Decadal Modulation of Precipitation Patterns over Eastern China by Sea Surface Temperature Anomalies

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ABSTRACT

Annual precipitation anomalies over eastern China are characterized by a north–south dipole pattern, referred to as the “southern flooding and northern drought” pattern (SF/ND), fluctuating on decadal time scales. Previous research has suggested possible links with oceanic forcing, but the underlying physical mechanisms by which sea surface temperature (SST) variability impacts the dipole pattern remains unclear. Idealized atmospheric general circulation model experiments conducted by the U.S. CLIVAR Drought Working Group are used to investigate the role of historical SST anomalies associated with Pacific El Niño–Southern Oscillation (ENSO)-like and the Atlantic multidecadal oscillation (AMO) patterns in this dipole pattern. The results show that the Pacific SST pattern plays a dominant role in driving the decadal variability of this dipole pattern and the associated atmospheric circulation anomalies, whereas the Atlantic SST pattern contributes to a much lesser degree. The direct atmospheric response to the Pacific SST pattern is a large-scale cyclonic or anticyclonic circulation anomaly in the lower troposphere occupying the entire northern North Pacific. During the warm phase of the Pacific SST pattern, it is cyclonic with northwesterly wind anomalies over northern China pushing the monsoon front to the south and consequently SF/ND. During the cold phase of the Pacific SST pattern, the circulation anomaly reverses with southeasterly winds over northern China allowing the monsoon front and the associated rainband to migrate northward, resulting in southern drought and northern flooding. The Atlantic SST pattern plays a supplementary role, enhancing the dipole pattern when the Pacific SST and Atlantic SST patterns are in opposite phases and weakening it when the phases are the same.

1. Introduction

Precipitation over eastern China exhibits distinctly decadal variations and strong regional features (Li et al. 2004). During the second half of the last century, a robust decreasing trend in precipitation over northern China was evident, and this dry episode lasted for approximately 30 years (Ma and Fu 2006), increasing the severity of water shortages (Xia et al. 2004; Zhang et al. 2014). Associated with the weakened East Asian summer monsoon (EASM), a major abrupt change in increased rainfall over the Yangtze River Valley occurred in the late 1970s (Yatagai and Yasunari 1994; Wang 2001; Gong and Ho 2002; Zhou et al. 2009).

The sources of the decadal/interdecadal changes in China precipitation are complex. For instance, Zuo et al. (2012) reported that spring rainfall over southern China exhibits an east–west opposite variation on interdecadal time scales in the late 1980s, with a decreasing trend over southeastern China and an increasing trend over...
southwestern China, which is attributable to the inter-
decadal downward shift of Eurasian spring snow in the
late 1980s. The Tibetan Plateau underwent interdecadal
warming around 2002, which led to the interdecadal shift
northward of the west Pacific subtropical high, and
consequently the interdecadal increase of summer pre-
cipitation over the Huaihe River valley during 2002–10
in comparison to 1979–2001 (Zhu et al. 2015). Li and
Leung (2013) found that there has been a tendency for
enhanced summer precipitation over southern China
and the Yangtze River valley, and drought over northern
and northeastern China after the end of the 1970s.
This is related to the Arctic spring warming. Compared
with the above factors, the role of sea surface tempera-
ture (SST) on the decadal variability of precipitation in
China has been investigated to the greatest extent
(Wang et al. 2000; Yang and Lau 2004; Ma 2007; Ding
et al. 2009; Li et al. 2010; Zhu et al. 2011). Yang and Lau
(2004) demonstrated that the upward trend of spring
precipitation over southeastern China and downward
trend of summer precipitation over northern China are
attributable to the warming trend of the ENSO-like
mode. The observed decadal weakening of the EASM
during the latter half of the twentieth century is induced
by the SST forcing from the tropics, and the greenhouse
gas plus aerosol forcing contributes to a much lesser
degree (Li et al. 2010). Ding et al. (2009) also noted that
SSTs in the tropical central and eastern Pacific have a
positive correlation with summer precipitation in the
Yangtze River valley and most of southern China, and a
negative correlation in northern China.

