Influences of Atmospheric Rivers on North Pacific Winter Precipitation: Climatology and Dependence on ENSO Condition

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(Manuscript received 26 April 2020, in final form 2 October 2020)

ABSTRACT: The atmospheric river (AR) is a unique mover of moisture from the low latitudes to mid- and high latitudes and a potential cause for regional flooding. This study explores the ARs' influence on wintertime precipitation (including extreme precipitation) over the pan-North Pacific during 1996–2018 from the climatological perspective and during the ENSO condition, via distinguishing precipitation and moisture transport between the AR-group and the non-AR-group. Climatologically, the AR-group contributes 30%–45% of total winter precipitation, and up to 70% of total extreme precipitation over the eastern Pacific and along the North American west coast between 25° and 45°N. The above area is the core region of the ARs' influence on precipitation. The AR-group's precipitation in the core region is mostly determined by AR-produced in situ moisture convergence, while the non-AR-group's precipitation is attributed to evaporation from Earth's surface. The AR frequency is increased (decreased) in the core region during El Niño (La Niña) winters. As a result, the AR-group contributes more than half of the positive (negative) anomalies in total precipitation in the core region, due to AR-related moisture convergence anomalies. Besides, during El Niño winters, the AR-group also contributes almost half of negative anomalies in total precipitation over the middle basin between 40° and 55°N. An anomalous moisture sink (source) always acts to increase (decrease) in situ precipitation for both the AR-group and the non-AR-group. It is also shown that the moisture transport and its divergence anomalies are primarily decided by changes in wind fields and second by moisture. Furthermore, changes in moisture can cause asymmetric features of anomalies in moisture transport and its divergence between El Niño and La Niña but with limited effects.

KEYWORDS: Atmospheric circulation; ENSO; Extreme events; Precipitation; Water vapor; Interannual variability

1. Introduction

Atmospheric moisture transport and its convergence are primary processes to form precipitation (Trenberth 1999; Sohn et al. 2004; Trenberth et al. 2007; Chen et al. 2004; Schneider et al. 2010). The feature of moisture transport shows diversity over the ocean basins (e.g., the North Pacific and the North Atlantic). The time-mean circulation moves moisture zonally within ocean basins (Trenberth 1999; Newman et al. 2012). The filament-shaped conduits with large water vapor transport, often called atmospheric rivers (ARs), transport moisture from the lower latitudes to the middle and high latitudes (Newell et al. 1992; Zhu and Newell 1998; Ralph et al. 2006; Dettinger 2013; Guan and Waliser 2015; Liu et al. 2016; Guan et al. 2018; Nash et al. 2018; Ralph et al. 2019). Due to copious moisture fluxes, ARs have a crucial role in shaping the precipitation over the pan-North Pacific region (Kim et al. 2013; Kamae et al. 2017; Tsuji and Takayabu 2019). After traveling northeastward through ocean region, some ARs make landfall and create flooding, extreme precipitation events and other impacts over the west coast regions (Neiman et al. 2008; Guan et al. 2010; Lavers and Villarini 2015; Payne and Magnusdottir 2014; Gimeno et al. 2016; Hagos et al. 2016; Waliser and Guan 2017;

Brands et al. 2017; Ralph et al. 2019). Because of above hydrological influences and their unique meteorological characteristics, ARs have become an important issue in the field of hydrometeorology over the past decade (Ralph et al. 2017, 2019; Shields et al. 2018; DeFlorio et al. 2018).

ARs in the North Pacific occur mostly over the central basin between 20° and 40°N and curve to the northeastern Pacific during winter (Rutz et al. 2014; Guan and Waliser 2015; Mundhenk et al. 2016; Kamae et al. 2017). Landfalling ARs and their influences on land were well documented. Landfalling ARs often create large amounts of precipitation over the western United States (Neiman et al. 2008; Lavers and Villarini 2015; Eldardiry et al. 2019). They contribute 30%–50% of all precipitation along the U.S. West Coast (Dettinger et al. 2011; Dettinger 2013), and 10%–30% of the cold-season precipitation totals in California (Kim et al. 2013). It has been reported that the majority of extreme precipitation along the West Coast is associated with ARs (Warner et al. 2012; Gimeno et al. 2016). The extreme precipitation events (EPEs) are largely fueled by abundant water vapor transported by landfalling ARs from the Pacific to the mountainous region (Leung and Qian 2009; Rivera et al. 2014; Waliser and Guan 2017; Lu et al. 2018).

Compared to landfalling ARs, ARs over the ocean region carry plenty of moisture equally. Some of the transported moisture converges over the ocean region, being favorable to in situ precipitation. However, the contribution of ARs to the precipitation over the North Pacific is unclear. In addition, climatic extremes like extreme precipitation, heat waves and wind extremes also occur over the ocean regions (Malloy et al.

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DOI: 10.1175/JCLI-D-20-0301.1

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2015; Waliser and Guan 2017; Oliver et al. 2018). Those extreme events have nonnegligible impacts on the ocean ecosystem and marine transportation. Thus, investigation about the ARs' impact on the precipitation, including extreme precipitation over the whole pan-North Pacific is required.

