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Interdecadal seesaw of precipitation variability between North China and the Southwest US

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Abstract

This paper reports a consistent seesaw relationship between interdecadal precipitation variability over North China and the Southwest United States (US), which can be found in observations and simulations with several models. Idealized model simulations suggest the seesaw could be mainly driven by the Interdecadal Pacific Oscillation (IPO), through a large-scale circulation anomaly occupying the entire northern North Pacific, while the Atlantic Multidecadal Oscillation (AMO) contributes oppositely and less. Modulation of precipitation by the IPO tends to be intensified when the AMO is in the opposite phase, but weakened when the AMO is in the same phase. The warm IPO phase is associated with an anomalous cyclone over the northern North Pacific and consequently, anomalous southwesterly winds bring more moisture and rainfall to the Southwest US, while northwesterly wind anomalies prevail over North China with negative rainfall anomalies. The east-west seesaw of rainfall anomalies reverses sign when the circulation anomaly becomes anticyclonic during the cold IPO phase. The IPO-related tropical SST anomalies affect the meridional temperature gradient over the North Pacific and adjacent regions and the mean meridional circulation. In the northern North Pacific, the atmospheric response to IPO forcing imposes an equivalent barotropic structure throughout the troposphere. An important implication from this study is the potential predictability of drought-related water stresses over these arid and semiarid regions, with the progress of our understanding and prediction of the IPO and AMO.

Key words: precipitation variability, interdecadal seesaw, Interdecadal Pacific

Oscillation, drought, water resources

1. Introduction

Precipitation variability has profound impacts on society and ecosystems because it is closely related to drought, floods and water resources. Any useful prediction skills on precipitation will be greatly beneficial and normally associated with certain climate modes within the coupled climate system, such as the Interdecadal Pacific Oscillation (IPO; Zhang et al. 1997; Power et al. 1999) and the Atlantic Multidecadal Oscillation (AMO; Kerr 2000). The AMO, for example, is found to be strongly coupled with the global water cycle (Vellinga and Wu, 2004). Anthropogenic climate change is also affecting the global water cycle with regional impacts (Wu et al. 2013; 2015; Zhang et al. 2017; Kang and Eltahir, 2018). There are certain regions over the world, which are particularly sensitive to episodes of climate related precipitation variability on decadal or multidecadal timescales, such as North China and the Southwest United States (US).

Both North China and the Southwest US are typical arid and semi-arid regions, often hard hit by serious droughts. Many studies have attributed their interdecadal precipitation variability to the IPO, although the underlying mechanism of which is still under intensive debate (Farneti et al. 2014; Di Lorenzo et al. 2015; Newman et al. 2016; Si and Hu 2017; Henley 2017; Henley et al. 2017). The warm IPO phase corresponds to below-normal precipitation over North China (Ma and Shao 2006; Ma 2007; Zhou et al. 2013; Qian and Zhou 2014; Huang et al. 2017), but above-normal precipitation over the

Southwest US (Meehl and Hu 2006; Dai 2013), implying an obvious out-of-phase relationship for precipitation regime shift. Following the IPO cold-to-warm phase shift around 1977, there is an evident drying trend over North China, whereas a significant wetting trend is shown in the Southwest US since the 1950s; increased precipitation in the Huang-Huai River region (southern North China) after 2000, and a robust drying trend over the Southwest US since the 1980s are thought to be largely caused by the IPO warm-to-cold phase transition around 1999 (Ma 2007; Zhu et al. 2011; 2015; Dai 2013; Chylek et al. 2014; Qian and Zhou 2014). Additionally, the AMO contributes to the out-of-phase decadal precipitation pattern (Li and Bates 2007; Mo et al. 2009; Schubert et al. 2009; Feng et al. 2011; Zhu et al. 2016; Si and Ding 2016). The warm AMO phase tends to induce a stronger East Asia Summer Monsoon (EASM), leading to more northward transport of moisture and enhanced rainfall over North China, but dry conditions in the Southwest US (Lu et al. 2006; Sutton and Hodson 2005; 2007; Hu et al. 2011; Feng et al. 2011). The combined effects of the IPO and AMO are complicated and important (Schubert et al. 2009; Zhu et al. 2016; Si and Hu 2017; Yang et al. 2017). For instance, more than half (52%) of the spatial and temporal variance in multidecadal drought frequency over the US is attributable to the AMO and the Pacific Decadal Oscillation (PDO, Mantua et al. 1997; Mantua and Hare 2002), which is the North Pacific component of the IPO (McCabe et al. 2004).

The purposes of this study are to identify the interdecadal seesaw of precipitation variability between North China and the Southwest US, to further understand the associated formation mechanism related to the IPO and AMO, and to answer why there

is an out-of-phase decadal precipitation pattern between North China and the Southwest US through analysis of decadal ocean forcings.

Although many studies have investigated the contrasting relationship of precipitation variability between Asia and North America (e.g., Lau and Weng 2002; Lau et al. 2004; Li et al. 2005; Ma and Fu 2007; Hua et al. 2011; Zhao et al. 2011; 2016; Wang et al. 2014; Fang et al. 2014; 2015; Yang and Fu 2016; Zhu and Li 2016), the circulation mechanism for the seesaw relationship remains unclear. This is because that previous researches have focused on inconsistent study areas (Zhao et al. 2011; 2016; Fang et al. 2015), time scales (Lau and Weng 2002; Lau et al. 2004; Fang et al. 2014; Wang et al. 2014), and precipitation-related variables (Li et al. 2005; Yang and Fu 2016). Additionally, for attribution of precipitation variability, more attentions have been paid to the Asian-Pacific Oscillation (Zhao et al. 2011; Fang et al. 2015), East Asian subtropical monsoon heating (Zhu and Li 2016), Eurasian non-monsoon land heating (Zhao et al. 2016), and North Pacific sea surface temperature (SST) anomaly (Lau and Weng 2002; Lau et al. 2004), rather than the IPO and AMO. We aim to address these shortcomings in this study.

The observed precipitation records are shorter than 150 years over the US and the quality of the records decline significantly backward in time. In China, most of meteorological stations were established after 1960s and only few stations were available before 1960s, resulting in only about 60 stations with approximately 100 years of precipitation observations. These datasets are just enough to cover one (or two) full cycles of the AMO and the IPO, which limits their utility for diagnosing robust

regional climate impacts linked with the IPO and AMO. For instance, Newman et al. (2016) indicated that climate impacts correlated with the PDO are different from climate impacts that are predicted by the PDO, because that climate impacts and the PDO may be both driven by a common forcing function. It is difficult to distinguish these two relationships in observation. Atmospheric general circulation models (AGCMs) with prescribed observed or idealized SST patterns (e.g., Li et al. 2010; Hu et al. 2011; Dai 2013; Schubert et al. 2009) are effective tools to confirm or reject conclusions reached from observational analysis. Thus, in addition to observational and reanalysis data, a series of AGCM experiments designed by the US Climate Variability and Predictability (CLIVAR) Drought Working Group (Schubert et al. 2009) are also employed in this study. As they are not fully coupled, these experiments are not suitable to disentangle air-sea interaction. Detailed physical mechanisms of the interdecadal oceanic modes and their potential influence to the seesaw relationship have not been addressed in this study, and further follow-up work is needed.

The rest of the paper is organized as follows. In section 2, we describe the data, AGCM experiments and methods used in this study. The observed seesaw pattern and associated circulation are presented in section 3. The possible mechanisms are provided in section 4. A summary and discussion are given in section 5.

2. Data and methods

a. Data

The following datasets are used in this study.

- 131 1) Global merged monthly precipitation (based on gauge records) for 1850-2014 on a
132 2.5° latitude \times 2.5° longitude grid obtained from Dai (2011; 2013). We focused on the
133 period 1900-2014 because precipitation observations are sparse over China before
134 around 1900.
- 135 2) Global land monthly precipitation for 1901-2015, with a high resolution of 0.5°
136 latitude \times 0.5° longitude, obtained from CRU TS4.0 (University of East Anglia
137 Climatic Research Unit, 2017).
- 138 3) Chinese long-term gridded precipitation data for 1900-2009 obtained from the China
139 Meteorological Administration.
- 140 4) Global atmospheric reanalysis monthly data for circulation for 1948-2016 on a 2.5°
141 latitude \times 2.5° longitude grid, from the U.S. National Centers for Environmental
142 Prediction/National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al.
143 1996).
- 144 5) Global gridded monthly SST for 1901-2016 on a 2° latitude \times 2° longitude grid, from
145 the National Oceanic and Atmospheric Administration Extended Reconstructed SST
146 version 4 (ERSST v4; Huang et al. 2015).
- 147 6) The annual IPO index for 1920-2015, from Dai (2013), who defined the smoothed
148 (by applying a 9-year moving average twice) associated principle component of the
149 second leading empirical orthogonal function (EOF) of the 3-year moving averaged
150 SST from the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST;
151 Rayner et al. 2003), using data for 1920-2011 and 60°S – 60°N .
- 152 7) The monthly AMO index for 1856-2016 (Enfield et al. 2001) downloaded from

<https://www.esrl.noaa.gov/psd/data/timeseries/AMO/>.

b. AGCM experiments

The US CLIVAR Drought Working Group initiated a series of global climate model experiments to address the physical mechanisms that link global SST variations to regional drought and flood (Schubert et al. 2009). Associated forcing SST fields for experiments were prescribed as follows.

1) The Rotated Empirical Orthogonal Function (REOF) method was applied to global annual-mean SST anomalies (Rayner et al. 2003) from 1901 to 2004 to obtain the leading patterns of SST anomalies.

2) The REOF2 (Fig. 1a) was scaled by $\pm 2\sigma$ (σ is the standard deviation of the associated Rotated Principal Component (RPC2, Fig. 1b)) and then superimposed onto the 1901-2004 monthly climatology, forming a forcing SST anomaly called the Pacific pattern.

3) Applying the method in (2) to the REOF3 (Fig. 1c) yields the Atlantic pattern.

