Disentangling the Driving Mechanisms of the Tripole Mode of Summer Rainfall over Eastern China

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ABSTRACT: The spatial distribution of summer rainfall anomalies over eastern China often shows a tripole pattern with rainfall anomalies over the Yangtze River basin varies in opposite phase with North China and South China. It is not clear whether this tripole pattern is an intrinsic atmospheric mode or it is remotely forced. Using two sets of model outputs from 20 models participating in phase 5 of the Coupled Model Intercomparison Project (CMIP5), this paper investigates the driving mechanisms of this leading rainfall mode and its major influencing factors. One set (piControl) is fully coupled atmosphere–ocean simulations under constant preindustrial forcing and the other (sstClim) is atmosphere-alone models forced by prescribed climatological sea surface temperatures (SSTs). By comparing results from these two different sets of simulations, it is found that the tripole pattern is the leading mode of summer precipitation variability over eastern China with or without oceanic forcing. It can be regarded as an intrinsic atmospheric mode although air–sea interaction can modify its temporal variability. The cyclonic–anticyclonic atmospheric circulation anomaly over the northern North Pacific is identified as a key factor in both experiments. As atmospheric internal variability, it is related to a circumglobal zonal wave train propagating along the westerly jet stream. When air–sea interactions involved, modulation from SST anomalies is exerted through the meridional Pacific–Japan/East Asia–Pacific wave train propagating along the East Asian coast. Our results suggest that the North Pacific could be another key region providing potential predictability to the East Asian monsoon in addition to the Indo-Pacific.

KEYWORDS: Air-sea interaction; Atmospheric circulation; Rainfall; Climate models; Climate variability

1. Introduction

Eastern China is a concentrated area of dense population and massive economic and agricultural activities. Rainfall variability is a key climate factor of great importance because of its links to droughts, floods, and water resources. As a typical monsoon climate, precipitation over eastern China is strongly seasonal with the main rainband migrating northward in early summer and southward in late summer. The speed and extent of this migration often results in banded structures in spatial distribution of summer-mean rainfall anomalies. Shifts in position or changes in intensity of the climatic rainfall pattern on interannual and inter-decadal time scales often trigger regional droughts and floods, with implied risks to human life and ecosystem functions (Chang 2004; Huang et al. 2012).

The most prominent characteristic of summer rainfall anomalies over eastern China is the meridionally multipolar spatial distribution (Wang et al. 2008; Zhang 2015). Evidence from historical proxy data and observational measurements confirms the existence of tripole, dipole, or monopole EOF modes with variable fractional variances on time scales from interannual to century (Zhu and Wang 2002; Yang and Lau 2004; Ding et al. 2008; Han and Zhang 2009; Lei et al. 2011; Huang et al. 2011; Ye and Lu 2012). Among these modes, the tripole mode is of great importance during the recent decades, especially on interannual and interdecadal time scales (Hsu and Lin 2007; Ding et al. 2008; C. He et al. 2017). Centered over the Yangtze River basin, the tripole mode features rainfall anomalies over both North and South China with an opposite sign. This mode has been shown as the first EOF mode of eastern China summer rainfall during the recent decades.

Efforts have been made in recent years to understand the formation mechanisms and influencing factors of the tripole mode to improve long-term predictions. Signals from the oceans are an obvious source of potential predictability (Zhou et al. 2009; Huang et al. 2012; Yu et al. 2015). It is believed that ENSO (El Niño–Southern Oscillation) has a major effect on precipitation variability over East Asia, depending on different phase of the ENSO event (Huang et al. 2012). On the decaying phase of ENSO, under the joint influence from the Indian Ocean and the
western North Pacific, summer rainfall anomalies over eastern China tend to exhibit a tripole mode (Liu et al. 2008; Sun et al. 2010). Heating anomalies over the western Pacific warm pool is also of great importance, as it triggers the meridional Pacific–Japan/East Asia–Pacific (PJ/EAP) wave train (Nitta 1987; Huang and Li 1987), which could then induce the tripole rainfall pattern over Eastern China (Hsu and Lin 2007; Jin et al. 2016). In the middle to high latitudes, spring’s Arctic circulation anomalies have been suggested as a possible precursor of the tripole pattern. A positive Arctic Oscillation phase in the spring has been shown to be related with a tripole pattern rainfall anomaly feature as deficient rainfall over the Yangtze River basin and abundant rainfall over Southern China and part of North China (S. He et al. 2017). A recent study further emphasized the importance of sea ice conditions over the Barents Sea in predicting the tripole mode (He et al. 2018).