The Pacific decadal oscillation (PDO; Mantua et al.
1997; Mantua and Hare 2002) and the interdecadal Pa-
cific oscillation (IPO; Zhang et al. 1997; Power et al.
1999; Dong and Dai 2015) are the leading modes of
decadal and interdecadal climate variability in the Pa-
cific Ocean (Henley et al. 2015), corresponding to SST
anomalies in the North Pacific poleward of 20°N and
globally, respectively. The PDO is often referred to as
the North Pacific component of the IPO that extends to
the whole Pacific basin (Zhang et al. 1997; Dai 2013;
Dong and Dai 2015). Many studies found that the PDO
and IPO exert a decadal modulation effect on the re-
regional climate (Trenberth and Hurrell 1994; Gershunov
and Barnett 1998; Hu and Huang 2009; Dai 2013; Wang
et al. 2014; Newman et al. 2016). Previous studies have
investigated the PDO’s influence on precipitation over
China. For example, Ma (2007) suggested that the phase
shift of the PDO is closely related to decadal variabil-
ity in northern China precipitation. During the warm phase
of the PDO, precipitation is below normal, with in-
creased drought over northern China, and vice versa
(Ma and Fu 2006; Ma and Shao 2006; Ma 2007; Qian and
Zhou 2014; Zhang and Zhou 2015). Zhu et al. (2011)
found that increased summer rainfall in the Huang-Huai
River region and decreased rainfall in the Yangtze River
region from 2000 to 2008 compared with the period of
1979–99 were induced by the phase transition of the
PDO from warm to cold around 1999. Chen et al. (2013)
demonstrated that a weak East Asian winter monsoon
associated with ENSO tends to be followed by a strong
EASM and vice versa, and this relationship is modulated
by the PDO. Duan et al. (2013) showed that the PDO
also modulates the predictability of the interannual
variation of early summer rainfall over southern China
by influencing ENSO-related SST anomalies.

In addition to the Pacific SST, the North Atlantic SST
may also affect precipitation over eastern China on dec-
cadal time scales (Gu et al. 2009; Zhang et al. 2013).
Using a climate model, Liu and Chiang (2012) showed
that the North Atlantic cooling can induce a dipole pre-
cipitation pattern in eastern China with a negative
anomaly in northern China and a positive anomaly along
the Yangtze River valley, which is consistent with the
result of Li and Bates (2007). A recent study by Si and
Ding (2016) confirmed this link between the Atlantic
multidecadal oscillation (AMO; Kerr 2000) and the
PDO through the AMO–Northern Hemisphere tele-
connection wave train. That is, the AMO can affect the
decadal variability of eastern China rainfall by modu-
lating the PDO. Zhu et al. (2016) determined that sig-
nificant positive summer rainfall anomalies occurs over
the lower reaches of the Yangtze River Valley in the
presence of a warm PDO combined with a cold AMO,
whereas significant negative anomalies correspond to a
cold PDO combined with a warm AMO.

Although previous studies have investigated links
between decadal precipitation variations over eastern
China with the Pacific and Atlantic SST, the physical
mechanism involved this phenomenon remains unclear
because 1) the observed significant correlations between
precipitation anomalies and SST do not demonstrate a
causal relationship if they cannot be reproduced, and
2) the interference of other external forces (e.g., Indian
Ocean dipole, greenhouse gas concentrations, aerosol,
natural solar and volcanic activity, etc.) cannot be re-
moved completely by statistical methods using instru-
mental data. The experimental design of the U.S. Climate
Variability and Predictability Research (CLIVAR)
Drought Working Group (Schubert et al. 2009)
provides a valuable resource for mechanistic studies of
the Pacific and the Atlantic SSTs’ influence on the hy-
droclimate over eastern China. Idealized atmospheric
general circulation model (AGCM) experiments were
forced by prescribed SST patterns, which were com-
posed of the Pacific, Atlantic, and long-term warming
SST patterns in several different configurations (Schubert et al. 2009). Reasonable global annual mean stationary waves and precipitation patterns were reported to be successfully reproducible by the AGCMs (Schubert et al. 2009). These experimental results were analyzed in many regions, and intrinsic connections between oceanic heating conditions and regional dry/wet variations were found (e.g., Mo et al. 2009; Findell and Delworth 2010; Pegion and Kumar 2010; Feng et al. 2011; Hoell et al. 2015). Therefore, using the U.S. CLIVAR Drought Working Group’s idealized experiments, the possible physical mechanism involved how the Pacific and Atlantic SST modulate the decadal variability in eastern China precipitation on interannual and longer time scales can be identified.