As shown in Fig. 1a, the Pacific pattern is analogous to the IPO-associated SST anomaly, and RPC2 is significantly correlated with the IPO index; thus, the Pacific pattern is deemed the IPO in this study. Likewise, the Atlantic pattern is deemed the AMO. Note that the prescribed SST fields vary monthly with the climatological (1901-2004) seasonal cycle, but have no inter-annual or longer-term variability.

We focused on nine baseline experiments, which are combinations of the Pacific (P) and Atlantic (A) patterns of cold (denoted by c ; scaled by -2σ), neutral (n ; zero

anomaly), and warm (w ; scaled by $+2\sigma$) anomalies (denoted by $Px Ay$ shown in Table 1, here $x, y=c, n, w$). These baseline experiments were performed by five AGCMs: the NASA Seasonal-to-Interannual Prediction Project AGCM (NSIPP1, Bacmeister et al. 2000), the Global Forecast System AGCM (GFS, Campana and Caplan 2005), the Geophysical Fluid Dynamics Laboratory AGCM (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). All simulations ran for 50 years, except the GFS (35 years). Additional experiments (performed by only GFDL and NSIPP1) forced by the tropical SST component of the Pacific pattern (Fig. 1a, blue box) were also analyzed. For more information and an overview of the US CLIVAR Drought Working Group, please see Schubert et al. (2009).

c. Methods

We focused on interdecadal precipitation variations and used a 9-year moving average twice, which is equivalent to a 17-year low-pass filter with unequal weights, to remove short-term variations. Regression analysis and epoch composites were employed to depict the spatial patterns of anomalous SST and atmospheric circulation associated with the precipitation and the IPO. The threshold of $\pm 0.5\sigma$ of the IPO index was used to define the IPO cold and warm phases. The long-term trend in global SST was removed by regressing the SST with the time series of global annual mean SST, while the long-term trend in other variables was removed using a linear least square fit. The Student's t -test (Wilks 2005) was used to test the difference of mean during

different composite periods, and detect the statistical significance of linear regression coefficients and Pearson correlation coefficients, after adjusting the degrees of freedom (in supplement). In addition, simulations from all five AGCMs were averaged to obtain an ensemble mean, which often reduces model uncertainties introduced by sub-grid scale parameterizations and produces signals closer to observations (Rowell 1998; Wang et al. 2005; Mo et al. 2009).

3. Interdecadal seesaw and associated circulations

Figure 2a shows detrended and smoothed regional average precipitation anomalies over North China and the Southwest US, as well as the IPO and AMO indices. Precipitation variations over North China are significantly negatively correlated with those over the Southwest US, with wet (dry) over North China aligning with dry (wet) over the Southwest US, implying an apparent interdecadal seesaw pattern.

Note that a significant positive correlation is found between Southwest US precipitation and the IPO index, with the maximum correlation ($r = 0.90$) at zero lag, implying they vary in phase. North China precipitation is significantly anti-correlated with the IPO index at zero lag, suggesting they vary out of phase. This means that the IPO may be associated with the interdecadal seesaw pattern, with the warm IPO phase aligned with below-normal precipitation over North China but above-normal precipitation over the Southwest US and the cold IPO phase aligned with wet over North China but dry over the Southwest US (Fig. 2b). It is also noted that the maximum

negative correlation ($r = -0.62$) occurs when the IPO leads North China precipitation by about 8 years (Fig. S2 in supplement). The 8-year lagged anti-correlation could be one reason why the PDO trend during 1971–2012 is nearly zero, however, there is a significant decline in North China precipitation mentioned by Zhou et al. (2013).

Unlike the IPO, the AMO has an insignificant positive correlation with North China precipitation at zero lag, implying the AMO's contemporaneous influence on precipitation is smaller than the IPO's. The maximum positive correlation ($r = 0.85$) is found when the AMO leads precipitation by about 15 years, or approximately one-quarter of an AMO cycle. The AMO has a significant anti-correlation with precipitation over the Southwest US, with maximum negative correlation ($r = -0.81$) when the AMO leads precipitation by about 11 years. This implies that the AMO has opposite effect on the interdecadal seesaw with respect to the IPO. Additionally, the AMO can only strengthen (weaken) the magnitude of the IPO-induced precipitation anomaly, when the AMO is out of phase (in phase) with the IPO (Fig. 2b), respectively.

We also performed the same analysis using the CRU TS4.0 precipitation data. The results (Fig. S1 in supplement) are analogous to those shown in Fig. 2a using the Dai precipitation data, indicating that the relationships are robust and not sensitive to the choice of data.

Given that the IPO may play a dominant role in the interdecadal seesaw pattern, the IPO phase composite anomalies of SST and precipitation over North China and the Southwest US are shown in Fig. 3. During the first cold IPO phase (1947-1972), precipitation shows a north-south dipole, with above-normal precipitation over North

China but below-normal precipitation over South China (Fig. 3a). Meanwhile, most of the contiguous US receives below-normal precipitation except parts of the northwest and southeast, where precipitation increases (Fig. 3b). During the warm IPO phase (1977-1998), the spatial pattern of precipitation anomalies resembles that associated with the first cold IPO phase, but with opposite sign. However, note that the two cold IPO phases have distinct precipitation anomalies. For the recent cold phase (2003-2014), above- and below-normal precipitation is expected over North China and the Southwest US, respectively. However, precipitation decreases in both regions. A comparison of the SST anomalies associated with the two cold IPO phases (Fig. 3c and 3i), shows opposite-signed SST anomalies, except in the North Pacific. This implies that other interdecadal SST modes, e.g., AMO, may influence regional precipitation anomalies; over North China, their influences tend to be comparable to that of the IPO, but over the Southwest US they are relatively smaller. In addition, the 8-year lag anti-correlation between precipitation over North China and the IPO for 1920-2014 is similar to that for 1920-2000 (Fig. S3 in supplement), suggesting that the lag anti-correlation is robust. Therefore, the 8 years' lag could be another reason for the negative precipitation anomaly in North China during the recent IPO cold phase, which has thus far existed for only approximately a quarter of a traditional IPO cycle.

To explore global large-scale atmospheric circulation anomalies associated with increased precipitation over North China and the Southwest US, some key circulation variables as well as SST were separately regressed onto the smoothed regional mean precipitation anomalies over the two regions (Fig. 4).

Associated with increased precipitation over North China, the predominant SST feature is a basin-wide warming in the northern North Pacific and cooling in the tropical eastern Pacific (Fig. 4a), which resembles the IPO cold phase (Fig. 3c). There is an anomalously low sea-level pressure (SLP) over China and Mongolia, while an anomalously high SLP occupies the entire northern North Pacific. A positive height anomaly in the upper troposphere is also found over the northern North Pacific, suggesting the anomalous high pressure has an equivalent barotropic structure (Fig. 4c). It is associated with an anomalous anticyclone extending from west coast of North America to east coast of Asia. The lower-tropospheric circulation over East China features anomalous southwesterlies, indicating an enhanced EASM circulation. These circulation anomalies favor water vapor transport from the tropics and convergence into North China, associated with increased precipitation over North China but reduced precipitation over South China.

Compared with North China, increased precipitation over the Southwest US is associated with opposite-signed anomalies in SST and circulation. The spatial pattern of SST anomalies is analogous to the warm IPO phase (Fig. 3f). The northern North Pacific is also dominated by an equivalent barotropic structure, but it is an anomalous low. The associated anomalous cyclone induces anomalous southwesterlies and increased precipitation over the Southwest US (Fig. 4d). Meanwhile, anomalous northerlies are found over East China, implying a weakened EASM and reduced precipitation over North China.

4. Possible formation mechanism of the interdecadal seesaw

a. Impact of the IPO

Illustrated in Fig. 5 are multi-model ensemble mean anomalies of regional mean annual and seasonal precipitation responses in the eight AGCM experiments over North China and the Southwest US. In PwAn (the Pacific warm SST anomaly and Atlantic SST in neutral condition), below-normal precipitation occurs over North China, whereas the Southwest US receives above-normal precipitation, implying a seesaw pattern. The seesaw pattern reverses sign in PcAn. The AMO also contributes to the seesaw pattern, but has the opposite influence, with wet (dry) anomalies over North China and dry (wet) anomalies over the Southwest US associated with PnAw (PnAc). With respect to the annual-mean precipitation in PnAn, the IPO causes precipitation variations of approximately 6.4% and 39.8% of the mean over North China and the Southwest US, respectively, while the AMO only induces variations of approximately 4.1% and 13.5% of the mean. These results suggest that the IPO is the primary influence on the seesaw pattern; its modulation tends to be intensified when the AMO is in the opposite phase, but weakened when the AMO is in the same phase. Besides, note that the intermodel consensus is much stronger for the precipitation responses over the Southwest US than that over North China, implying that the linkage between the IPO (AMO) and precipitation variations is stronger over the Southwest US, whereas there are some uncertainties over North China.

Generally, the AGCMs in this study simulate well the observed contrasting precipitation variability between North China and the Southwest US, as well as the

dominant role of the IPO in driving this contrast. The precipitation response over the Southwest US to the IPO is much larger than that over North China. This is consistent with Dong and Dai (2015), which found a robust precipitation response over the Southwest US for two cold IPO phases in a CanAM4 simulation forced by observed SSTs from 1950 to 2009, whereas the precipitation response was inconsistent over North China. Additionally, the similarity between the precipitation responses in the annual and seasonal averages, especially over the Southwest US, may be related to imposing the annual-mean IPO or AMO SST anomaly onto the monthly climatology (Schubert et al. 2009).