Although several climate modes are thought to be related to the tripole rainfall pattern in eastern China, their relationships may not be statistically stationary. Jin et al. (2016) found that the out-of-phase rainfall pattern between the Yangtze River basin and northern China is related to the PJ/EAP pattern during 1979–95, but the relationship weakened significantly afterward. In 2016, in the absence of an earlier ENSO event, a tripole rainfall pattern still appeared and was attributed to the Silk Road wave train over the midlatitudes (Li et al. 2017). Moreover, under different decadal backgrounds, such as different phases of the Pacific decadal oscillation (PDO), rainfall patterns driven by an ENSO decaying phase can also be dipole patterns instead (Feng et al. 2014). A robust mechanism driving the tripole rainfall mode is still lacking.

Based on observational data, Hsu and Lin (2007) showed that the tripole mode is related to wave activities from the tropical western Pacific, the Eurasian continent, and the Tibetan Plateau. They suggested that the tripole pattern might be an intrinsic dynamic mode that could be triggered by various factors. However, it is difficult to isolate the atmospheric internal signal by analyzing the observational data alone. Using a set of experiments of CESM model without SST anomalies, C. He et al. (2017) also show that the tripole and dipole modes of eastern China might be atmospheric internal variability. While using a set of CLIVAR experiments that forced by prescribed SST anomalies, Yang et al. (2017) also obtained the out-of-phase relationship of rainfall between North China and the Yangtze River basin.

As a typical monsoon climate, summer rainfall over eastern China plays a very important role in agriculture, water resources, as well as risks of regional droughts and floods. A good understanding of its driving mechanisms may help to search for leading influencing factors and potential predictability. Current literature does not provide a clear consistent picture. By taking advantage of two sets of existing multimodel simulations from phase 5 of the Coupled Model Intercomparison Project (CMIP5), this paper aims to clarify the nature of dominant pattern of summer rainfall anomalies over eastern China. One set of the simulations uses fully coupled atmosphere–ocean models under constant preindustrial forcing and the other atmosphere-only models forced by climatological mean SSTs. The following questions are asked: 1) Is ocean coupling a necessity? 2) Are the mechanisms different in coupled and atmosphere only simulations? 3) Is there any key circulation system integrating different sources of influence?

The paper is organized as follows. A description of the models and methods used in the study is given in section 2. Sections 3 and 4 investigate the mechanisms forming the tripole mode in atmosphere–ocean coupled system and atmospheric only variability. Section 5 discusses the role of northern North Pacific circulation in forming the tripole mode. Discussion is presented in section 6, followed by main conclusions.

2. Data and methods

a. Observations

Observational and reanalysis data are applied to investigate the tripole mode during 1961–2013, including 1) gridded monthly precipitation data on a 0.25° × 0.25° grid from the Chinese Meteorological Administration, version 5.1 (CN05.1; Wu and Gao 2013) to obtain the observational tripole mode in eastern China; 2) monthly precipitation dataset on a 0.5° × 0.5° grid from the University of East Anglia, version 4.0 (CRU4.0; Harris et al. 2014); 3) monthly Japanese 55-year Reanalysis dataset with 1.25° × 1.25° resolution from the Japan Meteorological Agency (JRA-55; Kobayashi et al. 2015); and 4) monthly sea surface temperature data on a 1° × 1° grid from the Hadley Centre (HadISST; Rayner et al. 2003).

b. Model experiments

To examine the differences in mechanisms forming the tripole pattern in atmosphere–ocean coupled and atmospheric only system, outputs from two experiments of 20 models (Table 1) participating in CMIP5 (Taylor et al. 2012) are investigated. The first one (piControl) is coupled atmosphere–ocean simulation. This simulation with constant anthropogenic forcing is ideal to investigate the internal variability of the atmosphere–ocean coupled system. To make the length of data uniform for each model, the last 450 years of output of the original data are used in the piControl experiment.