The rest of the paper is organized as follows. The data, simulations, and methodology are described in section 2. Section 3 presents the observed precipitation characteristics over eastern China, and the precipitation and atmospheric circulation responses of the AGCMs. Discussions and conclusions are provided in sections 4 and 5, respectively.

2. Data and methods

a. Data

Several datasets were used in this study: 1) the 160-station monthly precipitation dataset from 1951 to 2015 obtained from the China Meteorological Administration (http://bcc.ncc-cma.net/channel.php?channelId=106); 2) monthly geopotential heights from the U.S. National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NCEP-1; 1948–2013; Kalnay et al. 1996); and 3) the time series of the EASM index (1948–2015), which is defined as an area-averaged June–August (JJA) dynamical normalized seasonality measured by use of the monthly variation magnitude of the wind field at 850 hPa within the East Asian monsoon domain (10°–40°N, 110°–140°E) (Li and Zeng 2002; http://ljp.geess.cn/dct/page/65577).

b. AGCM experiments

A series of global climate modeling experiments were initiated and conducted by the U.S. Drought Working Group in 2008 (Schubert et al. 2009). In the preparation of the SST forcing fields, global annual mean SST anomalies (Rayner et al. 2003) from 1901 to 2004 were analyzed using the rotated empirical orthogonal function (REOF) method. The three leading REofs and associated principal components (RPCs) are shown in Fig. 1. The first REOF shows the long-term warming mode, the second REOF is a pan-Pacific ENSO-like pattern with strong interannual and decadal variability, and the third is a pattern associated with the AMO. These three REofs are referred to as the anomaly patterns scaled by ±σk (k = 0, 1, 2; σ is the standard deviation of the associated principal components) to form the anomalous part of the forcing fields: the neutral (denoted by n, when k = 0), the extreme cold (c; k = −2 for the Pacific and Atlantic patterns while k = −1 for the long-term trend pattern), and the warm (w; k = 2 for the Pacific and Atlantic patterns while k = 1 for the long-term trend pattern) anomalies. They were then superimposed onto monthly climatology derived from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003) for the period of 1901 to 2004, forming the forcing SST fields. It is important to note that the SST forcing fields are monthly varying without interannual or longer-term variability.

In this study, we focused on nine baseline experiments, which are combinations of Pacific (P) and Atlantic (A) patterns of cold, neutral, and warm anomalies (i.e., PwAn, PcAn, PnAw, PnAc, PwAc, PwAw, PcAc, and PnAn). For example, experiment PwAc stands for the Pacific cold SST and Atlantic warm SST. In addition to PnAn, which was used as the control experiment, with Pacific and Atlantic SSTs in neutral conditions (i.e., climatology), eight combinations of SST forcing anomaly patterns are shown in Fig. 2. Five AGCMs, including the NASA Seasonal-to-Interannual Prediction Project (NSIPP1; Bacmeister et al. 2000), the Global Forecast System (GFS; Campana and Caplan 2005), the Geophysical Fluid Dynamics Laboratory CM2.0 (GFDL; Delworth et al. 2006), the Community Atmospheric Model (CAM3.5; Chen et al. 2010), and the Community Climate Model (CCM3; Kiehl et al. 1998), were forced with the above SST forcing fields. With the exception of the GFS (with a duration of 35 yr), all simulations ran for 50 yr. AGCM responses to the idealized forcings were obtained from the mean differences between the forced run and the control run (PnAn). For more information and an overview of the U.S. CLIVAR Drought Working Group, please see the overview paper by Schubert et al. (2009).

c. Methods

It has been suggested that an ensemble of multimodel results can help reduce model uncertainties introduced by subgrid-scale parameterizations over any individual model and produce results closer to actual observations (Rowell 1998; Wang et al. 2005; Mo et al. 2009). Therefore, the arithmetic mean of the five AGCMs’ outputs was used in the study. In addition, the leading patterns of precipitation variability over eastern China were extracted from observations using the EOF.
method with the $t$ test (see the supplemental information and Wilks 2005) for statistical significance.