To clarify the impact of the IPO on the seesaw, Fig. 6 shows the annual-mean atmospheric circulation response to PwAn and PcAn. In PwAn, the predominant feature of the SLP (Fig. 6a) and height responses at 500 hPa (Fig. 6c) is a negative anomaly occupying the entire northern North Pacific, implying a deepened Aleutian low. This is accompanied by a large-scale cyclonic anomaly extending from the west coast of North America to northern China. Meanwhile, there is an anticyclonic anomaly centered over the northwest Pacific. Combined, these circulations induce anomalous northwesterlies over North China and southwesterlies over both the Southwest US and South China, and a belt of anomalous moisture transport from the Bay of Bengal, South China Sea and the subtropical Pacific to the west coast of North America (Fig. 6e). This increased moisture transport is associated with a belt of increased precipitation, including the Southwest US and South China (Fig. 6g). Less precipitation falls over North China, related to the increase in moisture convergence over South China

associated with the weakened EASM (Yang et al. 2017). The simulated circulation patterns resemble those related to increased precipitation over the Southwest US in observations (Fig. 4b and 4d). In PcAn (right column in Fig. 6), the spatial patterns of the circulation responses are analogous to those in PwAn but with opposite signs, as well as those related to increased precipitation over North China in observations (Fig. 4a and 4c).

Both observations and simulations suggest the IPO-induced height anomaly over the northern North Pacific is critical in driving the seesaw pattern, via opposing wind and moisture anomalies on its eastern and western sides. Next, we consider the possible mechanisms for this height anomaly.

In PwAn, warm SST anomalies over the equatorial central-eastern Pacific warm the tropical troposphere through enhanced surface heat fluxes from the ocean to the atmosphere (Fig. 7a). Meanwhile, a zonal belt of extensive cooling exists over approximately 30°N-60°N, which may be associated with changes in the eddy-driven mean meridional circulation (Seager et al. 2003). Then, the meridional temperature gradient (MTG), computed as the temperature difference from south to north, strengthens over the region 15°N-45°N, collocated with enhanced westerlies in the upper troposphere via thermal wind balance. In the tropics and high latitudes, the weakened MTG is associated with anomalous easterlies. Associated with these wind anomalies is a dipole pattern of relative vorticity changes at 200 hPa over the North Pacific, with a cyclone over the northern North Pacific and an anticyclone over the southern North Pacific, with a dividing line at approximately 40°N (Fig. 7c).

Consequently, an anomalous upper-troposphere low-pressure center forms over the northern North Pacific.

On the other hand, the mean meridional circulation over the North Pacific changes in response to the increased atmospheric heating over the tropical ocean. The thermally direct Hadley cell is strengthened by enhanced tropical convection (Fig. 7g), itself due to enhanced surface evaporation and low-level moisture convergence. The strengthened descending motion in the subsiding branch of the Hadley cell, centered at approximately 20°N, aligns with an anomalous anticyclone at 850 hPa (Fig. 7e). In the lower troposphere, the northward flow from the subtropical anomalous anticyclone converges in the mid-latitudes and enhances the ascending branch of the Ferrel cell, forming an anomalous cyclone over the northern North Pacific. Therefore, in PwAn, a barotropic low-pressure anomaly extends across the northern North Pacific, which is clearly related to the planetary-scale response of the atmosphere to the tropical warm SST anomalies.

Collocated with vertical velocity anomalies (upward-downward-upward from south to north, Fig. 7g) over the North Pacific, there is above-normal precipitation in the tropics (10°S-10°N), below-normal precipitation in the subtropics (10°N-30°N), and above-normal precipitation in the mid-latitudes (30°N-50°N, Fig. 7i). Note that the above-normal precipitation overlies cold SST anomalies across the northern North Pacific. The opposing signs of the precipitation and SST anomalies suggests that the increased precipitation is forced remotely, not by local SST anomalies (Wu and Kirtman 2007), strengthening the conclusion that the negative height anomaly over the

northern North Pacific is a response to the IPO-associated tropical warm SST anomalies via the atmospheric bridge.

Then, a question naturally arises: Do the tropical SST component of the IPO induce the height anomaly over the northern North Pacific? To answer the question, additional experiments (performed by only GFDL and NSIPP1) forced by the tropical SST component of the Pacific pattern were also analyzed and compared with the baseline experiments.

Overall, circulation responses in AGCMs forced by the tropical SST anomaly only (TP) support the above finding (Fig. 8). Like PwAn, TPwAn also induces a tripole pattern of temperature anomalies over the North Pacific (warm-cold-warm from south to north), which is associated with a tripole structure of zonal wind anomalies (easterlies-westerlies-easterlies), due to the MTG changes. These favor a dipole pattern of relative vorticity shear in the upper troposphere, with positive vorticity over the northern North Pacific and negative vorticity over south of it. The former is associated with a barotropic low-pressure anomaly, accompanied by a large-scale cyclonic flow over the northern North Pacific and adjacent regions in the lower troposphere. Consequently, the seesaw pattern forms (Fig. 9 and Fig. S5 in supplement), characterized by dry over North China and wet over the Southwest US.

The atmospheric processes associated with PcAn (right column in Fig. 7) and TPcAn (Fig. S4 in supplement) resemble those associated with PwAn and TPwAn, respectively, but with the opposite sign. A barotropic high-pressure anomaly extends across the northern North Pacific in response to the IPO-associated tropical cold SST

anomalies.

b. Impact of the AMO

Both observations (Fig. 2b) and simulations (Fig. 5) suggest that compared with the IPO, the AMO plays an opposite and secondary role in the contrasting precipitation variability between North China and the Southwest US. This finding is also supported by the height response over the northern North Pacific, which is a critical circulation system associated with the seesaw pattern. As clearly shown in Fig. 10, opposite pressure anomalies are associated to the IPO and AMO. In addition, the magnitude of the AMO-induced height anomaly is only approximately one-third to one-half that induced by the IPO, suggesting the IPO plays a dominant role. The IPO-induced height anomaly is intensified when the AMO is in the opposite phase (PwAc and PcAw), whereas it is slightly weakened when the AMO is in the same phase (PwAw and PcAc).

How does the AMO affect the IPO? It has been suggested that the impact of the AMO on the IPO could be through two pathways: 1) the mid-latitude atmosphere process, the AMO could modify the atmospheric anomalies over Eurasia and further the northern North Pacific via downstream energy propagation at the mid-high latitudes (e.g., Si and Ding, 2016); 2) the tropical atmosphere process, the AMO could generate a trans-basin SLP seesaw, characterized by opposite SLP trends in the Pacific and the Indo-Atlantic region, and further change SST over the eastern tropical Pacific via a modification of the Walker circulation involving low-level wind anomalies (e.g., McGregor et al. 2014). No matter through which pathways, the warm

(cold) AMO phase tends to induce the cold (warm) IPO phase. This is supported that there exists a significant lag anti-correlation between the AMO and the IPO indices with the AMO index leading by approximately 11~12 years (Wu et al. 2011; Chylek et al. 2014).

In the CLIVAR AGCMs experiments, the AMO may affect the modulation of the IPO on circulation and precipitation through the first pathway. PnAw (PnAc) drives an eastward-propagating wave train over Eurasia and then, induces a barotropic high (low)-pressure anomaly over the northern North Pacific (Fig. 6 in Yang et al. (2017); also seen Fig. S6 in supplement), which is consistent with the height anomaly associated to PcAn (PwAn). Consequently, circulation and precipitation responses to PnAw (PnAc) closely resemble those associated with PcAn (PwAn), although with smaller magnitude. When the AMO in combination with the IPO in the opposite phases, PwAc and PcAw (Fig. S7 in supplement), precipitation and circulation responses resemble those in PwAn and PcAn (Fig. 6), respectively, but the strengthened height anomaly over the northern North Pacific is associated with larger anomalies of wind, moisture flux and precipitation (Fig. 11 and Fig. S8 in supplement).

5. Conclusions and discussion

Using data from observations, reanalysis and a set of AGCMs simulations forced by idealized IPO- and AMO-associated SST anomalies, we compared the interdecadal precipitation variations over North China and the Southwest US, as well as the associated circulations. Our main findings are summarized as follows:

Firstly, on interdecadal scales, precipitation variations over North China and the Southwest US are anti-correlated, implying a seesaw pattern. The IPO could play a dominant role in driving the seesaw pattern, with the warm IPO phase associated with less precipitation over North China but more over the Southwest US; the cold phase is associated with the opposite-signed pattern. The AMO contributes oppositely and less. The IPO-induced precipitation anomaly intensifies when the AMO is in the opposite phase, whereas it is slightly weakened when the AMO is in the same phase. The IPO has a much stronger influence on precipitation variations over the Southwest US than that over North China. AGCM simulations from the US CLIVAR Drought Working Group capture these relationships well.

Secondly, for the IPO, the large-scale lower-tropospheric cyclonic or anticyclonic circulation anomaly across the northern North Pacific is the predominant factor in driving the seesaw pattern. During the warm IPO phase, North China and the Southwest US, which are located at the western and eastern parts of the deepened Aleutian low, experience anomalous northwesterlies and southwesterlies, and receive below-normal and above-normal precipitation, respectively. Opposite-signed circulation anomalies are associated with the cold IPO phase.

Thirdly, the height anomaly over the northern North Pacific, which exhibits an equivalent barotropic structure, is part of the planetary-scale atmospheric response to the IPO-associated tropical SST anomaly. For instance, the warm IPO phase induces a tripole pattern of temperature anomalies over the North Pacific (warm-cold-warm from south to north), that strengthens the mid-latitude meridional temperature gradient but

weakens it in the tropics and high latitudes. By thermal wind balance, these are accompanied by a tripole structure of zonal wind anomaly (easterlies-westerlies-easterlies) that favors a dipole pattern of upper-tropospheric relative vorticity shear, with positive vorticity over the northern North Pacific and negative vorticity to the south. Consequently, a barotropic cyclonic anomaly extends across the northern North Pacific.

Given the association between IPO (AMO) phase and interdecadal precipitation variations over North China and the Southwest US, improved prediction of the IPO (AMO) could provide a potential predictability of drought-related water stresses over the two regions, although there are still many uncertainties in our understanding and prediction of these interdecadal oceanic modes. If the phase of the IPO turns positive, as it is projected in late 2014 (Meehl et al. 2016), North China may experience anomalously decreased precipitation, whereas precipitation may enhance across much of North America, including the Southwest US. However, we caution that this analysis considers the IPO and AMO only, and neglects other processes, for instance anthropogenic greenhouse gases and aerosols, which may also induce interdecadal precipitation variability, either through a direct effect on precipitation or an indirect influence on the magnitude or period of the IPO and AMO (e.g., Dong et al. 2014; Smith et al. 2016; Liguori and Di Lorenzo 2018).