The other experiment (sstClim) is atmosphere-only simulation, forced by prescribed climatological annual cycle of SST. This simulation is able to reveal the atmospheric internal variability. As most models only have 30 years output in the sstClim simulation, to ensure a uniform length of data for each model the last 30 years of data are used.

c. Methods

Leading modes in summer rainfall are obtained by applying empirical orthogonal function (EOF) method on the normalized anomalies of June–August (JJA) seasonal mean rainfall. All data are regridded to a common resolution of 2.5° × 2.5° to convenient comparison. Before the data processing, linear trends in all data are first removed. The performance of models on simulating the leading modes of eastern China summer rainfall is evaluated at first by calculating the pattern correlation coefficients (PCCs) between the observational EOFs and
each model’s simulation. After comparison, 14 better models are then selected to conduct rest of the study.

The wave activity flux (WAF) proposed by Takaya and Nakamura (2001) is applied to show the propagation of stationary Rossby waves associated with the tripole mode. The horizontal components of the WAF under the pressure coordinate are calculated as

\[
W = \frac{1}{2|U|} \left[ \tau(x, y) \psi - \psi(x, y) \tau \right] + \frac{1}{2|U|} \left[ \tau(x, y) \psi - \psi(x, y) \tau \right]
\]

where \( U = (u, v) \) is the horizontal wind velocity and \( \psi \) is the streamfunction. The overbars represent the climatology, calculated as the long-term mean during the whole period of the experiment, and the primes denote the anomalies with respect to the climatology.

The observed PDO index is obtained from Washington University (http://research.jisao.washington.edu/pdo/), defined as the leading principal component of the SST anomalies (SSTAs) over the northern North Pacific (poleward of 20°N). The SSTAs are obtained by removing both the climatological annual cycle and the global-mean SSTAs from the data at each grid point. The observed Niño-3.4 index is obtained from NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/data/indices), defined as the area average SST over east central tropical Pacific (5°N–5°S, 170°E–120°W). The same methods have been applied on the model output to calculate the PDO index and Niño-3.4 index.

### 3. The tripole mode in observations and coupled atmosphere–ocean model simulation

Figure 1 shows the first two EOF modes of summer-mean rainfall anomalies over eastern China during 1961–2013. Consistent with previous studies, the first EOF shows a tripole pattern with 18.67% of variance contribution. Rainfall anomalies over the Yangtze River basin varies in opposite phase with both North China and South China. The second EOF shows a dipole structure with opposite rainfall anomalies between the north and south of the Yangtze River. These two modes can be well separated based on the North criteria (North et al. 1982).

The fidelity of the 20 CMIP5 models on simulating the leading modes of eastern China summer rainfall in piControl run is shown in Fig. 2. The order of leading modes might be different in different models. As long as the model can produce the first two leading mode (tripole and dipole mode) in observation in its EOF1 to EOF3 we consider this model able to reproduce the leading modes of eastern China summer rainfall. Detailed processes are as following. First, the EOF1 to EOF5 in each model during the study period are obtained. Then the PCCs between these EOFs with the observational tripole and dipole mode (as shown in Fig. 1) are calculated. At last, the maximum of PCCs is selected and only those for which the PCCs are larger than 0.6 are considered as the tripole or dipole mode and are marked in Fig. 2.

As shown in Fig. 2, there are 14 models out of these 20 models that could reproduce both the tripole and dipole mode in their
first three leading modes. The pattern of tripole and dipole in each model along with their corresponding EOF number are shown in Figs. S1 and S2 (in the online supplemental material), respectively. Among all these models, the BCC-CSM1-1 and BNU-ESM have the tripole as the first leading mode. Although some other models have the tripole mode in their second or third mode, their PCCs with the observational tripole mode are larger than 0.8 (e.g., CanESM2, CCSM4, CNRM-CM5, FGOALS-G2, GISS-E2-H, and GISS-E2-R). These 14 models are selected to further study the mechanisms forming the tripole mode.