3. Results

a. Observed precipitation characteristics over eastern China

Annual accumulated precipitation from 1951 to 2015 was analyzed using the EOF method, and the leading spatial mode with explained variance of 10.4% is shown in Fig. 3a. Opposing precipitation anomalies were visible over southern and northern China, representing a well-known north–south dipole pattern of precipitation, with a dividing line at approximately 32°N. As shown in Fig. 3b, this north–south dipole pattern exhibited obvious decadal variation. During the 1950s and 1960s (Fig. 3c), there was less precipitation over southern China and more over northern China [referred to as the “southern drought and northern flooding” pattern (SD/NF)], whereas above-normal precipitation over southern China and below-normal precipitation over northern China [referred to as the “southern flooding and northern drought” pattern (SF/ND)] occurred in the 1990s (Fig. 3d). After 2002 (Fig. 3e), the SD/NF pattern reappeared. It has been suggested that phase changes in the PDO could have induced the decadal shift in precipitation patterns over eastern China in the late 1970s and early 2000s (Zhu and Yang 2003; Gu et al. 2005; Ma 2007; Li et al. 2010; Zhu et al. 2011; Zhou et al. 2013; Qian and Zhou 2014).
b. Annual mean AGCM precipitation response

Figure 4 shows the regional mean annual precipitation responses of the five AGCMs to the eight different forcing anomaly patterns shown in Fig. 2. In each experiment, highly consistent precipitation responses were found over southern China for the five AGCMs (Fig. 4a). Compared with PnAn, the annual mean precipitation was significantly less (mean of the five AGCMs: $-0.24 \text{ mm day}^{-1}$) for PcAn but significantly more ($0.31 \text{ mm day}^{-1}$) for PwAn. This finding indicates that southern China tends to be dry and wet in correspondence to the cold and warm phases of the
Pacific pattern, respectively, when the Atlantic Ocean is in a neutral condition. Additionally, significantly more precipitation (0.07 mm day$^{-1}$) is induced by PnAc, whereas significantly less precipitation ($-0.04$ mm day$^{-1}$) is caused by PnAw. Thus, the cold and warm phases of the Atlantic pattern result in more and less precipitation over southern China, respectively, when the Pacific Ocean is in a neutral condition. This finding is opposite to the precipitation response to the Pacific pattern. It is important to note that contributions of the Pacific pattern to precipitation over southern China are approximately five times those of the Atlantic pattern. As a result, the cold phase of the Pacific pattern (PcAc, PcAn, and PcAw) inhibits precipitation over southern China, whereas the warm phase of the Pacific pattern (PwAc, PwAn, and PwAw) promotes precipitation, regardless of the Atlantic SST conditions. Furthermore, modulations of precipitation may be enhanced when SST conditions of the Pacific and Atlantic pattern are reversed. For example, PcAw and PwAc induce the largest precipitation deficits and surpluses, $-0.34$ and $0.40$ mm day$^{-1}$, respectively.

Compared with southern China, opposing modulations of the Pacific and Atlantic patterns on precipitation over northern China are shown in Fig. 4b, although the consistency of the precipitation response among the five AGCMs is relatively lower. The individual cold (warm) phase of the Pacific pattern induces more (less) precipitation, whereas the individual cold (warm) phase of the Atlantic pattern induces less (more) precipitation. Unlike in southern China, the contributions of the Pacific pattern on precipitation over northern China are basically the same as those of the Atlantic pattern. Thus, the leading role of the Pacific pattern in precipitation over northern China is not as prominent as that over southern China. However, the cold phase of the Pacific pattern (PcAc, PcAn, and PcAw) still clearly tends to promote precipitation over northern China, whereas the warm phase of the Pacific pattern (PwAc, PwAn, and PwAw) tends to inhibit precipitation, regardless of the Atlantic SST conditions. In addition, when the Pacific and Atlantic patterns are in opposite phases, modulations of precipitation are enhanced. For example, PcAw induces the
largest precipitation surpluses (0.15 mm day$^{-1}$). Negative precipitation anomalies for PwAc, $-0.11$ mm day$^{-1}$, were found in five AGCMs, although they were slightly less pronounced than those for PwAn ($-0.15$ mm day$^{-1}$).