The observed seesaw pattern is the result of air-sea interactions, although the SST may play a more active role than the atmosphere. However, AGCM simulations used in this study cannot reflect the feedback of the atmosphere to the SST, which may

lead to erroneous attribution conclusions for decadal-scale circulation and precipitation variability, especially in East Asia (Dong et al. 2017). Additionally, the AGCM simulations show only the steady-state response, which cannot distinguish which circulation feature occurs first in response to the tropical SST anomaly, and thus may cause uncertainty in the potential pathway described here. The Pacific SST forcing (Fig. 1a) used in the AGCM simulations includes a same-signed SST anomaly in the Indian Ocean, which has been shown to contribute to precipitation variations over the US (e.g., Hoerling and Kumer 2003) and North China. The role of the Indian Ocean in the anti-correlation of precipitation over North China and Southwest US is not clear. These issues require further investigation to verify the link between the interdecadal seesaw pattern and the IPO and AMO.

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1 **Table Caption List**

2 **Table 1.** The combinations of Pacific and Atlantic SST anomaly patterns used to force
3 the AGCMs. Here *w* refers to the warm phase of the pattern (scaled by $+2\sigma$), *n* denotes
4 neutral (zero anomaly), and *c* refers to the cold phase (scaled by -2σ). The *PnAn*
5 experiment denotes the control run forced with the annually varying climatological
6 SST (Schubert et al. 2009).

7

8 **Figure Caption List**

9 **Fig. 1** The second and third leading REOFs ($^{\circ}\text{C}$) and associated time-series RPCs ($^{\circ}\text{C}$)
10 of annual mean SST from 1901 to 2004 (Schubert et al. 2009). (a) The Pacific
11 ENSO-like SSTA pattern of REOF2 and (b) associated RPC2 and the IPO index. (c)
12 The Atlantic AMO SSTA pattern of REOF3 and (d) associated RPC3 and AMO index.
13 The blue curves (b and d) are smoothed time series obtained by applying a 9-year
14 moving average twice to the bars to emphasize the interdecadal variations. The same
15 method is applied to the IPO and AMO indices. *r* and *p* represent the correlation
16 coefficients between red and blue curves, and the statistical significance level,
17 respectively. The percentages indicate the corresponding explained variances.

18

19 **Fig. 2** (a) Detrended monthly precipitation anomalies over North China ($110^{\circ}\text{E}\sim 118^{\circ}\text{E}$,
20 $34^{\circ}\text{N}\sim 42.5^{\circ}\text{N}$) and the Southwest US ($105^{\circ}\text{W}\sim 120^{\circ}\text{W}$, $30^{\circ}\text{N}\sim 40^{\circ}\text{N}$) and the IPO and
21 AMO indices, obtained by applying a 109-month moving average twice. Observed
22 precipitation anomalies over North China are referred to as “North China_station”.

Black dotted lines represent $\pm 0.5\sigma$ of the IPO index. (b) Annual mean precipitation anomaly percentage (%) over North China and the Southwest US during different periods: cold IPO (IPO-), cold IPO plus warm AMO (IPO-AMO+), cold IPO plus cold AMO (IPO-AMO-), warm IPO (IPO+), warm IPO plus cold AMO (IPO+AMO-), and warm IPO plus warm AMO (IPO+AMO+), with respect to the climatology from 1920 to 2014. Statistically significant anomalies at the 5% level are indicated by black triangles.

Fig. 3 The IPO phase composite anomaly (relative to 1900-2014) maps of the detrended precipitation (mm day^{-1}) over North China (left column) and the Southwest US (middle column), and annual mean SST ($^{\circ}\text{C}$, right column) for the cold (a, b, and c, 1947-1972; g, h, and i, 2003-2014) and warm epochs (d, e, and f, 1977-1998), respectively. The boundaries of North China and the Southwest US are outlined in blue boxes. The dotted areas represent statistically significant anomalies at the 5% level.

Fig. 4 Regression maps of the detrended monthly (a) (b) SST ($^{\circ}\text{C}$, shaded) and SLP (hPa, contours), (c) (d) 200 hPa geopotential height (Z, m, contours) and 850 hPa wind (UV, m s^{-1} , vector) regressed onto the detrended monthly precipitation anomalies over North China and the Southwest US. The SST, circulation variables and precipitation are smoothed by applying a 109-month moving average twice. Only statistically significant ($p < 0.05$) regression coefficients of 850 hPa wind are illustrated. The dotted and shaded areas represent significant ($p < 0.05$) regression coefficients of

SST and 200 hPa geopotential height, respectively.

Fig. 5 Multi-model ensemble mean anomalies of annual and seasonal precipitation (mm day⁻¹) over (a) North China and (b) the Southwest US relative to the control run (PnAn). Error bars indicate the intermodel range. Here, P and A denote the Pacific (IPO) and Atlantic (AMO) SST anomaly patterns; *w*, *n* and *c* refer to the warm, neutral and cold phases, respectively (Table 1).

Fig. 6 Multi-model ensemble mean anomalies of annual mean (a) (b) SLP (hPa, shaded) and its climatology in PnAn (hPa, contours); (c) (d) 500-hPa geopotential height (*Z*, m, shaded) and 850 hPa wind (UV, m s⁻¹, vectors); (e) (f) column-integrated moisture divergence (mm day⁻¹, shaded) and moisture flux (g cm⁻¹ s⁻¹, vectors); (g) (h) precipitation (Pre, mm day⁻¹, shaded), for PwAn (left column) and PcAn (right column). Note that an unequal contour interval is used to highlight the response over land. Stippling indicates areas where more than four of the five AGCMs agree on the sign.

Fig. 7 Multi-model ensemble mean anomalies of annual mean (a) (b) air temperature (*T*, from surface to 200 hPa, contours, K) and 200 hPa zonal wind (*U*, shaded, m s⁻¹); wind (UV, m s⁻¹, vectors) and relative vorticity (scaled by 1e5, s⁻¹, shaded) at (c) (d) 200 hPa, and (e) (f) 850 hPa; (g) (h) meridional (*V*, m s⁻¹, vectors) and vertical (*W*, 10⁻³ m s⁻¹, shaded) circulation, and (i) (j) SST (scaled by 2, °C) and precipitation (Pre, mm day⁻¹) over the Pacific (average 150°E~120°W), for PwAn (left column) and PcAn (right

column). For convenience in comparing quantitatively the precipitation responses in different experiments, the zonal-mean precipitation anomalies in experiments with the warm (Pw) and cold IPO (Pc), as well as PnAc and PnAw, are illustrated in (i) and (j), respectively.

Fig. 8 Anomalies of annual mean (a) (b) air temperature (T , from surface to 200 hPa, contours, K) and 200 hPa zonal wind (U , shaded, m s^{-1}); wind (UV , m s^{-1} , vectors) and relative vorticity (scaled by $1e5$, s^{-1} , shaded) at (c) (d) 200 hPa, and (e) (f) 850 hPa for TPwAn in GFDL (left column) and NSIPP1 (right column).

Fig. 9 Responses of annual mean precipitation (mm day^{-1} , shaded) to the Pacific pattern (PwAn and PcAn) and its tropical SST component (TPwAn and TPcAn) in GFDL. The dotted areas represent statistically significant anomalies at the 5% level.

Fig. 10 Multi-model ensemble mean anomalies of annual mean geopotential height (m) over the northern North Pacific (30° - 65° N, 160° E- 140° W) from surface to 70 hPa.

Fig. 11 Left column: Multi-model ensemble mean differences between PwAc and PwAn: (a) SLP (hPa, shaded) and SLP climatology in PwAn (hPa, contours); (c) 500 hPa geopotential height (Z , m, shaded) and 850 hPa wind (UV , m s^{-1} , vectors); (e) column-integrated moisture divergence (mm day^{-1} , shaded) and moisture flux ($\text{g cm}^{-1} \text{ s}^{-1}$, vectors); (g) precipitation (Pre , mm day^{-1} , shaded). Right column is the same as left

89 one, but for differences between PcAw and PcAn.

90

91 **Tables**

92 **Table 1.** The combinations of Pacific and Atlantic SST anomaly patterns used to force
93 the AGCMs. Here *w* refers to the warm phase of the pattern (scaled by $+2\sigma$), *n* denotes
94 neutral (zero anomaly), and *c* refers to the cold phase (scaled by -2σ). The *PnAn*
95 experiment denotes the control run forced with the annually varying climatological
96 SST (Schubert et al. 2009).