El Niño–Southern Oscillation (ENSO) affects the interannual variability of precipitation and extreme precipitation over the pan-North Pacific region. During El Niño winters, greater precipitation over the southernmost United States and drier conditions over the midlatitude United States are observed (Ropelewski and Halpert 1986; Brown and Comrie 2004; Larkin and Harrison 2005; Yu and Zou 2013; Deser et al. 2018). Meanwhile, increased precipitation is seen over southeastern China (Dai and Wigley 2000; Chou et al. 2009; Feng et al. 2010; Zhou et al. 2014). The southwest United States responds to El Niño with strong increases in extreme precipitation, while Southeast Asia experiences moderate increases in extreme precipitation (Cayan et al. 1999; Meehl et al. 2007; Kenyon and Hegerl 2010).

ENSO influences the precipitation via altering the moisture transport (Ropelewski and Halpert 1987; Wang et al. 2000; Seager et al. 2012; Kim and Alexander 2015; Yang et al. 2018). During El Niño winters, positive anomalies in moisture transport extend equatorward over the middle Pacific basin, and then move northeastward toward the west coast of North America as a result of a deeper Aleutian low. Over the western Pacific, anomalous northeastward transport of moisture along eastern coastal China is observed (Chen et al. 2014; Wang and Chen 2010; Zhou and Wu 2010). ENSO also affects the interannual variability of ARs frequency over the North Pacific (Payne and Magnusdottir 2014; Guan and Waliser 2015; Kim and Alexander 2015; Kim et al. 2017). However, as a distinctive form of moisture transports, the role of ARs in precipitation anomalies during ENSO winters over the North Pacific is unclear. In this study, we divided daily precipitation over the North Pacific into two groups: during AR days and non-AR days. Based on this thought, we can underscore the ARs' influence on precipitation, including extreme precipitation over the pan-North Pacific on climatological aspect and during ENSO winters.

The goal of the study is to unveil AR's influence on precipitation, including extreme precipitation, over the pan-North Pacific on climatology and dependence on ENSO condition. The paper is organized as follows: section 2 describes the data and methods. Section 3 shows the climatological features of ARs, moisture transport and precipitation over the pan-North Pacific, and AR's contribution. Section 4 analyzes the anomalies in ARs during ENSO winters, and the role of ARs in precipitation anomalies. Section 5 discusses the relative contributions of dynamic, thermodynamic and nonlinear processes to the anomalies in moisture transport. Section 6 focuses on extreme precipitation. Section 7 is conclusions and discussion.

2. Data and methods

a. Data

We use daily products from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim; Dee et al. 2011) for the period from 1

January 1979 to 28 February 2019 with resolution of $0.75^\circ \times 0.75^\circ$. The daily variables [specific humidity q , zonal u and meridional v winds at 1000, 925, 850, 700, 600, 500, 400, and 300 hPa, and surface latent heat flux] are averaged from twice-daily analysis, at 0000 and 1200 UTC. Evaporation is obtained by latent heat flux divided by the latent heat of vaporization L_e . Daily precipitation data are the satellite-gauge blend of the Global Precipitation Climatology Project (GPCP) One-Degree Daily Precipitation (version 1.2) from 1 October 1996 to 28 February 2019 with resolution of $1^\circ \times 1^\circ$, covering both ocean and land regions (Huffman et al. 2001). The Niño-3.4 index, defined as mean sea surface temperature (SST) anomalies in the equatorial central-eastern Pacific (5°S – 5°N , 170° – 120°W), is used as an indicator of ENSO conditions (Trenberth 1997). Monthly values of the Niño-3.4 index are obtained from National Oceanic and Atmospheric Administration/Climate Prediction Center (NOAA/CPC). In this study, an El Niño (La Niña) event is selected when the Niño-3.4 index is above 1°C (or below -1°C) for three consecutive months. There are nine El Niño events (1982/83, 1986/87, 1987/88, 1991/92, 1994/95, 1997/98, 2002/03, 2009/10, 2015/16), and seven La Niña events (1984/85, 1988/89, 1998/99, 1999/2000, 2007/08, 2010/11, 2011/12) meet above criteria from 1979 to 2018. Among them, four El Niño (1997/98, 2002/03, 2009/10, 2015/16) and five La Niña events (1998/99, 1999/2000, 2007/08, 2010/11, 2011/12) are during 1996–2018. Because the GPCP data begins from 1996, the present study mainly focuses on the winter seasons (December, January, and February) from 1996 to 2018. When analyzing precipitation results, we also use the precipitation data in ERA-Interim from 1979 to 2018 in parallel.