It is clear that five AGCMs do reproduce the observed north–south dipole pattern of annual precipitation over eastern China. The Pacific pattern makes a major contribution, while the Atlantic pattern contributes to a lesser degree. The cold phase of the Pacific pattern tends to reduce precipitation over southern China and enhance precipitation over northern China, resulting in SD/NF, whereas the opposing precipitation pattern, SF/ND, corresponds to the warm phase of the Pacific pattern, regardless of the Atlantic SST conditions. The largest response in eastern China precipitation consistently occurs in five AGCMs when the Pacific and Atlantic

**FIG. 4.** Difference in (a) southern China ($22^\circ$–$30^\circ$N, $110^\circ$–$122^\circ$E) and (b) northern China ($35^\circ$–$42.5^\circ$N, $110^\circ$–$117.5^\circ$E) average annual mean precipitation (mm day$^{-1}$) in eight experiments from that of the control experiment (PnAn) for all five participating AGCMs.
patterns are in opposite phases. Specifically, the combination of a cold Pacific and warm Atlantic (PcAw) results in the largest precipitation deficits over southern China and the largest precipitation surpluses over northern China (SD/NF), whereas the combination of a warm Pacific and cold Atlantic (PwAc) produces the largest precipitation surpluses over southern China and the largest precipitation deficits over northern China (SF/ND).

c. Annual mean AGCM atmospheric circulation response

As the observed north–south dipole pattern of annual precipitation over eastern China was reasonably reproduced in the five AGCMs, the corresponding atmospheric circulation and dynamic processes are further elaborated in this subsection using the ensemble mean of the five AGCMs.

Figures 5 and 6 show the ensemble mean anomalies of annual mean precipitation, 500-hPa geopotential height, and 850-hPa wind in the eight combinations of experiments shown in Fig. 2, respectively. For PwAn (Fig. 5a), the SF/ND precipitation pattern over eastern China is associated with a north–south dipole pattern of 500-hPa height over the North Pacific and East Asia, characterized by an anomalous low pressure over the northern North Pacific and a broad region of anomalous high pressure over the tropical and subtropical Pacific. An anomalous cyclone is located over the northern North Pacific. It induces anomalous northwesterly flow in northern China, whereas anomalous southwesterly flow occurs in southern China. This anomalous circulation does not favor the northward transport of tropical moisture and the associated rainband into northern
China, and tends to decrease precipitation there but
enhance precipitation to the south. The opposite circu-
lation structure, that is “south negative–north positive”
height anomalies, corresponding to the SD/NF pre-
cipitation pattern, is evident for PcAn in Fig. 5b. There is
anomalous southeasterly flow into northern China in-
duced by an anomalous anticyclone over the northern
North Pacific, and anomalous northeasterly flow into
southern China caused by an anomalous cyclone over
the northwestern Pacific. It is also noted that although
height anomalies over the northern North Pacific for
PcAn and PwAn are opposite, the amplitude of height
anomalies for PwAn (220.3 m) is approximately twice
that for PcAn (10.9 m) (Fig. 7). This means that atmo-
spheric circulation response to the Pacific positive and
negative pattern is not linearly symmetric.

As shown in Fig. 6a, an eastward-propagating wave
train is driven by PnAw. Although the wave train is
slightly different from the AMO–Northern Hemisphere
teleconnection wave train defined by Si and Ding (2016),
an anomalous high pressure over the northern North
Pacific is evident in both. Compared with the anomalous
high pressure induced by PcAn, the amplitude of height
anomalies for PnAw (5.6 m) is approximately one-half.
An anomalous low pressure center located over the
northern North Pacific is associated with PnAc (Fig. 6b),
which is consistent with PwAn but with a smaller am-
plitude, approximately one-fourth. These indicate that
circulation response to the Atlantic pattern is roughly
reversed from that to the Pacific pattern, but with
less amplitude. Therefore, compared with PwAn and
PcAn, anomalies of geopotential height and wind are