To figure out the corresponding circulation anomalies related to the tripole mode, the 850-hPa low-level winds anomalies and the large-scale rainfall anomalies are regressed onto the PC of the tripole mode. As shown in Fig. 3a, during 1961–2013, the tripole-related low-level winds shown as a pair of anomalous cyclonic and anticyclonic circulation over East Asia, resembling the PJ/EAP wave pattern. There are also suppressed convective activities around the Philippine Sea (Fig. S3 in the online supplemental material), which can excite the PJ/EAP teleconnection (Nitta 1987; Huang and Li 1987; Kosaka and Nakamura 2010). These anomalous circulations induce convergence in Yangtze River basin, resulting in abundant rainfall, whereas North China and South China are controlled by anomalous northerlies and anticyclone, respectively, leading to deficient rainfall. Therefore, the tripole pattern of rainfall anomalies forms.

Figure 3b presents the 14-model ensemble mean of 850-hPa wind and rainfall anomalies related to the tripole mode. It displays the common signals among these models that induce the tripole mode by reducing the noises from other internal variabilities and random model biases, to identify the key system. As shown in Fig. 3b, the multimodel ensemble (MME) of the 14 models can well reproduce the PJ/EAP pattern over East Asia that induces the tripole rainfall pattern. A clearer structure of the pair of cyclonic and anticyclonic anomaly is extracted in the MME compared with the reanalysis data (Fig. 3a) since most noises are reduced. Consistent with observational results, there are also deficient rainfall anomalies and suppressed convection (Fig. S3) over the Philippine Sea that is able to trigger the EAP/PJ pattern.

As revealed in previous studies, the tripole rainfall mode is closely related to the SSTAs over the tropics. Figure 4a gives the SSTAs associated with the tripole mode during 1961–2013. Corresponding to the positive rainfall anomalies over the Yangtze River basin while negative rainfall anomalies over North and South China, there are significant SSTAs over the tropics and the mid- to high-latitude North Pacific. Over the tropics, an El Niño–like SST pattern is evident. The warm SSTAs over the eastern Pacific and cold SSTAs over the western North Pacific are revealed to be critical in forming and maintaining the western North Pacific anomalous anticyclone (Wang et al. 2000, 2013; Xiang et al. 2013). The warming over eastern Pacific induces convection anomalies over the central Pacific (Fig. S3a), triggering a cyclonic anomaly to the northwest of the warming as result of the Gill response (Fig. 3). The easterlies on the northern flank of the cyclonic anomaly superpose on the mean northeasterly trades and lead to cooling in sea surface over the western North Pacific. The convections there are suppressed, which generates an anomalous anticyclone by stimulating descending Rossby wave to its west, and forms a PJ-like wave pattern along East Asian coast.

Figure 4b presents the MME result of the tripole-related SSTAs in the 14 CMIP5 models. The SSTA pattern resembles the observational result (Fig. 4a) with cooling over western North Pacific and warming over eastern tropical Pacific, indicating that the air–sea interactions contributing to the formation of the tripole mode could also be well reproduced by the models.
However, compared with observational results, the MME results also show extended warming over central tropical Pacific and significant warming over the Indian Ocean. These SSTAs could induce anomalous Walker circulation resulting in descending motion over the western North Pacific. Moreover, the warm Indian Ocean SSTAs could also stimulate easterly equatorial warm Kelvin wave over the western Pacific (Xie et al. 2009, 2016; He et al. 2022). These differences in SSTAs compared with observation therefore lead to a stronger anomalous anticyclone over the western North Pacific dam or evident structure of EAP/PJ pattern along the East Asian coast in the piControl MME.

4. The tripole mode as atmospheric internal variability

Although previous research has indicated that the tripole mode could be internally driven in atmosphere (Hsu and Lin 2007; C. He et al. 2017), the differences of the tripole mode and its associated circulations between the coupled system and atmosphere alone are still unclear. The comparison of multi-model results in piControl and sstClim simulations enables us to address the question. The multimodel results could also largely reduce the influence of model dependency.