b. AR detection

The integrated vapor transport (IVT) is calculated by using the following formula:

$$\text{IVT} = \frac{1}{g} \int_{p_t}^{p_s} q \mathbf{V} dp, \quad (1)$$

where g represents the gravitational acceleration (m s^{-2}), q is the specific humidity (kg kg^{-1}), p_s is set to 1000 hPa, p_t is set to 300 hPa, p is the pressure (hPa), and $\mathbf{V}$ is the horizontal wind vector (m s^{-1}). The ARs are detected using the technique developed by Guan and Waliser (2015). The process for AR detection isolates contiguous regions of enhanced IVT exceeding a certain threshold ($>85\text{th}$ percentile or $100 \text{ kg m}^{-1} \text{ s}^{-1}$, whichever is greater) first. Then those regions are checked for the geometry requirements of length $> 2000 \text{ km}$, the ratio of length to width > 2 , the requirements on IVT direction and other considerations (see Guan and Waliser 2015). When a grid is in the detected AR region, it is declared as an AR grid, the corresponding date is grouped as an AR day. Otherwise, the grid is a non-AR grid and the corresponding date is a non-AR day. The AR frequency (the ratio of the number of AR days to the number of days in a whole winter) is calculated for winters during 1979–2018. The precipitation, IVT, and divergence of IVT ($\nabla \cdot \text{IVT}$) in the AR days (AR-group) and non-AR days (non-AR-group) at each grid are summed up, respectively, to obtain their individual accumulated values for each winter.

c. Definition of 2-day extreme precipitation event

Daily precipitation at each grid for each winter during 1996–2018 is ranked from small to large. Only days with daily precipitation exceeding 1 mm are counted, to ensure that dry days are excluded. The value at 95th percentile is selected as the threshold for extreme precipitation (Peterson et al. 2008; Vittal et al. 2013; Hagos et al. 2016; Lu et al. 2018). The procedure for identifying a 2-day extreme precipitation event (2-day EPE) at a grid is as follows. 1) An extreme day with precipitation above the threshold of 95% is picked for a particular grid; 2) precipitation values in the day prior to the extreme day and after that are compared, and the day with larger value together with the extreme day are considered as a 2-day EPE. These two consecutive days are counted as EPE days (Wu et al. 2018; Shang et al. 2020). On this basis, an AR-EPE is defined when a 2-day EPE contains at least one AR day. Similarly, precipitation, IVT, and $\nabla \cdot \text{IVT}$ on the 2-day EPE days and AR-EPE days are also summed up, respectively.

d. Decomposition of IVT and $\nabla \cdot \text{IVT}$

The changes in moisture transport can be attributed to changes in the circulation (dynamic process), moisture (thermodynamic process), and nonlinear processes (Kim et al. 2017; Ren et al. 2017; G. Chen et al. 2019). When a variable is decomposed into its time mean (denoted with an overbar), interannual (denoted with a prime), and noninterannual components, IVT and $\nabla \cdot \text{IVT}$ on an interannual time scale [(IVT)' and $(\nabla \cdot \text{IVT})'$] can be expressed, respectively, as

$$\underbrace{\frac{1}{g} \int_{p_t}^{p_s} (q\mathbf{V})' dp}_{\text{T}} = \underbrace{\frac{1}{g} \int_{p_t}^{p_s} (\bar{q}\mathbf{V}') dp}_{\text{A}} + \underbrace{\frac{1}{g} \int_{p_t}^{p_s} (q'\bar{\mathbf{V}}) dp}_{\text{B}} + \underbrace{\frac{1}{g} \int_{p_t}^{p_s} (q'\mathbf{V}') dp}_{\text{C}} + \text{residual}, \quad (2)$$

$$\underbrace{\nabla \cdot \frac{1}{g} \int_{p_t}^{p_s} (q\mathbf{V})' dp}_{\text{T}} = \underbrace{\nabla \cdot \frac{1}{g} \int_{p_t}^{p_s} (\bar{q}\mathbf{V}') dp}_{\text{A}} + \underbrace{\nabla \cdot \frac{1}{g} \int_{p_t}^{p_s} (q'\bar{\mathbf{V}}) dp}_{\text{B}} + \underbrace{\nabla \cdot \frac{1}{g} \int_{p_t}^{p_s} (q'\mathbf{V}') dp}_{\text{C}} + \text{residual}. \quad (3)$$

Equations (2) and (3) indicate that interannual variability of IVT and $\nabla \cdot \text{IVT}$ (term T) can be decomposed into dynamic process (term A), thermodynamic process (term B), nonlinear process of interannual variables (term C) and residual term. The residual term represents other nonlinear interaction besides term C (e.g., between interannual and noninterannual components). The residual term is much smaller and ignorable in this study (not shown).

The procedure of extracting the components of interannual variations from daily data has two steps. First, the daily climatology is removed from the daily data. Second, the daily anomalies are filtered using the Butterworth filter (Murakami 1979). The filtering window is from 90 days to 8 years.