	Warm	Neutral	Cold
	Atlantic	Atlantic	Atlantic
Warm Pacific	PwAw	PwAn	PwAc
Neutral Pacific	PnAw	PnAn	PnAc
Cold Pacific	PcAw	PcAn	PcAc
Warm tropical Pacific	-	TPwAn	-
Cold tropical Pacific	-	TPcAn	-

97

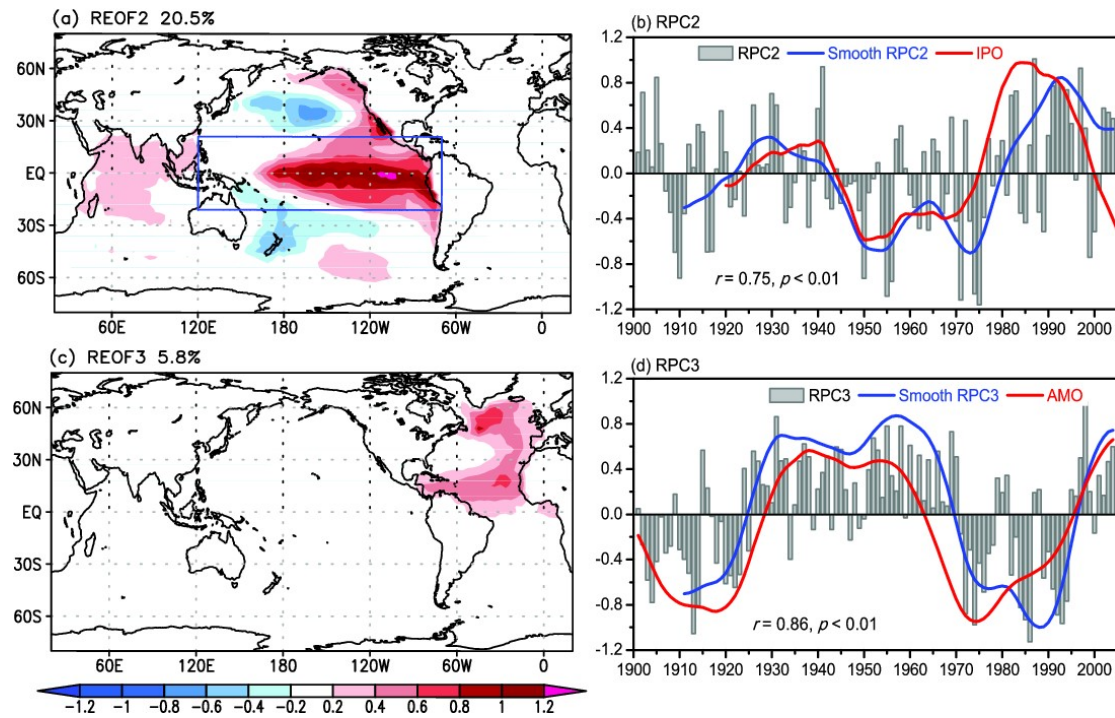


Fig. 1 The second and third leading REOFs ($^{\circ}\text{C}$) and associated time-series RPCs ($^{\circ}\text{C}$) of annual mean SST from 1901 to 2004 (Schubert et al. 2009). (a) The Pacific ENSO-like SSTA pattern of REOF2 and (b) associated RPC2 and the IPO index. (c) The Atlantic AMO SSTA pattern of REOF3 and (d) associated RPC3 and AMO index. The blue curves (b and d) are smoothed time series obtained by applying a 9-year moving average twice to the bars to emphasize the interdecadal variations. The same method is applied to the IPO and AMO indices. r and p represent the correlation coefficients between red and blue curves, and the statistical significance level, respectively. The percentages indicate the corresponding explained variances.

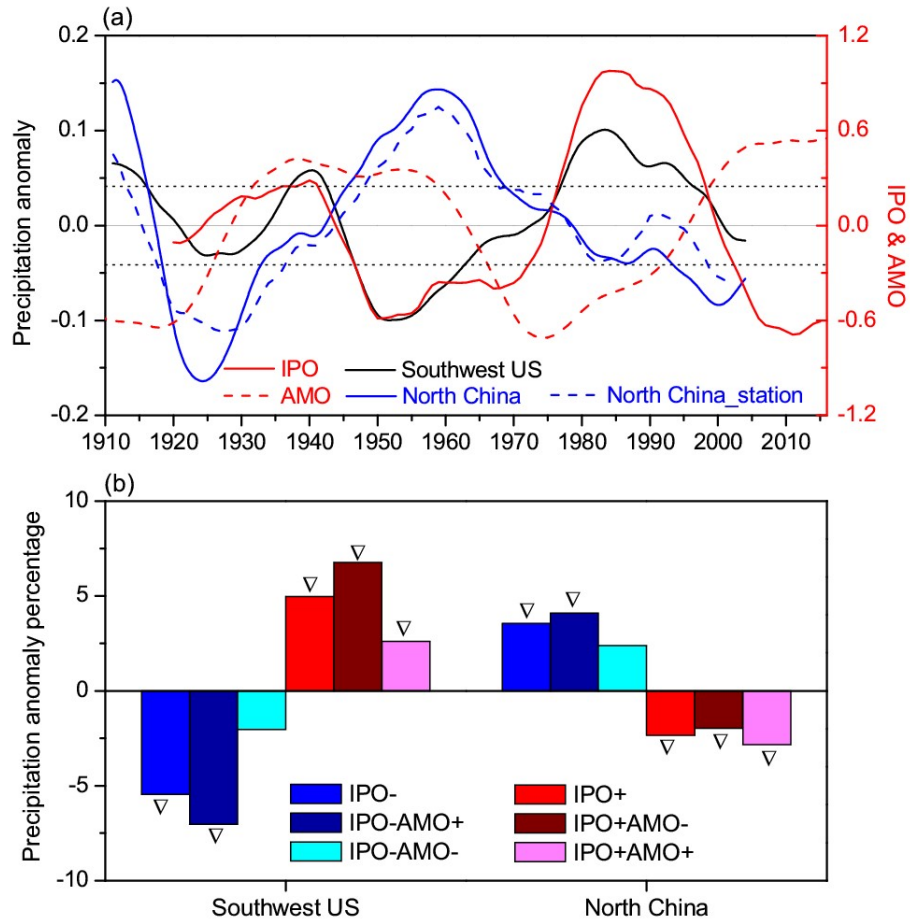


Fig. 2 (a) Detrended monthly precipitation anomalies over North China (110 °E~118°E, 34 °N~42.5°N) and the Southwest US (105 °W~120°W, 30 °N~40°N) and the IPO and AMO indices, obtained by applying a 109-month moving average twice. Observed precipitation anomalies over North China are referred to as “North China_station”. Black dotted lines represent $\pm 0.5\sigma$ of the IPO index. (b) Annual mean precipitation anomaly percentage (%) over North China and the Southwest US during different periods: cold IPO (IPO-), cold IPO plus warm AMO (IPO-AMO+), cold IPO plus cold AMO (IPO-AMO-), warm IPO (IPO+), warm IPO plus cold AMO (IPO+AMO-), and warm IPO plus warm AMO (IPO+AMO+), with respect to the climatology from 1920 to 2014. Statistically significant anomalies at the 5% level are indicated by black triangles.

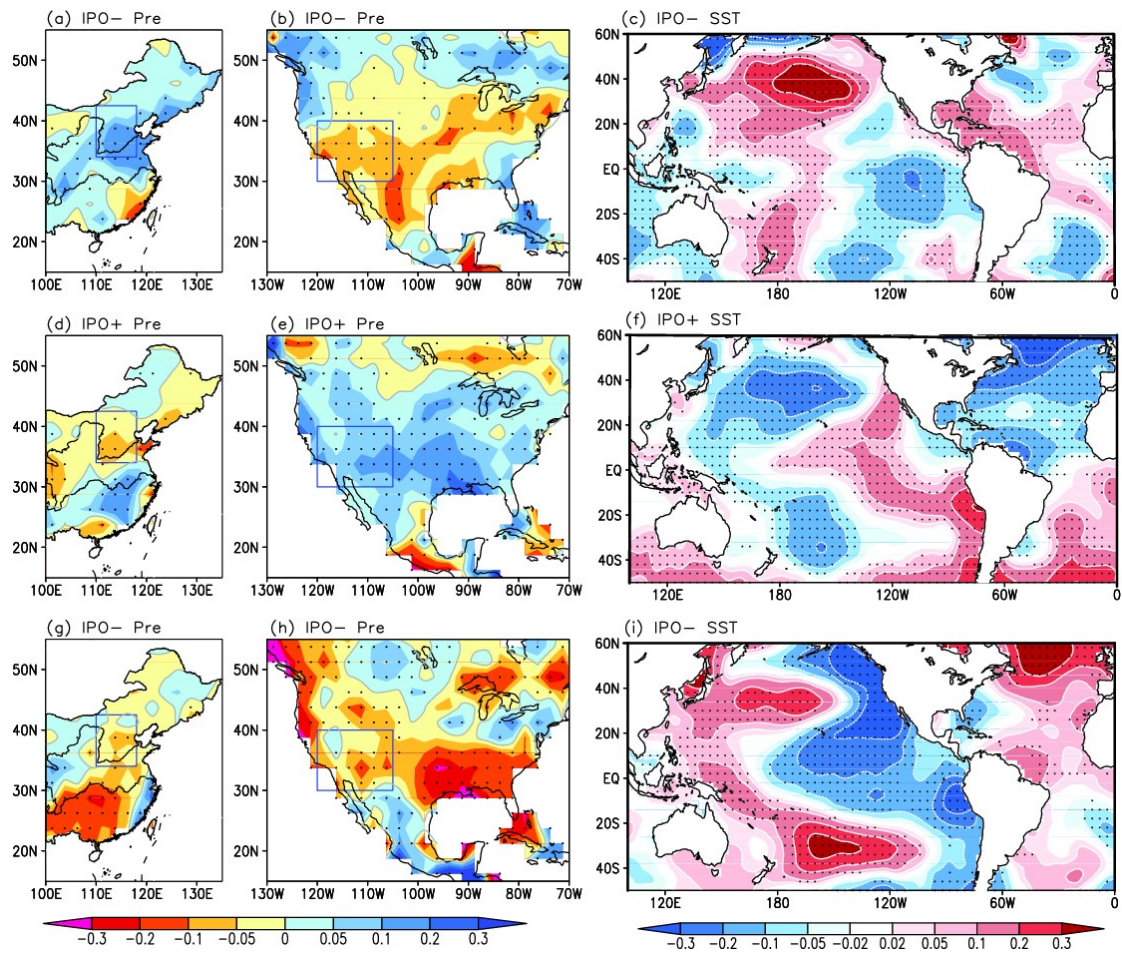


Fig. 3 The IPO phase composite anomaly (relative to 1900-2014) maps of the detrended precipitation (mm day^{-1}) over North China (left column) and the Southwest US (middle column), and annual mean SST ($^{\circ}\text{C}$, right column) for the cold (a, b, and c, 1947-1972; g, h, and i, 2003-2014) and warm epochs (d, e, and f, 1977-1998), respectively. The boundaries of North China and the Southwest US are outlined in blue boxes. The dotted areas represent statistically significant anomalies at the 5% level.