There are 9 models out of these 14 better models that also conducted the sstClim simulation. Using the same method as in piControl simulations from the 14 selected CMIP5 models, obtained by linear regression onto the tripole’s corresponding principal components (PCs). In the observation, coefficients that are statistically significant at the 10% level are marked by dots for precipitation and black arrows for winds. The same plotting convention is used for the MME when there are at least 10 models that are consistent with the sign of MME.

Fig. 3. Tripole mode associated 850-hPa winds (arrows; units: m s\(^{-1}\)) and precipitation (shading; unit: mm day\(^{-1}\)) anomalies in (a) observational analysis during 1961–2013 and (b) the ensemble mean of piControl simulations from the 14 selected CMIP5 models, obtained by linear regression onto the tripole’s corresponding principal components (PCs). In the observation, coefficients that are statistically significant at the 10% level are marked by dots for precipitation and black arrows for winds. The same plotting convention is used for the MME when there are at least 10 models that are consistent with the sign of MME.

Fig. 4. Tripole mode associated SSTAs (units: K) in (a) observational analysis during 1961–2013 and (b) the ensemble mean of piControl simulations from the 14 selected CMIP5 models, obtained by linear regression onto the tripole’s corresponding PCs. In the observation, coefficients that are statistically significant at the 10% level are marked by dots. The same plotting convention is used for the MME when there are at least 10 models that are consistent with the sign of MME.

Fig. 2, Fig. S4 examines whether these models could produce the leading modes of eastern China summer rainfall in their atmosphere only runs. The results show that there are five models that can capture the tripole mode and dipole mode in their sstClim simulation. This means that the tripole mode could also be produced by these models’ atmospheric internal variability. The tripole mode of summer rainfall in the eastern China is therefore an intrinsically atmospheric mode.

To compare the tripole mode in atmosphere-only and atmosphere–ocean coupled systems, these five models (Fig. 5) that can reproduce the tripole mode both in their sstClim and piControl experiment are selected. It can be seen that the spatial similarity of the tripole in the sstClim experiment (Fig. 5a) with the observational tripole are slightly smaller than in the piControl experiment (Fig. 5b), indicating that the atmospheric internal mode could be modulated by air–sea interactions in the atmosphere–ocean coupled system.

To investigate the differences in atmospheric circulation anomalies forming the same tripole pattern between sstClim and piControl simulation, we project the normalized summer rainfall anomalies of model output onto the observed tripole rainfall pattern to obtain a pseudo-PC of the tripole mode in these two different simulations. The linear regressions are then applied onto these pseudo-PCs to present the tripole mode associated circulation anomalies.

Figure 6 compares the MME of the tripole mode related 850-hPa winds and large-scale rainfall anomalies between the
piControl and sstClim simulation of these five selected models. Different from the result in piControl simulation (Fig. 6b), the western North Pacific anticyclonic circulation anomaly is less obvious and of smaller scale in the sstClim simulation (Fig. 6a), particularly the part over the ocean. In contrast, the northern North Atlantic, and northeastern Asia. The anomaly center locate between them, and the amplitude is relatively smaller. Moreover, a significant anomaly center out of phase with the northern North Pacific circulation anomaly exists over the Arctic region, extending to northeastern Asia.

In the piControl experiment (Figs. 7b,d), the mid- to high-latitude wave train shown in the sstClim experiment still exists, but is evidently weaker. The meridional PJ/EAP wave train along the East Asian coast to the North Pacific is significant with stronger amplitude both in the high and low levels, which nearly disappears in the sstClim run. This suggests that except for the mid- to high-latitude wave train in the atmosphere alone, the PJ/EAP pattern, which can be triggered by air–sea interactions, could also modulate the tripole rainfall pattern over eastern China in the coupled system. As the common center of the zonal and meridional wave trains, the northern North Pacific cyclonic anomaly plays an important role in forming the tripole pattern. It can also be seen that in atmosphere–ocean coupled system, the amplitude of the zonal wave train is relatively weaker than the meridional EAP/PJ teleconnection, indicating a more active role of air–sea coupling in forming the tripole pattern than the atmospheric internal variability.