The T test is used to examine the credibility of the differences between two sample groups (Chervin and Schneider 1976; Zwiers and Storch 1995; Q. Chen et al. 2019). There are l winters including m El Niño winters and n La Niña winters. We

take the test on m El Niño winters for example. The $\bar{x}^l$ and $\bar{x}^m$ in (4) and (5) are the mean values of the variable X of these two sample groups. With the null hypothesis that the overall averages of the two samples have no significant differences, the statistics t follows t distribution with $(l + m - 2)$ degrees of freedom. The s^2 in (5) is the unbiased estimator of the variance of the difference and x_i is the winter accumulated value of each winter:

$$t = \frac{\bar{x}^l - \bar{x}^m}{s \sqrt{\frac{1}{l} + \frac{1}{m}}}, \quad (4)$$

$$s^2 = \frac{\sum_{i=1}^l (x_i^l - \bar{x}^l)^2 + \sum_{i=1}^m (x_i^m - \bar{x}^m)^2}{l + m - 2}. \quad (5)$$

The corresponding critical value t_α can be found with a given significance level (α) and degrees of freedom. If $t > t_\alpha$, we reject the null hypothesis and think the differences are significant.

3. Influence on winter precipitation: Climatological aspect

Figure 1 depicts climatological winter accumulated precipitation and AR frequency over the pan-North Pacific. Winter accumulated GPCP precipitation is large in the midlatitude basin and along the North American west coast (Fig. 1a). The precipitation is more than 500 mm winter⁻¹ over the central basin region, and more than 700 mm winter⁻¹ along the northwest coastal region. ERA-Interim shows a similar pattern as GPCP over the pan-North Pacific region (Fig. 1b). However, it is higher than GPCP in the midlatitude basin. The main body of ARs with frequency of 11% or above occurs over the central Pacific and curves northeastward to the northwest coast (Fig. 1c). The ARs band with frequency of 7% or above also extends westward to southeast China. Above ARs features are consistent with previous studies (Guan and Waliser 2015; Mundhenk et al. 2016; Kamae et al. 2017).

Figure 2 plots climatological winter accumulated precipitation for AR-group and non-AR-group and AR fraction. The difference is robust between AR-group and non-AR-group over the whole ocean regions. Both GPCP and ERA-Interim show that precipitation for AR-group is concentrated in two regions: the midlatitude basin and northeastern Pacific, and along the North American northwest coast (Figs. 2a,d). Non-AR days' precipitation spreads over almost the whole North Pacific region, with large value along 40°N and along the northwest coast (Figs. 2b,e). The AR fraction of 30%–45% is conspicuous over the eastern Pacific and along the west coast between 25° and 45°N (Fig. 2c) in which ARs frequency is about 5%–15% (Fig. 1c). Namely, ARs in the red box region are highly efficient in generation of precipitation. Thus, we pick the region over the eastern Pacific and along the west coast between 25° and 45°N (red box region) as a core region of the ARs' influence on precipitation. The AR fraction in ERA-Interim is similar as that of GPCP, except that ERA-Interim is slightly overestimated for AR fraction in the midlatitude basin and along the west coast between 20° and 45°N (Fig. 2f).

ARs are well known as strong moisture conveyor belts. Therefore, it is necessary to show the differences of IVT and $\nabla \cdot \text{IVT}$ between AR-group and non-AR-group over the pan-North Pacific. Figure 3 plots climatological winter accumulated

FIG. 1. Climatological winter accumulated precipitation (mm winter^{-1}) of (a) GPCP during 1996–2018 and (b) ERA-Interim during 1979–2018. (c) Climatological winter atmospheric rivers (AR) frequency (%) during 1996–2018. The blue contour in (c) indicates climatological winter ARs frequency of 11% (the same below).

IVT and $\nabla \cdot \text{IVT}$ during 1996–2018 and those for AR-group and non-AR-group. Because of dominant westerly wind, climatological total IVT is mostly zonal over the extratropics to the west of the date line, and then poleward over the eastern margins of the North Pacific basin (Fig. 3a). It is no surprise to see that the IVT magnitude for AR-group is markedly stronger in the ARs main body region than it is around (Fig. 3b). The direction of IVT in the ARs main body region for AR-group is more poleward than that for non-AR-group (Figs. 3b,c).

Climatological winter total moisture sources are seen over the subtropics and the northwestern Pacific. Meanwhile, moisture sinks are observed over the northeastern Pacific–North American

continent (Fig. 3a). There are considerable discrepancies between AR-group and non-AR-group over the pan-North Pacific. For AR-group, a moisture sink occupies almost the whole basin (Fig. 3b). For non-AR-group, a moisture sink is only seen over the northeastern Pacific north of 35°N (Fig. 3c). Both groups are important for the moisture sink over the North American west coast.

We now focus on the core region of the ARs' influence (the red box region in Fig. 2c, as well as Figs. 3b,c). According to the moisture budget (moisture balance equation) of an atmospheric column, precipitation P is closely related with the processes of convergence of moisture transportation $\nabla \cdot \text{IVT}$ and evaporation at Earth's surface E (Trenberth et al. 2007). In the core region, AR-group produces an in situ moisture sink ($\nabla \cdot \text{IVT} < 0$, Fig. 3b), while non-AR-group shows a moisture source ($\nabla \cdot \text{IVT} > 0$) in general (Fig. 3c). Therefore, the closeness of relationship between P and $\nabla \cdot \text{IVT}$ in the core region for AR-group is different from that for non-AR-group.