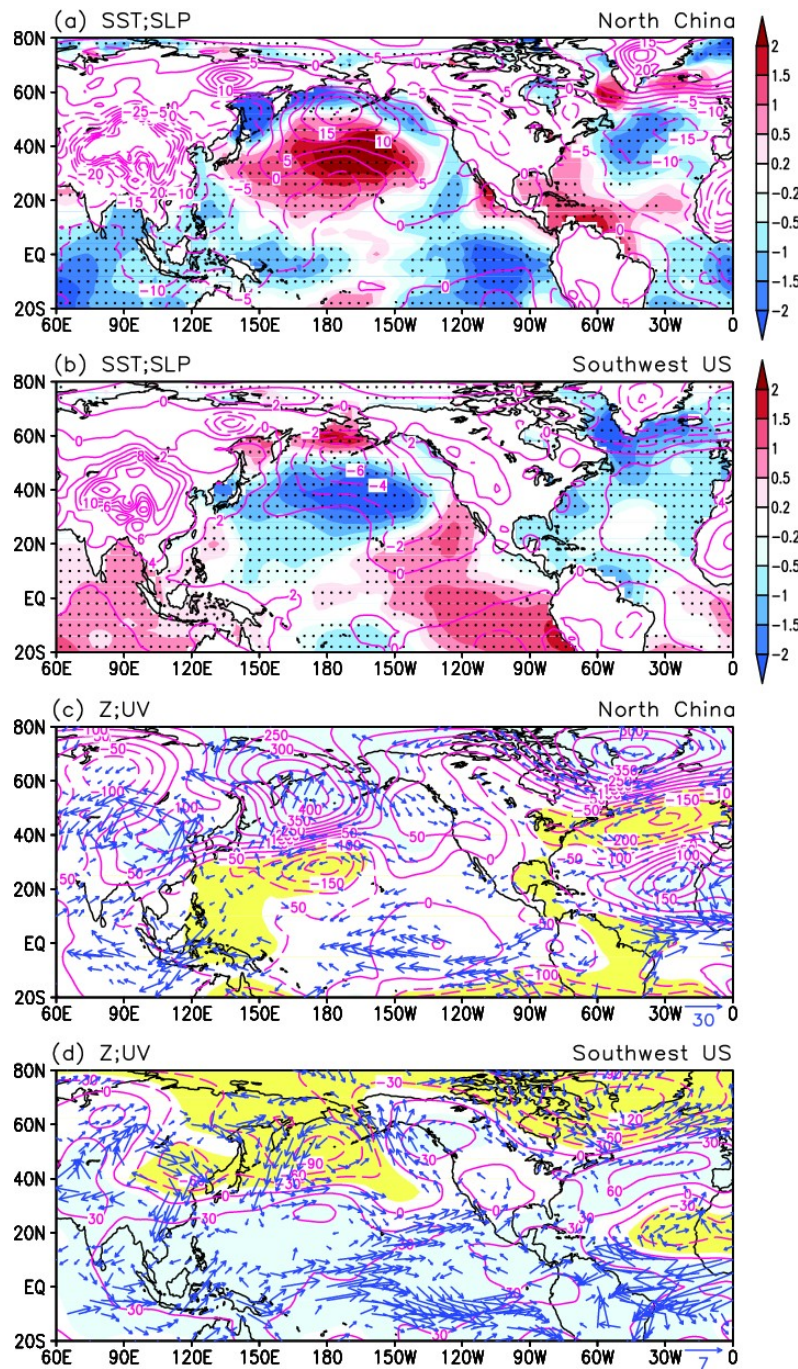


Fig. 4 Regression maps of the detrended monthly (a) (b) SST ($^{\circ}\text{C}$, shaded) and SLP (hPa, contours), (c) (d) 200 hPa geopotential height (Z , m, contours) and 850 hPa wind (UV, m s^{-1} , vector) regressed onto the detrended monthly precipitation anomalies over North China and the Southwest US. The SST, circulation variables and precipitation are smoothed by applying a 109-month moving average twice. Only statistically significant ($p<0.05$) regression coefficients of 850 hPa wind are illustrated. The dotted and shaded areas represent significant ($p<0.05$) regression coefficients of SST and 200 hPa geopotential height, respectively.

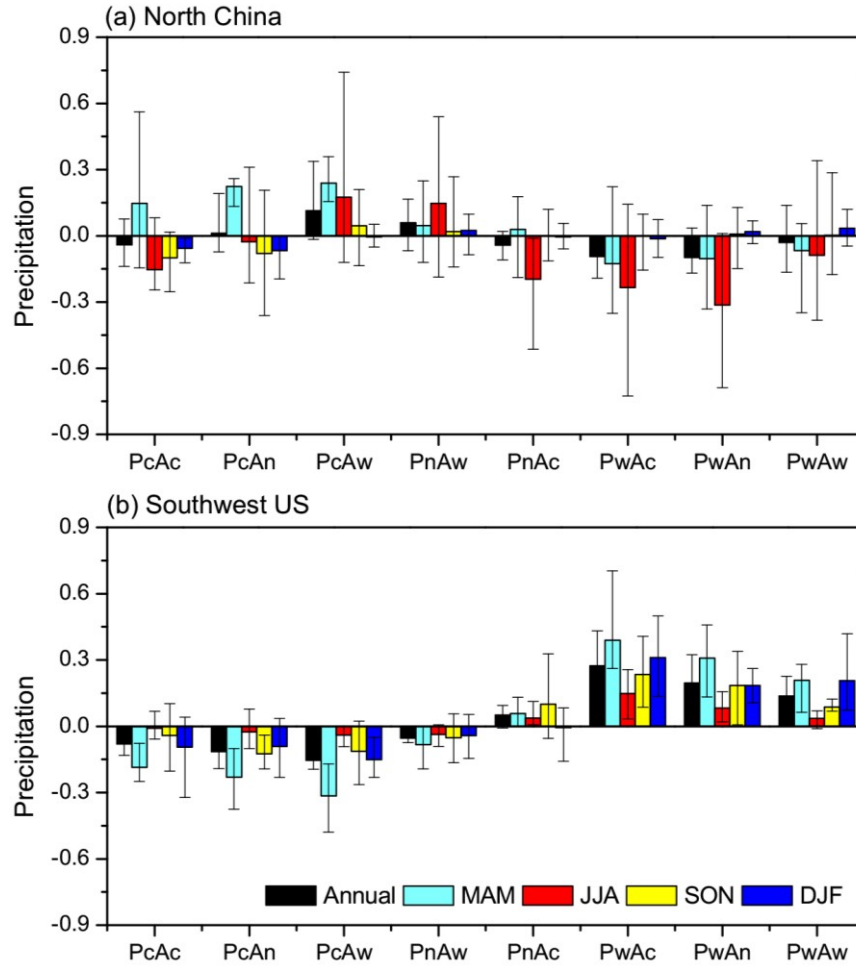


Fig. 5 Multi-model ensemble mean anomalies of annual and seasonal precipitation (mm day⁻¹) over (a) North China and (b) the Southwest US relative to the control run (PnAn). Error bars indicate the intermodel range. Here, P and A denote the Pacific (IPO) and Atlantic (AMO) SST anomaly patterns; *w*, *n* and *c* refer to the warm, neutral and cold phases, respectively (Table 1).