To investigate the differences between the atmospheric circulation forming the tripole mode in the atmosphere only and the atmosphere–ocean coupled system, Fig. 7 compares the wave activities related to the tripole mode in sstClim and piControl experiments. In the sstClim experiment (Figs. 7a,c), the most obvious system that directly affects East Asia is the northern North Pacific cyclonic anomaly, spanning from North China to the northern North Pacific. This circulation anomaly is part of a circumglobal zonal wave train propagating along the Northern Hemisphere westerly jet stream. This wave train consists of five significant centers that are in phase with the northern North Pacific circulation anomaly. The remaining four centers are located at the Ural Mountains, central North America, the northern North Atlantic, and northeastern Asia. The anomaly centers out of phase with the northern North Pacific circulation...
The MME variance is 7.33 (with model spread ranges from 6.14 to 9.69) in the piControl simulation, and 6.66 (with model spread ranges from 4.71 to 7.73) in the sstClim simulation. The stronger variances of tripole PCs in piControl simulation indicate an exacerbated tripole mode in air–sea coupled system than that in the atmospheric internal variability.

5. The role of northern North Pacific circulation anomalies

By comparing the atmospheric circulation forming the tripole mode in atmosphere-only and atmosphere–ocean coupled system, the role of the northern North Pacific circulation anomaly has been emphasized. To further investigate the impact of this circulation anomaly on eastern China, here we construct a northern North Pacific atmospheric circulation index (NPCI). The NPCI is defined as the area averaged vorticity anomalies over the northern North Pacific region (30°–60°N, 150°E–160°W), representing the strength of the cyclonic/anticyclonic anomaly over this region. A positive NPCI value indicates a cyclonic circulation anomaly over the northern North Pacific region, and vice versa.

The NPCI during 1961–2013 are calculated based on the JRA-55 data. The 850-hPa wind anomalies, SSTA, and land rainfall anomalies are obtained by regressing onto the NPCI (Fig. 8a). When the NPCI is positive, an anomalous cyclone spans over the northern North Pacific. The northerly winds on its west edge affect North China, impeding moisture transportation to North China and enabling moisture convergence on
Yangtze River basin. Accompanying with it, an anticyclonic anomaly exits over the western North Pacific, suppressing convections over this region and also enhancing moisture convergence on the Yangtze River basin. Under these circumstances, the tripole pattern of rainfall anomaly forms. This indicates a close relationship between the variability of NPCI and the tripole rainfall pattern. Figure 8b gives the MME of NPCI-related 850-hPa wind anomalies, SSTA, and land rainfall anomalies in 14 CMIP5 models’ piControl experiment, highly resembling those in the reanalysis and observation (Fig. 8a). This further confirms that the relationship between NPCI and tripole rainfall mode is robust and can be well reproduced by the atmosphere–ocean coupled model.

To further investigate the structure and impact of this circulation anomaly, the vertical cross sections at 41°N (zonal section) and 118°E (meridional section) are given in Fig. 9. Along 118°E, in both observation and MME, anomalous downward northerly flow occupies North China from high to low levels, leading to negative precipitation anomalies over this region. Meanwhile, the Yangtze River basin is controlled by upward southerly flow from low to high levels, lifting the air and bringing sufficient moisture to this area. These two anomalous flows interface over the Yangtze River basin and form the positive precipitation anomaly here. Over South China, anomalous downward flow suppresses the convection and results in less rainfall over this region.

Figures 9c and 9d depict the vertical structure of the northern North Pacific circulation anomalies. From low to high levels, this anomalous circulation shows a barotropic structure. Over the eastern part of the anomalous cyclone in northern North Pacific, upward motion occurs over the North Pacific Ocean. Over the western part of it, descending motion prevails over North China, favoring negative rainfall anomalies over this region. Therefore, as shown in both observations and model simulations, the anomalous cyclone or anticyclone over the northern North Pacific can favor the tripole mode of rainfall anomalies over eastern China.