![Regional average multimodel ensemble anomalies of annual and seasonal mean 500-hPa geopotential height (m), with respect to the control run (PnAn), over the northern North Pacific (30°–65°N, 160°E–140°W). Value range of the AGCM response for each experiment is indicated by the box-and-whisker plots.](http://journals.ametsoc.org/jcli/article-pdf/30/17/7017/4678740/jcli-d-16-0793_1.pdf)
weakened slightly for PwAw and PcAc whereas enhanced distinctly for PwAc and PcAw, which are associated with the largest SF/ND and SD/NF precipitation patterns, respectively, over eastern China, as shown in Fig. 4.

Associated with the north–south dipole pattern of precipitation over eastern China, the direct atmospheric response is the north–south dipole pattern of geopotential height anomalies at 500 hPa over the North Pacific and East Asia, characterized by opposing anomalies over the northern North Pacific and the tropical/subtropical Pacific, with a dividing line approximately 30°N. A large-scale cyclonic or anticyclonic circulation anomaly in the lower troposphere occupying the entire northern North Pacific is evident. It is dominated by the Pacific pattern, while the influence of the Atlantic pattern is opposite and to a lesser degree. The largest circulation anomalies are presented when the Pacific and Atlantic patterns are in opposite phases (i.e., PwAc and PcAw).

d. Summer mean AGCM atmospheric circulation response

To elaborate on specific atmospheric processes through which the Pacific pattern influences the decadal variability in eastern China summer precipitation, the anomaly structure of which is found to be the main contributor to the north–south dipole pattern of annual precipitation (Yang et al. 2017), JJA mean precipitation, 500-hPa geopotential height, 850-hPa wind, moisture transport, and meridional–vertical circulation for PwAn and PcAn are presented in Fig. 8.

As shown in Fig. 8a, as with annual precipitation, the SF/ND pattern is clearly visible in JJA for PwAn. Associated with anomalous low pressure in the northern North Pacific, an anomalous cyclone is present, resulting in anomalous northwesterly flow into northern China. Meanwhile, anomalous southwesterly winds into southern China are associated with a broad region of
anomalous high pressure in the tropical and subtropical Pacific, which corresponds to an anomalous stronger west Pacific subtropical high, with its ridge line southward and ridge point westward, as shown in Fig. 9a. Using the NCEP-1 reanalysis dataset, it is also found that after the late of 1970s, the warm phase of the PDO is associated with an enhanced west Pacific subtropical high (Fig. 9b) and a weakened EASM (Fig. 9c). The anomalous northwesterly winds over northern China interrupt the northward seasonal migration of the EASM, causing abundant water vapor from the Bay of Bengal, Indian Ocean, and South China Sea that is difficult to be transported into northern China but converges over southern China (Fig. 8b). In addition, anomalous rising and sinking motions occur over southern and northern China (Fig. 8c), respectively. These lead to the south being wet while the north is dry, which is the SF/ND pattern.

For PcAn (Figs. 8d–f), the JJA mean precipitation and atmospheric responses are opposite to those for PwAn. Anomalous high pressure in the northern North Pacific induces an anomalous anticyclone, resulting in anomalous southeasterly flow into northern China, whereas anomalous northeasterly winds into southern China are caused by the weakened west Pacific subtropical high (Fig. 9a). These are associated with an enhanced EASM (Fig. 9c), which favors the summer rainband migrating northward into northern China. Combined with anomalous rising motion, anomalous moisture convergences
cause enhanced precipitation over northern China, whereas anomalous sinking motion and moisture divergences induce decreased precipitation over southern China, forming the SD/NF.

Consistent with PwAn (PcAn), the above-described precipitation and atmospheric circulation patterns in JJA can also be found clearly in PwAw and PwAc (PcAc and PcAw). In addition, responses of precipitation and atmospheric circulation for PwAc and PcAw are slightly enhanced (Fig. 10). Therefore, the Pacific pattern dominates precipitation and associated atmospheric circulation anomalies, and its modulation is enhanced by the Atlantic pattern in the opposite phase.