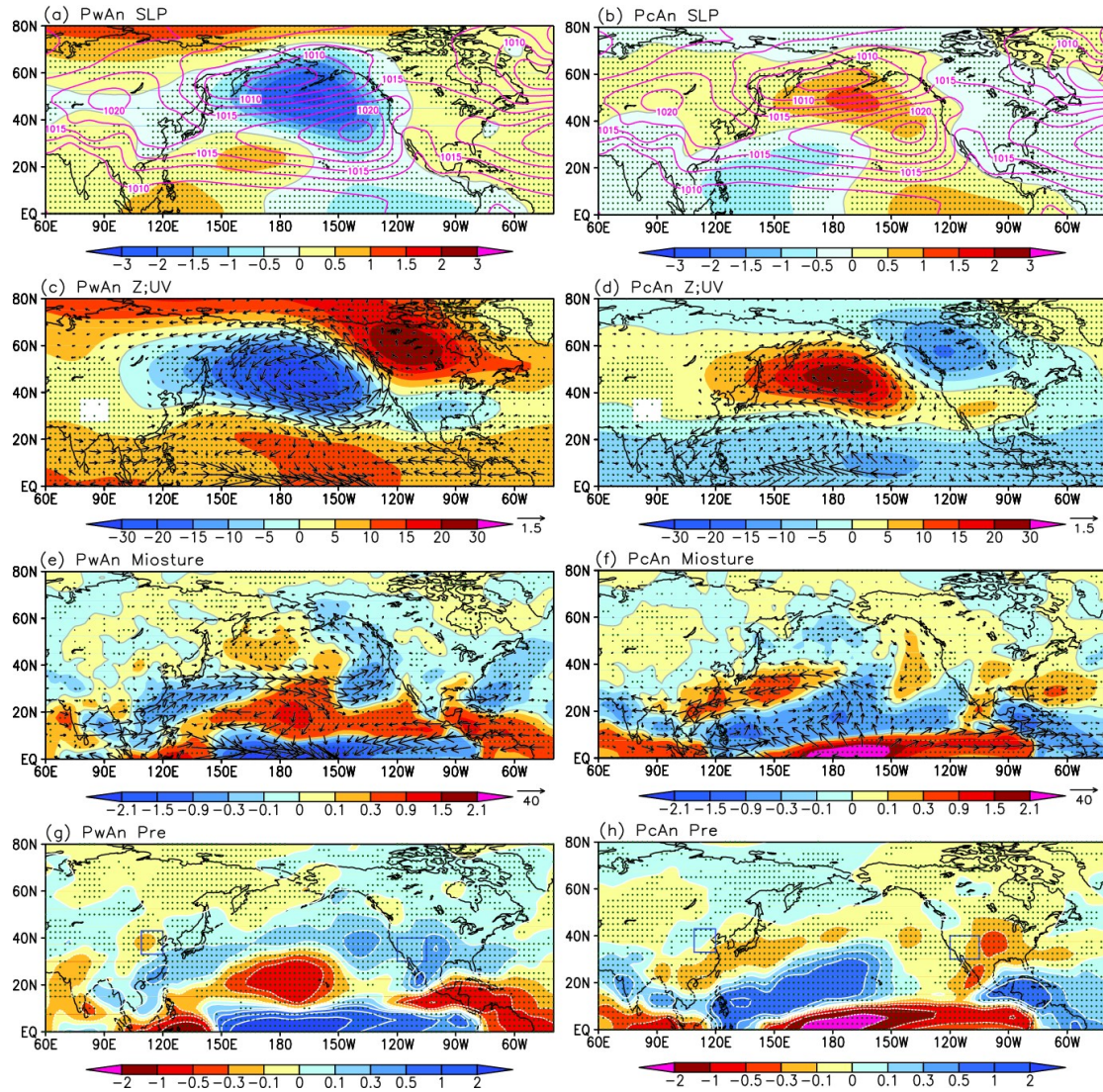


Fig. 6 Multi-model ensemble mean anomalies of annual mean (a) (b) SLP (hPa, shaded) and its climatology in PwAn (hPa, contours); (c) (d) 500-hPa geopotential height (Z, m, shaded) and 850 hPa wind (UV, m s^{-1} , vectors); (e) (f) column-integrated moisture divergence (mm day^{-1} , shaded) and moisture flux ($\text{g cm}^{-1} \text{s}^{-1}$, vectors); (g) (h) precipitation (Pre, mm day^{-1} , shaded), for PwAn (left column) and PcAn (right column).

Note that an unequal contour interval is used to highlight the response over land.

Stippling indicates areas where more than four of the five AGCMs agree on the sign.

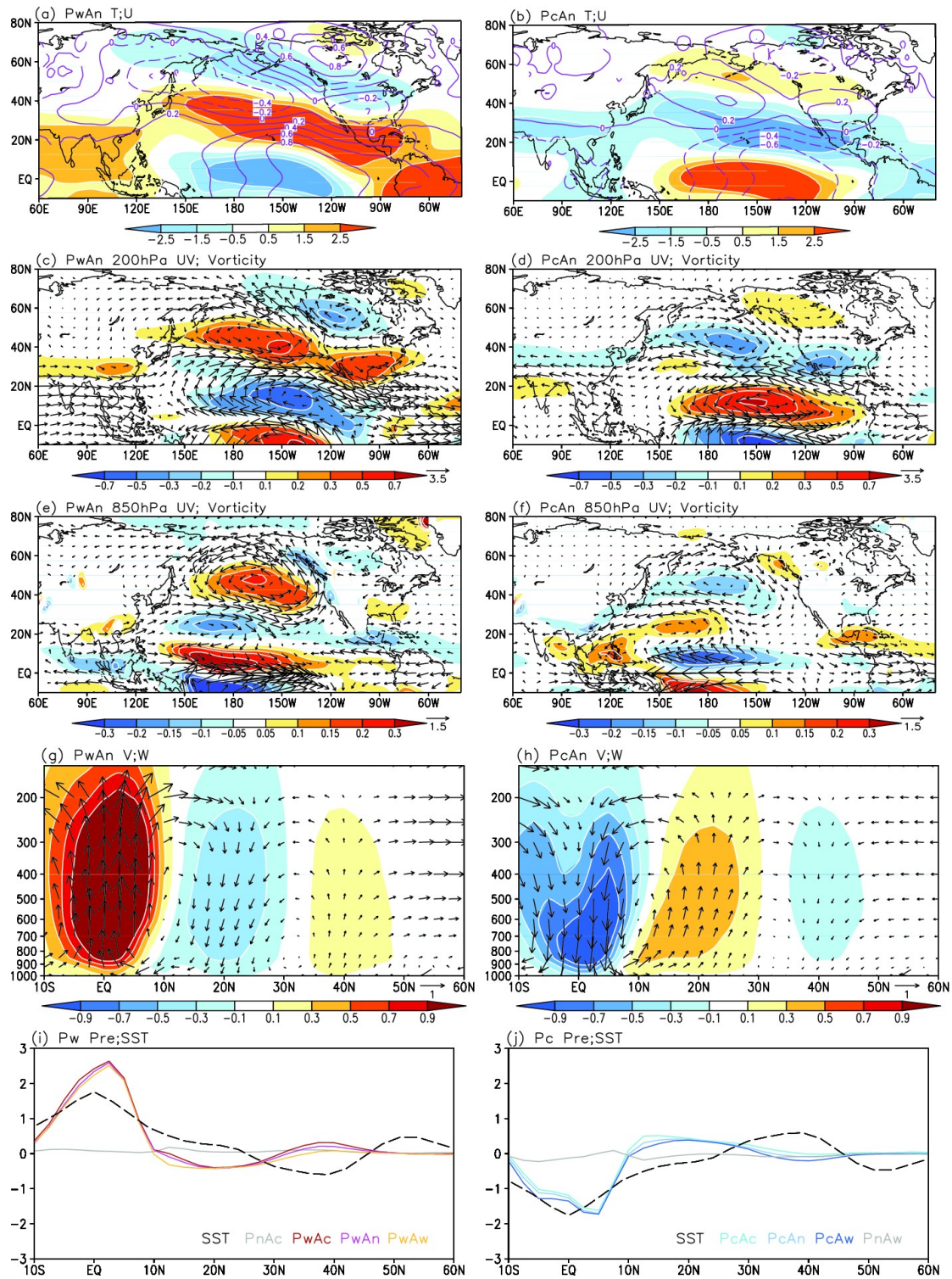


Fig. 7 Multi-model ensemble mean anomalies of annual mean (a) (b) air temperature (T, from surface to 200 hPa, contours, K) and 200 hPa zonal wind (U, shaded, m s^{-1}); wind (UV, m s^{-1} , vectors) and relative vorticity (scaled by $1\text{e}5$, s^{-1} , shaded) at (c) (d) 200 hPa, and (e) (f) 850 hPa; (g) (h) meridional (V, m s^{-1} , vectors) and vertical (W, 10^{-3} m s^{-1} , shaded) circulation, and (i) (j) SST (scaled by 2, $^{\circ}\text{C}$) and precipitation (Pre, mm day^{-1}) over the Pacific (average $150^{\circ}\text{E}\sim 120^{\circ}\text{W}$), for PwAn (left column) and PcAn (right

column). For convenience in comparing quantitatively the precipitation responses in different experiments, the zonal-mean precipitation anomalies in experiments with the warm (Pw) and cold IPO (Pc), as well as PnAc and PnAw, are illustrated in (i) and (j), respectively.

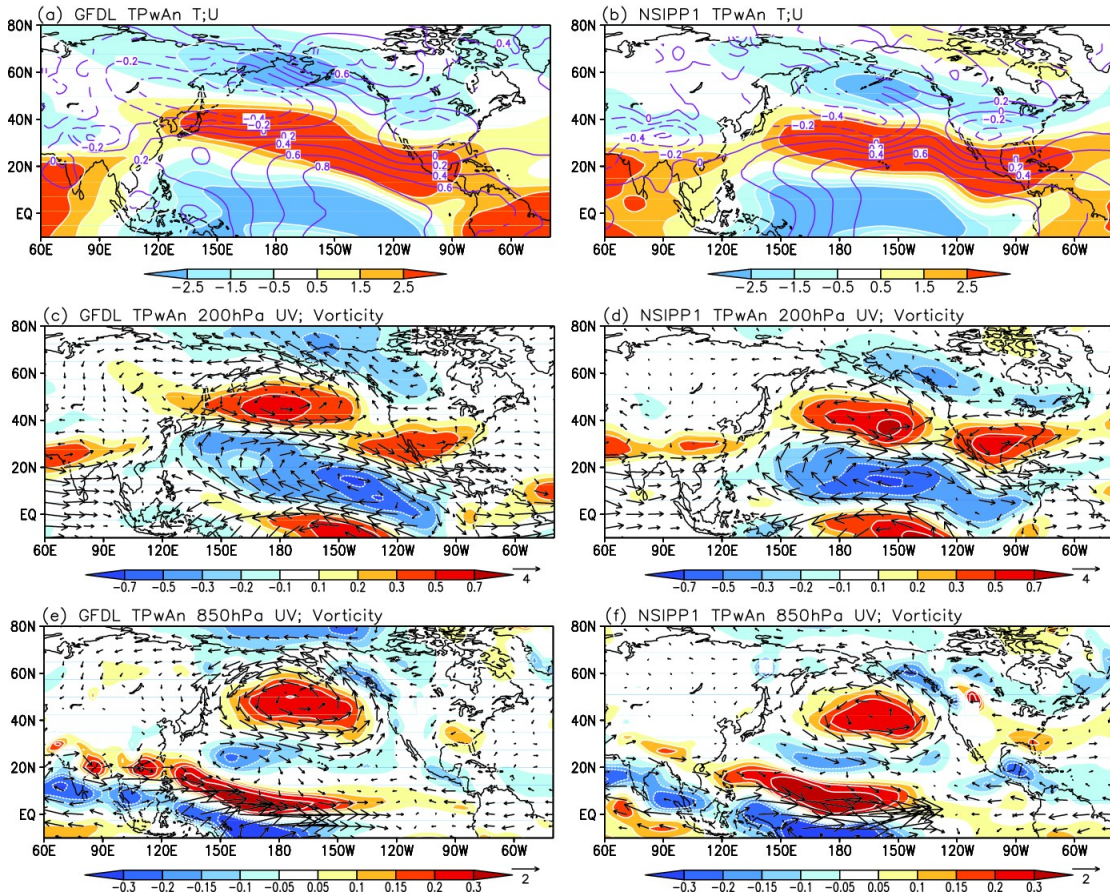


Fig. 8 Anomalies of annual mean (a) (b) air temperature (T, from surface to 200 hPa, contours, K) and 200 hPa zonal wind (U, shaded, m s⁻¹); wind (UV, m s⁻¹, vectors) and relative vorticity (scaled by 1e5, s⁻¹, shaded) at (c) (d) 200 hPa, and (e) (f) 850 hPa for TPwAn in GFDL (left column) and NSIPP1 (right column).