6. Discussion

a. Relationship of northern North Pacific anomalous circulation with ENSO and PDO

As shown in the above-mentioned analysis, the NPCI is related to an ENSO–PDO like SSTA. That is, a positive NPCI is accompanied with a warmer tropical eastern Pacific Ocean and cooler northern North Pacific. Figure 10a gives a power spectrum of NPCI in both observation and model outputs. Obvious interannual and decadal periods are shown (i.e., periods of 3 years, 5–7 years, and 9–10 years) and some of the model results also show significantly interdecadal periods around 15–25 years, which resemble the period of ENSO and PDO.

Figure 10b further gives the correlation coefficients of NPCI with the Niño-3.4 index and the PDO index. The NPCI shows a close relationship with both indices and all the coefficients are significant at a level of 0.05. Moreover, the relationship is stronger between the NPCI and PDO index than the Niño-3.4 index. The correlation coefficients between the NPCI and the PDO index range from 0.36 to 0.68, with an ensemble mean of 0.5 (shown by the black square), close to the observed correlation of 0.52 (red star). The correlation coefficients with ENSO are much weaker, ranging between 0.1 and 0.36. The ensemble mean is 0.23, smaller than 0.34 from observations. However, whether the SSTA over the tropical Pacific or the northern North Pacific play a more active role affecting the NPCI requires further numerical experiments. Moreover, according to the correlation coefficients, assuming the ENSO and PDO are independent of each other, their combined influences can explain at most 60% of the NPCI variability, indicating that except for ENSO and PDO, there are other factors affecting the variability of this circulation anomaly.

b. The northern North Pacific anomalous circulation as an atmospheric intrinsic mode

Lau et al. (2004) proposed that the North Pacific is a regulator for boreal summertime’s climate over East Asia and North America. They defined a North Pacific SST index as the EOF1 of the summertime SST over the North Pacific region on an interannual time scale. Our results in the atmosphere–ocean coupled simulation (piControl) and observational data are consistent with their findings, which show a significant relationship between SSTA over the northern North Pacific with rainfall anomalies over eastern China. However, our results further revealed that the northern North Pacific atmospheric anomalous circulation is the key system forming the tripole mode in the atmosphere-only experiment (sstClim). That means that this anomalous circulation also exists in the atmospheric internal variability without oceanic forcing. Therefore, basically it should be an atmospheric intrinsic
mode, which could be additionally modulated by SSTAs over the Pacific regions.

7. Conclusions

Summer-mean rainfall anomalies over eastern China often exhibit a tripole pattern on interannual to interdecadal time scales. It is important to understand the driving mechanisms of this mode in order to improve regional climate predictions for drought, flood, and water resources. There are many previous investigations, but it remains controversial whether this rainfall pattern is fundamentally an atmospheric intrinsic mode or it is forced by the oceans. By examining the outputs from two sets of numerical experiments from 20 CMIP5 models, one fully coupled (piControl) and the other atmosphere only (sstClim), this paper has clarified the intrinsic nature of the tripole rainfall mode as part of atmospheric internal variability. Land–sea thermal contrast and large-scale orography may have a role to play through planetary wave trains and atmospheric teleconnections. Atmosphere–ocean coupling is not a necessary condition for the tripole summer rainfall pattern to appear but including air–sea interaction can slightly strengthen its temporal variability. We have further identified the important role of a northern North Pacific large-scale atmospheric circulation mode in driving the tripole rainfall mode over eastern China.

To start with, we have analyzed 450 years of piControl simulations from each model to serve as a model evaluation. Among the 20 CMIP5 models, 14 are capable of reproducing the tripole mode as one of the leading modes in their piControl atmosphere–ocean coupled simulations. The rainfall mode associated with large-scale wind anomalies and SSTAs can also be well represented. In both observational analysis for the period 1961–2013 and the coupled piControl simulations, the tripole rainfall mode corresponds to a pair of anomalous anticyclonic–cyclonic circulation along the East Asian coast, resembling the PJ/EAP pattern.

