climate and the future changes revealed an enhancement of the extratropical wavelike perturbations associated with the NANC ARs, indicating an overall enhancement of dynamic component. This enhancement was consistent

FIG. 12. (top) Composites of 200-hPa wind and geopotential height anomalies associated with AR₇₅ that had at least five landfalling points in the NANC during (left) JJA and (right) SON in the present_exp, and (bottom) the differences between the warming_exp and present_exp. Unit: m s^{-1} and m. Vectors that are statistically significant at 0.05 level are shown. All geopotential height values are shown to present a complete picture of wavelike perturbation.

with the overall strengthening of the jet streams and storm tracks over North America and the extratropical North Atlantic (not shown).

5. Latitudinal dependence

The AR events that affected the NANC might originate in different latitudes and the degree of connection to the moist tropics varied. We separated the AR₇₅ events originating in the north and south of 30°N (named northern and southern events, respectively) and examined the major characteristics of circulation and moisture transport associated with the two types of event. The percentages of northern and southern events were 87% (173/198) and 13% (25/198), respectively, in JJA, based on the ERA-Interim in the studied period; the numbers were 44% (64/144) and 56% (80/144) in SON (Table 2). The composites of IVT and 850-hPa moisture flux anomalies of southern and northern events are presented in Fig. 13. The composites of both northern and southern events exhibit similar characteristics, except that southern ones (Figs. 13c,d) with larger meridional scale extended farther south than northern ones (Figs. 13a,b). In addition, those in SON were evidently much stronger in strength and larger in meridional extent than those in JJA. The results suggest stronger tropical connection in southern events, especially in

SON. The major characteristics were similar to those seen in the composites of all events.

To further understand how the extratropical synoptic perturbations connected with moisture source. Composites of total fields of IVT, 850-hPa moisture flux, integrated water vapor, and sea level pressure (SLP) are shown in Fig. 14 for both northern and southern events in JJA and SON. As discussed in preceding sections, the AR₇₅ IVT in the NANC were located between the North Atlantic anticyclone and a cyclonic circulation over northeastern North America (Figs. 14a,b,e,f). The major IVT signals along the NANC coast were collocated with a tongue of high IWV that was connected to high moisture in the Caribbean Sea and the tropical western North Atlantic (Figs. 14c,d,g,h). Generally speaking, the circulations in both JJA and SON exhibited similar characteristics, except the stronger tropical connection for those occurring in SON.

There were more northern events in JJA and more southern events in SON. This interesting contrast can be understood as follows. As shown above, the AR₇₅ events were associated with the extratropical synoptic systems with southwesterlies that penetrated into the lower latitudes and transported moisture poleward. In JJA, weather systems were more active in the higher latitudes, where the baroclinic zone were located, and their connection to the tropics were weaker than in SON due

TABLE 2. Numbers (percentage) of northern and southern AR₇₅ events originating in the north and south of 30°N in ERA-Interim and HiRAM simulations.

	JJA	SON
ERA-Interim		
Northern (>30°N)	173 (87%)	64 (44%)
Southern (≤30°N)	25 (13%)	80 (56%)
Total	198	144
HiRAM historical		
Northern (>30°N)	140 (79%)	40 (32%)
Southern (≤30°N)	38 (21%)	85 (68%)
Total	178	125
HiRAM RCP8.5		
Northern (>30°N)	107 (82%)	26 (23%)
Southern (≤30°N)	23 (18%)	85 (77%)
Total	130	111

likely to the weaker amplitude and smaller meridional extent. Nevertheless, the moister subtropics in JJA can still provide enough moisture for the occurrence of the AR₇₅ events in the NANC. By contrast, in SON when the major baroclinic zone shifted southward, the weather systems became stronger with larger meridional scale and stronger southwesterlies extending farther to the lower latitudes in both southern and northern events. As a result, southern and northern events tended to occur in

similar frequency. Evidently, the seasonality in the characteristics of background states and synoptic disturbances led to the contrast between JJA and SON seen in Table 2.

Similar contrasts in frequency, seasonal dependence, and circulation were also simulated in the historical experiments, although the HiRAM tended to simulate slightly more southern events (Table 2, figures not shown). In the warmer future, a higher percentage of southern events was projected for SON and resulted in the dominance of southern events in the future (23% northern events versus 77% southern events). The result implies stronger tropical–extratropical interaction and a larger tropical influence on the autumn AR₇₅ events in the warmer future.

6. Summary and discussion

In this study, AR activity and characteristics along the NANC in JJA and SON based on the data of ERA-Interim reanalysis were investigated, and the HiRAM was used for simulating the current climate and projecting the future climate (RCP8.5 scenario). The observed ARs in JJA were weaker on average but occurred more frequently than those in SON. The AR with IVT strength exceeding the 75th percentile occurred 5.2 and 3.8 days per year in summer and autumn, respectively.

FIG. 13. As in Figs. 4c and 4d, but for the (a),(b) northern and (c),(d) southern AR₇₅ events in (left) JJA and (right) SON.

FIG. 14. Composites of (a),(b),(e),(f) IVT and 850-hPa moisture flux and (c),(d),(g),(h) IWPV (cm) and sea level pressure (hPa) in (left) JJA and (right) SON for the northern and southern AR₇₅ events. Units for IVT and moisture flux are $\text{kg m kg}^{-1} \text{s}^{-1}$ and $\text{kg m}^{-1} \text{s}^{-1}$, respectively.