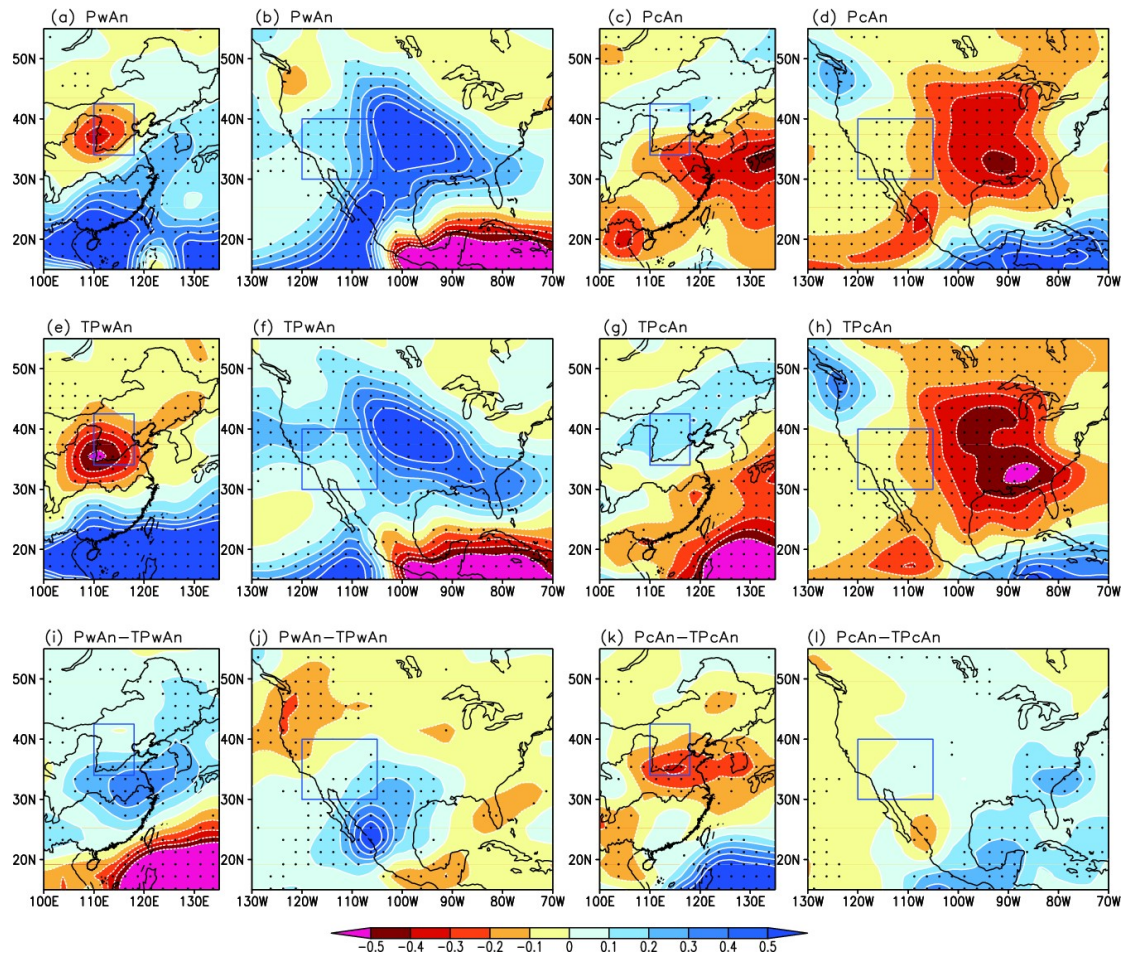


Fig. 9 Responses of annual mean precipitation (mm day^{-1} , shaded) to the Pacific pattern (PwAn and PcAn) and its tropical SST component (TPwAn and TPcAn) in GFDL. The dotted areas represent statistically significant anomalies at the 5% level.

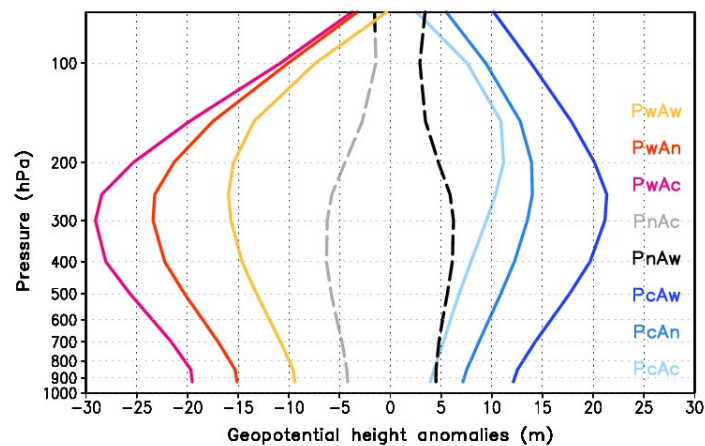


Fig. 10 Multi-model ensemble mean anomalies of annual mean geopotential height (m) over the northern North Pacific (30° - 65° N, 160° E- 140° W) from surface to 70 hPa.

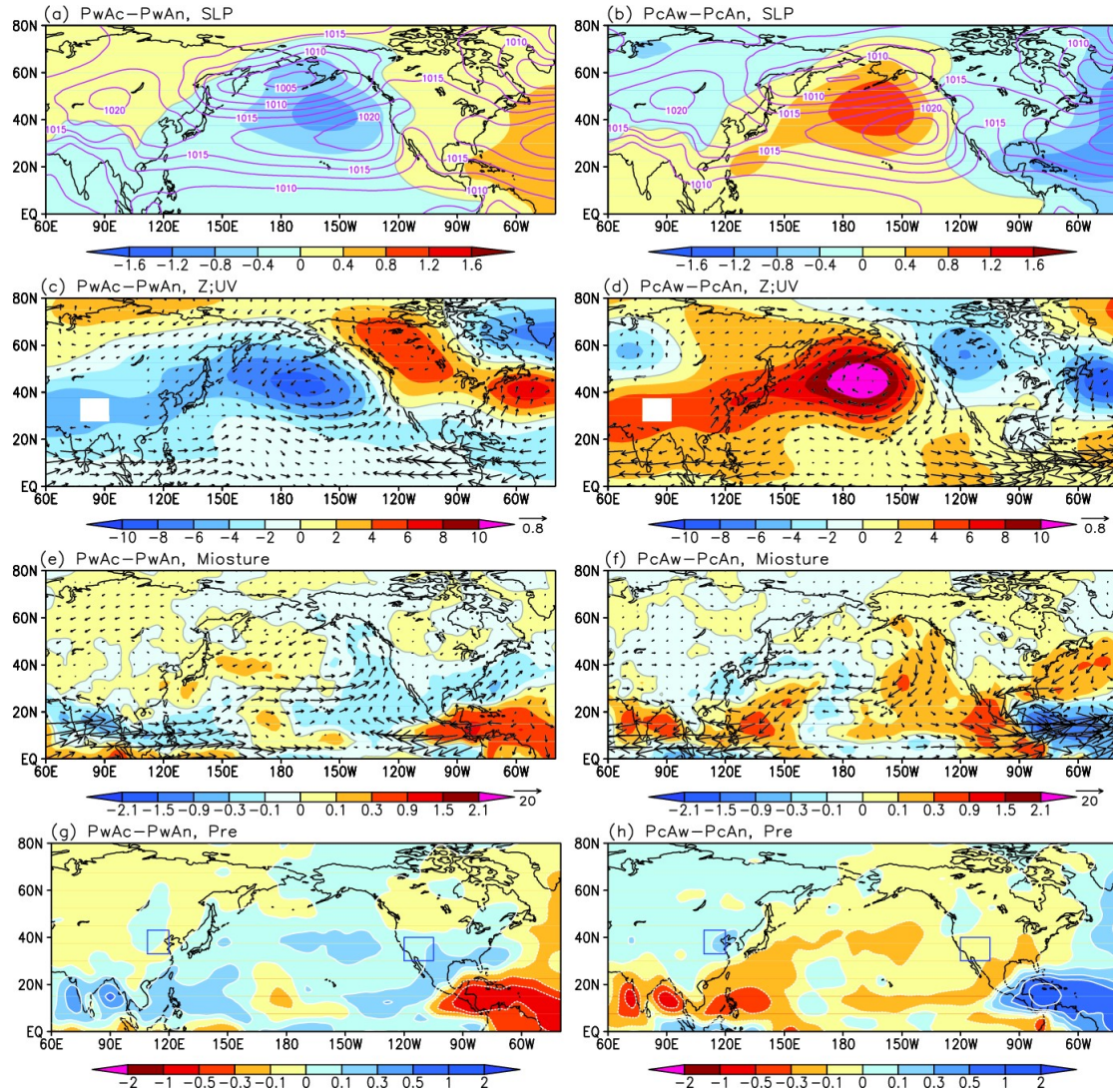


Fig. 11 Left column: Multi-model ensemble mean differences between PwAc and PwAn: (a) SLP (hPa, shaded) and SLP climatology in PwAn (hPa, contours); (c) 500 hPa geopotential height (Z, m, shaded) and 850 hPa wind (UV, m s^{-1} , vectors); (e) column-integrated moisture divergence (mm day^{-1} , shaded) and moisture flux ($\text{g cm}^{-1} \text{s}^{-1}$, vectors); (g) precipitation (Pre, mm day^{-1} , shaded). Right column is the same as left one, but for differences between PcAw and PcAn.