To demonstrate the above point, Fig. 4 depicts bar charts for climatological accumulated daily P , $\nabla \cdot \text{IVT}$, and E in the red box region during 1996–2018 winters, respectively, for all the AR grids and the non-AR grids. It is seen that, climatologically, AR-group's precipitation in the core region is mostly determined by the AR-produced moisture convergence ($\nabla \cdot \text{IVT} < 0$) but not E , while, non-AR-group's precipitation is attributed to E , which is mainly caused by evaporative moisture flux from the ocean. For non-AR-group, the divergence of moisture transport ($\nabla \cdot \text{IVT} > 0$) in the core region is unfavorable to in situ precipitation.

4. Influence on winter precipitation: Dependence on ENSO condition

Figure 5a shows the composite of accumulated GPCP precipitation anomalies for the four El Niño winters during 1996–2018. During El Niño winters, an enhanced precipitation is seen over East Asia and its coastal waters, the eastern Pacific and the coastal areas of California. Meanwhile, a decreased one is located over the central basin. Figure 5d plots the composite anomalies in ARs frequency for the four El Niño winters during 1996–2018. ARs frequency is increased by about 3%–4% in the core region (the red box region). Meanwhile, ARs frequency is decreased over the regions of southwestern America and middle basin between 40° and 50°N . The corresponding reason will be shown in section 5.

As stated earlier, winter accumulated GPCP precipitation anomalies for the four El Niño winters are also grouped into two parts: AR-group and non-AR-group. The composite for the two groups are shown in Figs. 5b and 5c. The pattern for AR-group (Fig. 5b) is similar to that of the total precipitation anomalies (Fig. 5a) and much likes that of ARs frequency anomalies except the region over southwestern America. Precipitation anomalies for AR-group contribute nearly 60% of the positive anomalies in the core region. They also determine almost half of negative ones over the middle basin between 40° and 55°N . It is also noticed that, the negative anomalies in total precipitation over the central Pacific between 20° and 30°N are mostly due to non-AR-group, not AR-group.

Above analyses are based on the composition for the four El Niño events during 1996–2018. To increase the number of samples, we also calculated the composites of winter accumulated ERA-Interim precipitation anomalies and corresponding AR-group's

FIG. 2. (left) Climatological winter accumulated precipitation (shaded; mm winter⁻¹) for (a) AR-group and (b) non-AR-group, and (c) AR precipitation fraction (percent of total precipitation) of GPCP during 1996–2018. (right) As in the left panels, but for ERA-Interim during 1979–2018. Dots indicate the areas where the differences between AR-group and non-AR-group are above 95% significance level. The red box in (c) indicates a core region with high ARs fraction (the same below).

and non-AR-group's contributions, and AR frequency anomaly for the nine El Niño events during 1979–2018 (right panels in Fig. 5). The composite of ERA-Interim precipitation during 1979–2018 bears some resemblance to that of GPCP during 1996–2018. The detectable difference is located over East Asia and its coastal waters for AR-group (Figs. 5b,f). ERA-Interim during 1979–2018 indicates that the positive precipitation anomalies over East Asia and its coastal waters are determined by non-AR-group but not AR-group. This result is because the AR frequency anomalies to the western part of the ARs main body during 1979–2018 (Fig. 5h) are not as robust as those during 1996–2018 (Fig. 5d). Despite of above discrepancy, the results around the core region (the red box region) during 1996–2018 are in consistent with those during 1979–2018.

The composites for the five La Niña winters during 1996–2018 are shown in the left panels of Fig. 6. It is noticeable that the pattern of GPCP precipitation anomalies during La Niña winters (Fig. 6a) is mostly opposite to that during El Niño winters (Fig. 5a). Especially, GPCP precipitation is significantly decreased over the eastern Pacific, and increased over the central Pacific (Fig. 6a). The pattern of ARs frequency anomalies during La Niña winters (Fig. 6d) is also nearly opposite to that during El Niño winters (Fig. 5d). But the areas above the significance level in Fig. 6d are relatively scattered. Most of the anomalous areas are not concentrated around the ARs main body region. Therefore, during the five La Niña winters, the magnitude of precipitation anomalies for AR-group (Fig. 6b) is robustly smaller than that for non-AR-group (Fig. 6c). Non-AR-group determines mostly of the total

FIG. 3. (a) Climatological winter accumulated integrated vapor transport (IVT) (vector; $10^5 \text{ kg m}^{-1} \text{ winter}^{-1}$) and $\nabla \cdot \text{IVT}$ (shaded; mm winter^{-1}) during 1996–2018. (b),(c) As in (a), but for AR-group and non-AR-group, respectively. Dots indicate the areas where the differences between AR-group and non-AR-group are above 95% significance level. Only values exceeding $2 \times 10^8 \text{ kg m}^{-1} \text{ winter}^{-1}$ are shown for IVT. The red box in (b) and (c) is as in Fig. 2c.

precipitation anomalies, except that over the eastern Pacific (the red box region) in which AR-group's contribution is nonnegligible.