A comparison between atmosphere-only (sstClim) simulations and fully coupled atmosphere–ocean (piControl) simulations suggests that the tripole mode is an atmospheric intrinsic mode. Coupling with the oceans is not necessary to produce the tripole mode but will slightly exacerbate it. Further examination indicates that the anomalous cyclone–anticyclone over the northern North Pacific is a key atmospheric circulation feature driving the tripole rainfall mode. In atmosphere-only simulations, this anomalous circulation is associated with a circumglobal zonal wave train propagating along the jet stream. In atmosphere–ocean coupled simulation, in addition to this zonal wave train, the meridional PJ/EAP wave train propagating along East Asian coast also plays an important role. The anomalous cyclonic–anticyclonic circulation over the northern North Pacific is a shared platform of both zonal and meridional wave trains.

By defining a circulation index based on vorticity anomalies over the northern North Pacific region, the tripole rainfall pattern can be easily recovered from a linear regression onto this index. Serving as an integrator of both midlatitude and tropical
influences, this northern North Pacific circulation index provides an alternative tool for monitoring and predicting summer rainfall anomalies over eastern China.

The intrinsic nature of the tripole mode verified by multimodel simulations here is consistent with the findings of Hsu and Lin (2007) and C. He et al. (2017). Although the tripole mode is a component of atmospheric internal variability, previous studies also show evidence of modulation from different atmospheric external forcings, such as oceanic forcing, snow cover in Tibetan Plateau, and anthropogenic activities (Lau et al. 2004; Liu et al. 2008; Ding et al. 2009; He et al. 2018; Wang et al. 2021). These conclusions are not contradictory. In this study, we have further revealed the differences in mechanisms forming the tripole mode between air–sea coupled and atmosphere-only system. Comparison between the two sets of simulations shows that the involvement of air–sea interaction can slightly exacerbate the tripole mode, which might be related to the enhanced EAP/PJ pattern compared with atmospheric internal variability. This is consistent with previous studies showing that the EAP/PJ wave train could bridge the signals from the tropical ocean to East Asia (Huang et al. 2011; C. He et al. 2017; Jin et al. 2016; Xie et al. 2016) and provide predictability for the tripole mode. Moreover, our results suggest that in the absence of oceanic signals, signals from the circumglobal wave train or atmospheric teleconnections related with the northern North Pacific anomalous circulation may be helpful in predicting the East Asian rainfall pattern.

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Data availability statement. CN05.1 data were obtained from the Chinese Meteorological Administration, and are available upon request to corresponding author. CRU data were downloaded from Climatic Research Unit (University of East Anglia) and NCAS through https://crudata.uea.ac.uk/cru/data/hrp/. The JRA-55 data were obtained from Japan Meteorology Agency (https://jra.kishou.go.jp/JRA-55/index.en.html). The HadISST data were downloaded from Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadisst/). The CMIP5 model outputs were downloaded from https://www.ipcc-data.org/sim/gcm_monthly/AR5/Reference-Archive.html.

REFERENCES


FIG. 10. (a) Power spectrum of the NPCIs in observations during 1961–2013 (red solid line), 14 models (gray lines), and their ensemble mean (black line) in ptControl simulation; the exceedance of 95% confidence interval is represented by a red dashed line for observation, and dots for each model. (b) Relationships between NPCI with the Pacific decadal oscillation (represented by the PDO index) and ENSO (represented by the Niño-3.4 index), where the red star is for observations, the black square is for MME, and other colors are for each model; all coefficients are statistically significant at the 5% level.

TABLE 1. Correlation coefficients between the NPCIs and the three key modes of the circulation: the EAP/PJ, the Arctic Oscillation (AO), and the PDO, during different PDO phases.

<table>
<thead>
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<th>PDO phase</th>
<th>EAP/PJ</th>
<th>AO</th>
<th>PDO</th>
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<td>0.75</td>
<td>0.62</td>
<td>0.85</td>
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<tr>
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<td>0.68</td>
<td>0.7</td>
<td>0.75</td>
</tr>
<tr>
<td>-ve</td>
<td>0.64</td>
<td>0.75</td>
<td>0.68</td>
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</tbody>
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