The IVT threshold for the 75th percentile in SON was 10% larger than the threshold in JJA. AR₇₅ tended to occur in the eastern flank of the anomalous cyclonic circulation where the southerlies or southwesterlies prevailed. The cyclonic circulation was embedded in a westward-tilting wavelike circulation pattern that originated in the extratropical North Pacific. The wavelike circulation pattern exhibited the characteristics of downstream development of baroclinic eddies with new

perturbations successively developing to the east. When the upper-level cyclonic perturbations developed over eastern North America, the low-level low pressure anomaly became mature and transported moisture along the southerlies or southwesterlies and produced precipitation over the NANC. Moisture transport was greatest near the surface and was confined to mostly below 700 hPa in JJA. In SON, the maximum moisture transport occurred near 900 hPa and decayed more slowly upward to 500 hPa. The

thicker moist layer in autumn was consistent with the higher IVT and precipitation over the NANC. Considering the large perturbations in the middle–upper troposphere that originated in the far west and the enlarged meridional extent of the low-level perturbations over the North American east coast, vertical coupling and tropical–extratropical interaction were likely the crucial processes that induced strong ARs.

The HiRAM with a spatial resolution of 25 km appropriately simulated the jet streams, storm tracks, and the major characteristics of ARs, such as the spatial distribution of occurrence, the probability distribution of the number of days and areas with ARs, the associated precipitation strength, and the vertical and spatial structures of circulations associated with AR₇₅ events. This simulation demonstrated the high reliability of HiRAM for future projection of ARs. Strong ARs were projected to occur more frequently and to cover a wider area with larger IVT in both summer and autumn and larger precipitation in autumn under a future warming scenario. The number of days with AR₇₅ (based on the threshold in the present_exp) was projected to be 1.8 (2.3) times of the current climate number in JJA (SON). The 75th percentile threshold was projected to be approximately 20% larger by the end of the twenty-first century. This projected enhancement was contributed to by two processes—a smaller contribution was from the weakened basin-scale North Atlantic anticyclone but with a higher moisture content (i.e., the thermodynamic effect), and a larger contribution was from the enhancement in anomalous circulation in AR₇₅ events. The enhancement of anomaly circulation was consistent with the enhanced wavelike circulation pattern crossing the North American continent from the extratropical North Pacific, and also the stronger moisture flux from the tropical eastern Pacific and the Caribbean Sea, especially in SON. These results suggest that the influence of strong AR₇₅ on the NANC may increase under future warming scenarios due to the combination of increased water vapor in the large-scale environment (thermodynamic effect) and enhanced anomalous circulations (dynamic effect).

Unsolved issues remain and should be further explored. First, ARs in the warm seasons reported in this study were likely associated with the extratropical cyclones moving eastward from the west and the tropical cyclones moving poleward along the North American east coast (Howarth et al. 2019). ARs could be associated with only one type of cyclone or induced when both types of cyclones appeared simultaneously and interacted through a tropical–extratropical coupling. This study did not attempt to separate AR events due to the tropical cyclones from those associated purely with the

extratropical cyclones. The composites shown in this study were likely a combination of both types in view of the large meridional extent of the anomalous cyclonic circulation and southerlies or southwesterlies covering the entire North American east coast. Our results indicated a larger meridional extent in SON than in JJA. This might reflect the observation that tropical cyclones were more active in late summer and early autumn. In addition, the moisture source for AR events could be either extratropical or tropical origin due to different physical processes or weather types. For example, southern AR events exhibited a stronger tropical connection than the northern AR events. Categorization of ARs and circulation characteristics is an interesting topic that will be explored in a following study. It is also interesting to note that the southern AR events with stronger tropical connection are projected to be more dominant in the autumn of warmer future, suggesting a stronger tropical influence on the NANC AR-associated synoptic perturbations.

Second, the future projection was conducted based on only one high-resolution atmospheric general circulation model (AGCM) and one simulation member. Investigation of whether the changes reported here will remain the same if different AGCMs are used should be conducted. Third, the numerical simulations were driven by prescribed SST. This study did not explore how atmosphere–ocean coupling might modify the projected changes. Nevertheless, the HiRAM appropriately simulated the key characteristics of AR₇₅ in present climate, thus suggesting the reliability of using HiRAM for climate simulations driven by prescribed SST. The findings presented here are especially useful considering the advantages of high-resolution models in simulating the small-scale extreme events.

Another uncertainty for this type of projection is rooted in the projected SST changes, which might have different impacts on the NANC ARs. Our study adopted ensemble SST changes based on 24 CMIP5 models. The magnitude and pattern of SST changes can be quite different among models, although the overall warming trends were qualitatively similar. The effect of different SST change patterns in forcing the high-resolution AGCMs has been explored in many studies (e.g., Mizuta et al. 2014; Kitoh and Endo 2016, 2019; Kusunoki 2018; Chen et al. 2019). The projected results could be different, especially for more localized phenomena (e.g., East Asian monsoon onset and retreat, typhoons, heavy rainfall). To the best of our knowledge, this study is likely the first one to investigate the changes in the NANC AR using a high-resolution AGCM. How the SST change patterns would affect the projected changes in the NANC AR and associated structures and circulations requires further studies by diagnosing the projected data driven by various SST change patterns. Such a study is being planned.

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Data availability. Data analyzed in this study can be made available upon a request to the corresponding author (Huang-Hsiung Hsu, hhhsu@gate.sinica.edu.tw).

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