The right panels in Fig. 6 are the same as the right panels in Fig. 5, but for the seven La Niña winters during 1979–2018. ERA-Interim shows a similar pattern of positive precipitation anomalies over the central Pacific and negative ones over the eastern Pacific as GPCP (Fig. 6e). Only the positive anomalies over the central Pacific in ERA-Interim occupy robustly larger area than those in GPCP. They are also largely contributed by non-AR-group (Fig. 6g). The pattern of AR frequency anomalies during 1979–2018 looks somewhat like that during 1996–2018, except that the decreasing around the core region during 1979–2018 (Fig. 6h) is more robust than that during 1996–2018 (Fig. 6d).

FIG. 4. Bar charts denoting climatological accumulated GPCP daily precipitation P (Δ ; mm day^{-1}), evaporation E ($+$; mm day^{-1}), and $\nabla \cdot \text{IVT}$ (div; $\times$; mm day^{-1}) for all the AR grids (cyan bars) and the non-AR grids (red bars) in the red box of Fig. 2c during 1996–2018 winters.

The above analyses of Figs. 5 and 6 indicate that, the ENSO-induced precipitation and ARs frequency anomalies in the core region are significant and are basically consistent between GPCP during 1996–2018 and ERA-Interim during 1979–2018. Therefore, we will compare precipitation anomaly between AR-group and non-AR-group, by taking the core region as an example.

As mentioned above, for AR-group, the positive (negative) precipitation anomaly in the core region is accompanied by the increased (decreased) in situ AR frequency during El Niño (La Niña) winters. This means the moisture convergence anomaly associated with ARs should be responsible for the precipitation anomaly in the core region during ENSO winters. To substantiate the relationship, we plot similar bar charts as in Fig. 4 but for anomalous values during ENSO winters of 1996–2018 (Fig. 7). It is seen that, for AR-group, the increased P in the core region is indeed attributed largely to the more in situ ARs and thus enhanced moisture convergence [$(\nabla \cdot \text{IVT})' < 0$] during El Niño winters, and vice versa for La Niña winters.

For non-AR-group, the increased P in the core region during El Niño winters is unequivocally attributed to the anomalous convergence of moisture transport [$(\nabla \cdot \text{IVT})' < 0$] (Fig. 7a). This relationship is different from the climatological result shown in Fig. 4. In addition, for non-AR-group, the decreased evaporation from Earth's surface has a role of reducing in situ precipitation. Therefore, non-AR-group needs larger quantity of anomalous moisture convergence than AR-group to produce above-normal precipitation equivalent to AR-group.

During La Niña winters, the decreased P in the core region for non-AR-group is partly due to the negative anomaly in E and partly to the anomalous divergence of moisture transport [$(\nabla \cdot \text{IVT})' > 0$]. However, the precipitation anomaly in the core region for non-AR-group is not as significant as that for AR-group (Figs. 6b,c). Thus, more La Niña samples are needed to verify the relationship among the three terms (P , $\nabla \cdot \text{IVT}$, and E) for non-AR-group.

5. Decomposition of IVT and $\nabla \cdot \text{IVT}$ during ENSO winters

The above investigation of the relationship between precipitation anomaly and $\nabla \cdot \text{IVT}$ anomaly is only confined to the

FIG. 6. As in Fig. 5, but (a)–(d) for the five La Niña winters during 1996–2018 and (e)–(h) for the seven La Niña winters during 1979–2018.

core region of the ARs' influence. In this section, we will show that, anomalies in IVT and $\nabla \cdot \text{IVT}$ are essential to anomalies in P over the pan-North Pacific during ENSO winters. In particular, the relative contributions of different physical process involving wind

fields and specific humidity to IVT and $\nabla \cdot \text{IVT}$ anomalies during ENSO winters are addressed in this section, based on the time-scale decomposition described in section 2d. For conciseness, only the results during 1996–2018 are shown in this section and next.

FIG. 7. (a) As in Fig. 4a, but for anomalous values during the four El Niño winter in 1996–2018. (b) As in (a), but for the five La Niña winter during 1996–2018.

Figure 8a shows composite of accumulated anomalies in IVT [the term T in Eq. (2)] and $\nabla \cdot \text{IVT}$ [the term T in expression (3)] for El Niño winters. The corresponding results for AR-group and non-AR-group are plotted in Figs. 8b and 8c.

FIG. 8. (a) Composite anomalies in winter accumulated IVT (vector; only the areas above the 95% confidence level are shown; $10^5 \text{ kg m}^{-1} \text{ winter}^{-1}$) and $\nabla \cdot \text{IVT}$ (shaded; mm winter^{-1}) for the four El Niño winters during 1996–2018. (b), (c) As in (a), but for AR-group and non-AR-group, respectively. The left oblique lines denote the areas exceeding the 95% significance level for $\nabla \cdot \text{IVT}$.

During El Niño winters, an anomalous cyclonic transport is located over the central and the northeastern Pacific, and anomalous northeastward transport over East Asia and its coastal waters. The $\nabla \cdot \text{IVT}$ anomalies show an anomalous moisture source over the central basin and anomalous moisture sinks over East Asia and its coastal waters and near the North American west coast (Fig. 8a). Above pattern of $\nabla \cdot \text{IVT}$ anomalies bears close resemblance to the pattern of precipitation anomalies in Fig. 5a. Thus, anomalous convergence of water vapor transport over the western and the eastern Pacific is conducive to the increased in situ precipitation. Meanwhile, anomalous divergence of water vapor transport over the central basin contributes to the decreased in situ precipitation.