4. Discussion

The main conclusion from the above analysis is the dominant role of the second REOF, the pan-Pacific ENSO-like pattern, in driving the eastern China dipole precipitation anomalies. As the driving SST pattern contains both interannual and decadal variability, a question naturally arises: Do the interannual or decadal components play similar roles or different ones?

In addition to the baseline experiments, further analysis was carried out using the U.S. CLIVAR Drought Working Group’s additional experiments with separate high- and low-frequency Pacific SST variability on regional precipitation for investigation. The high-frequency Pacific pattern (HF, analogous to ENSO; Fig. 11a) is the REOF1 of global monthly mean SST after the 6-yr filtered SST is removed, and low-frequency Pacific pattern (LF, analogous to IPO; Fig. 11c) is the REOF2 of global 6-yr filtered SST. However, these simulations were not performed by all modeling centers and thus drew less attention. It is noted that the NSIPPI is the only AGCM that performs all runs with HF and LF (Table 1).
Figure 12 shows the annual mean precipitation response in the NSIPP1 to the eight different forcing patterns shown in Table 1 in addition to PwAn and PcAn. The north–south dipole pattern of annual precipitation response is robust and comparable in all runs, although precipitation anomalies slightly vary in position and amplitude. The SF/ND pattern corresponds to PwAn, HFw, and LFw (Figs. 12a–c), with the largest (smallest) amplitude of precipitation response seen in PwAn (LFw) and southwestward precipitation negative anomalies with respect to the ensemble mean precipitation anomalies over northern China in Fig. 5a. PcAn, HFc, and LFc consistently induce SD/NF (Figs. 12d–f) and the amplitude of precipitation response is largest (smallest) in PcAn (LFc). This result suggests that precipitation response over eastern China to the Pacific pattern on decadal time scales resembles that on interannual time scales, but with a smaller amplitude. The same result also can be obtained from response of JJA mean 500-hPa geopotential height (Fig. 13). As shown in Figs. 13a–f, the amplitude of the height anomaly over the northern North Pacific, which could induce a large-scale pan-northern North Pacific cyclonic or anticyclonic circulation and then directly modulate precipitation anomaly structure over eastern China, gradually increases from LF to HF and the Pacific pattern. When LF and HF are in phase, responses of precipitation (Figs. 12g,h) and 500-hPa height (Figs. 13g,h) are greatly enhanced and comparable with that to the Pacific pattern (i.e., the largest SF/ND and SD/NF, corresponding to HFwLFw and HFcLFc, respectively). When LF and HF are out of phase, responses of precipitation (Figs. 12i,j) and 500-hPa height (Figs. 13i,j) are greatly weakened and dominated by responses to HF.

Burgman and Jang (2015) also found that, consistent with PcAn, LFc and HFc also simulated drought conditions over large regions of the contiguous United States. In addition, there was evidence that when LFc and HFc combine, constructive interference leads to an enhanced drought response over the Great Plains. Furthermore, based on observations and atmospheric reanalysis dataset, Wang et al. (2014) determined that when La Niña combined with the cold phase of the PDO, areas of La

| Indicators | SST anomaly patterns                  |
|------------|---------------------------------------|
| HFc        | Cold high frequency                    |
| HFw        | Warm high frequency                    |
| LFc        | Cold low frequency                     |
| LFw        | Warm low frequency                     |
| HFcLFc     | Cold high frequency + cold low frequency|
| HFwLFw     | Warm high frequency + warm low frequency|
| HFcLFw     | Cold high frequency + warm low frequency|
| HFwLFc     | Warm high frequency + cold low frequency|
Niña–induced precipitation could become wetter and areas of La Niña–induced drought could become drier. When combined with the warm phase of the PDO, El Niño–induced dry or wet changes are also magnified. As mentioned above, observations and simulations both suggest that the spatial patterns of precipitation anomalies induced by ENSO and the PDO are similar, and an enhanced precipitation pattern tends to occur.