The patterns of IVT and $\nabla \cdot \text{IVT}$ anomalies for AR-group (Fig. 8b) and non-AR-group (Fig. 8c) are all alike those in Fig. 8a to a certain extent. For AR-group, the cyclonic transport anomaly over the central and the eastern Pacific intensifies the northeastward moisture transport over the eastern Pacific, and weakens the poleward moisture transport over the middle basin. Above IVT anomalies lead to the anomalies in AR frequency during El Niño winters shown in Fig. 5d. AR-group contributes around 35% of accumulated anomalous moisture sink in the core region. It also decides nearly 40% of anomalous moisture source over the middle basin between 35° and 50°N .

The three processes contributing to anomalies in IVT and $\nabla \cdot \text{IVT}$, including the term A (dynamic process), the term B (thermodynamic process), and the term C (nonlinear process) during El Niño winters are calculated according to Eqs. (2) and (3), respectively. The upper panels in Fig. 9 plot the composite anomalies of the three terms for El Niño winters. The anomalous patterns of IVT and $\nabla \cdot \text{IVT}$ shown in Fig. 8a are preliminarily decided by the term A and second by the term B. The amplitude of term C is much smaller than those of terms A and B. Namely, changes in the circulation mostly determine the anomalies in IVT and $\nabla \cdot \text{IVT}$ during El Niño winters, which is consistent with previous suggestion (Seager and Naik 2012; Seager et al. 2012; Kim et al. 2017). The middle and bottom panels in Fig. 9 are results for AR-group and non-AR-group, respectively. Similarly, the term A is the first important and the term B is the second.

In addition, it is found that the pattern of thermodynamic process (the term B) is somewhat opposite to that of dynamic process (the term A), and there is a small phase difference

FIG. 9. (top) Composite anomalies in terms of (a) IVT_A (vector; only the areas above the 95% confidence level are shown; $10^5 \text{ kg m}^{-1} \text{ winter}^{-1}$) and $\nabla \cdot IVT_A$ (shaded: mm winter^{-1}), (d) IVT_B and $\nabla \cdot IVT_B$, and (g) IVT_C and $\nabla \cdot IVT_C$ for the four El Niño winters during 1996–2018. (middle), (bottom) As in the top panels, but for AR-group and non-AR-group, respectively. The left oblique lines denote the areas exceeding the 95% significance level for $\nabla \cdot IVT$.

between the two patterns during El Niño winters. Therefore, the effect of thermodynamic process (the term B) is to slightly weaken the dynamic process (the term A), and to blur the boundary between the positive and negative regions in the pattern of term A.

Figure 10 plots the composite for La Niña winters. The total IVT and $\nabla \cdot IVT$ anomalies during La Niña winters (Fig. 10a) show almost the same patterns but with opposite sign of those for El Niño winters (Fig. 8a). The anomalous moisture source over the western and eastern Pacific, and the anomalous moisture sink over the central Pacific (Fig. 10a) are conducive to the decreased and increased in situ precipitation, respectively (Fig. 6a). The total IVT and $\nabla \cdot IVT$ anomalies are mostly contributed by non-AR-group, except that over the eastern Pacific.

The three terms (A, B, and C) are also computed for La Niña winters (Fig. 11). Similar to what is seen during El Niño winters, the term A (dynamic process) is essential to the IVT and $\nabla \cdot IVT$ anomalies. The term C is also much smaller than the terms A and B during La Niña winters. We can see that the thermodynamic process (the term B) also acts to slightly weaken the dynamic

process (the term A), just like those during El Niño winters. Different from the results during El Niño winters, the pattern of term B (thermodynamic process) exhibits a nearly quadrature relation with that of the term A, no matter for AR-group or non-AR-group during La Niña winters. For example, the longitude position (about 175°W) of the negative centers of the term A in Fig. 11a is the dividing longitude between the left-positive and right-negative centers of the term B in Fig. 11d. The pattern of term A during La Niña winters is almost opposite to its counterpart during El Niño winters. Therefore, the term B (thermodynamic process) has a role in causing asymmetric features of IVT and $\nabla \cdot IVT$ anomalies between El Niño and La Niña. Due to the dominant role of the term A, the nonsymmetric effect caused by the term B is finite.

6. Extreme precipitation

In this section, we will show the extreme precipitation and its relationship with IVT ($\nabla \cdot IVT$) on climatological aspect and during ENSO winters. The upper panels in Fig. 12 depict climatological winter accumulated precipitation and total days

FIG. 10. As in Fig. 8, but for the five La Niña winters during 1996–2018.

of 2-day EPEs and the corresponding accumulated IVT and $\nabla \cdot \text{IVT}$ of 2-day EPEs, respectively. The second and third panels are the results for AR-group and AR-group fraction, respectively. It is seen that, the patterns of winter accumulated extreme precipitation and the corresponding total days (Figs. 12a,d) closely resemble that of the climatological winter accumulated precipitation (Fig. 1a). The patterns for AR-group (Figs. 12b,e) are alike that in Fig. 2a. AR-group contributes more than 50% of the total precipitation and total days of 2-day EPEs to the east of the date line. The fraction is up to 70% or above within the core region (Figs. 12c,f).