**Fig. 12.** Annual mean precipitation responses (mm day$^{-1}$) to (a) PwAn, (b) HFw, (c) LFw, (d) PcAn, (e) HFc, (f) LFc, (g) HFwLFw, (h) HFcLFc, (i) HFwLFc, and (j) HFcLFw with respect to PnAn in the NSIPP1. Anomalies exceeding the 95% confidence level are stippled.

**Fig. 13.** As in Fig. 12, but for JJA mean 500-hPa geopotential height (m). Shading indicates that anomalies are statistically significant at the 90% level.
when ENSO and the PDO are in phase. For the baseline experiments (Schubert et al. 2009), the Pacific pattern is analogous to the sum of ENSO and the IPO in phase. Consequently, the Pacific-induced precipitation and atmospheric responses in five AGCMs could be considered as the combined impact of ENSO and the IPO in phase, and ENSO tends to have a greater contribution.

5. Conclusions

It is well known that annual precipitation anomalies over eastern China fluctuate on decadal time scales with widespread climate impacts. The leading mode of variability has a north–south dipole structure usually referred to as the pattern of the “southern flooding and northern drought.” Previous studies have suggested possible links with oceanic forcing. Based on station observations, reanalysis data, and a set of AGCM experiments forced with idealized SSTs, this paper has shown that the observed pattern of precipitation variability as well as its oceanic links can be well reproduced, confirming findings from earlier research by others. The main focus of this paper has been to identify the corresponding atmospheric circulation anomalies associated with the dipole mode of precipitation variability over eastern China, and its driving mechanisms. Idealized AGCM experiments forced with different combinations of decomposed historical SSTs provide an excellent opportunity. The major findings are summarized as follows:

1) The north–south dipole pattern of annual precipitation anomalies is dominantly driven by the Pacific SST anomalies linked to ENSO and the IPO. The Atlantic SST anomalies also have an influence but to a much lesser degree.

2) The oceanic forcing is manifested in a large-scale pan-northern-North-Pacific cyclonic or anticyclonic circulation anomaly in the lower troposphere. The warm phase of the Pacific pattern corresponds to a cyclonic circulation anomaly with northwesterly winds blowing over northern China and southwesterly flow positioned with the west Pacific subtropical high. The anomalous northwesterly winds interrupt the northward seasonal migration of the EASM and the associated rainband, causing the south to be wet while the north is dry, which is the “southern flooding and northern drought” pattern. During the opposite phase, there is an anticyclonic circulation anomaly occupying the northern North Pacific combined with a weak eastward-shifted west Pacific subtropical high, with southeasterly winds prevailing all the way to northern China, allowing the EASM and rainband to migrate northward and consequently leading to more rain over the north and less over the south, or the “southern drought and northern flooding” pattern.

3) The Atlantic SST pattern plays a supplementary role, enhancing the dipole pattern when the Pacific SST and Atlantic SST patterns are in opposite phases but weakening it when there are in the same phase.

Given the quasi-periodic and low-frequency nature of the Pacific and Atlantic patterns, the decadal shift of this north–south dipole precipitation pattern over eastern China may be predictable. The Pacific pattern has been in its warm phase since the late 1970s, and a shift into its cold phase seemed to begin in the 2000s. Meanwhile, the Atlantic pattern shifted into its warm phase in the mid-1990s, and this phase may last for another 20 years. Thus, in light of the results presented, without considering the influences of natural atmospheric variation and other external forces, eastern China may experience a period of anomalous precipitation patterns similar to southern drought and northern flooding over the next 20 years. This prediction is consistent with the results of Gu et al. (2005) and Wang et al. (2014). However, a cautionary note must be made here that the relationship between the dipole pattern of eastern China rainfall and the Pacific SST anomalies is not linear, as shown by a number of other studies (e.g., Wu et al. 2003; Wu et al. 2009; He et al. 2017). A recent study by Yang et al. (2017) using monthly rainfall anomalies shows that although the correlation between the dipole pattern and the PDO is high but the explained variance is relatively low. This indicates that the Pacific SST pattern actually contains an interannual component dominated by ENSO and a decadal component dominated by the PDO. The influence of ENSO is asymmetric with a prominent rainfall response to El Niño but a subdued response to La Niña. The relationship between the dipole pattern and the Pacific SST anomalies becomes robust only on decadal time scales.

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