The direction of climatological total IVT for EPEs shows considerable eastward and northeastward transports over the western Pacific and poleward transports over the central and northeastern Pacific (Fig. 12g). The corresponding total $\nabla \cdot \text{IVT}$ shows a huge moisture sink over the whole basin. Two moisture sink centers of 2-day EPEs are seen over the middle basin between 30° and 45°N and along the west coast, respectively, contributing directly to the in situ extreme precipitation shown in Fig. 12a. The above pattern of total IVT and $\nabla \cdot \text{IVT}$ for 2-day EPEs are largely attributed to AR-group

(Fig. 12h). The very high fraction of AR-group (Fig. 12i) indicates that, climatologically, the AR-related extreme precipitation is overwhelmingly caused by AR-produced huge moisture sink over most of the basin, especially over the core region (the red box region).

ENSO also affects the variation of extreme precipitation over the pan-North Pacific region. The upper panels in Fig. 13 plot composite anomalies in accumulated precipitation and total days, as well as IVT and $\nabla \cdot \text{IVT}$ for 2-day EPEs for the four El Niño winters during 1996–2018, respectively. The extreme precipitation anomalies display a positive–negative–positive structure spanning from East Asia and its coastal waters to the eastern Pacific (Fig. 13a). The total number of 2-day EPEs is increased about 1 event per winter over the eastern Pacific and decreased about 1 event per winter over the central Pacific between 20° and 30°N. The extreme precipitation anomalies are closely related to their corresponding anomalies of IVT and $\nabla \cdot \text{IVT}$ (Fig. 13e). Compared with that of climatology (Fig. 12g), much stronger northward and north-eastward transports and increased moisture sinks are seen over eastern Asia and its coastal waters, and the eastern Pacific. Meanwhile, decreased poleward transports and decreased moisture sink are observed over the middle basin (Fig. 13e). Therefore, the increased moisture sink over the western and the eastern Pacific in Fig. 13e fuels in situ extreme precipitation in Fig. 13a. While, the decreased moisture sink over the central basin reduces the in situ frequency of extreme event and the corresponding total extreme precipitation.

The second panels in Fig. 13 show the results for AR-group. Obviously, AR-group has robust contributions to the total anomalies over the western and eastern Pacific, and middle basin, due to the in situ AR frequency anomalies during El Niño winters shown in Fig. 5d. There is no robust change in ARs frequency over the central Pacific between 20° and 30°N during El Niño winters (Fig. 5d). Therefore, the increased extreme precipitation and the corresponding total days in that region are contributed by non-AR-group.

The patterns of anomalies in accumulated precipitation, IVT and $\nabla \cdot \text{IVT}$ of 2-day EPEs over the North Pacific during La Niña winters are analogous to their El Niño counterpart but with opposite sign. Thus, we will not show figures and only describe briefly the conclusion. During La Niña winters, a significantly increased total precipitation for 2-day EPEs is seen over the central basin and a slightly decreased one over the eastern Pacific. These anomalies are also due to an enhanced and a reduced in situ moisture sinks of 2-day EPEs, respectively (figure omitted). AR-group only has a certain contribute to the decreased extreme precipitation and the corresponding $\nabla \cdot \text{IVT}$ anomaly over the eastern Pacific. This is because the reduced in situ AR frequency during La Niña winters shown in Fig. 6d.

7. Conclusions and discussion

a. Conclusions

This study investigates the influence of ARs on winter precipitation for climatology and during ENSO condition over the

FIG. 11. As in Fig. 9, but for the five La Niña winters during 1996–2018.

pan-North Pacific region, by using statistical analysis of the fields from GPCP (1996–2018) and ERA-Interim (1979–2018) daily data. We divided total values of precipitation, IVT and $\nabla \cdot \text{IVT}$ into AR-group and non-AR-group. We underscored the ARs' influence on total precipitation and extreme precipitation by evaluating and comparing the contributions of the two groups to precipitation and water vapor transport.

The main body of climatological wintertime ARs is located over the central Pacific and curves northeastward to the northwest coast. Precipitation for AR-group is concentrated over the central and northeastern Pacific and along the northwest coast. AR-group contributes about 30%–45% of the climatological total winter precipitation, and up to 70% of total precipitation and total days of 2-day EPE over the eastern Pacific and along the west coast between 25° and 45°N. We picked the above area as the core region of the ARs' influence on precipitation.

Our results show that, climatologically, AR-group produces a moisture sink ($\nabla \cdot \text{IVT} < 0$) occupying almost the whole basin, while non-AR-group demonstrates a moisture sink only over the northeastern Pacific north of 35°N. Thus, in the core region, the relationship between precipitation and moisture convergence for AR-group is different from that for non-AR-group. AR-group's precipitation in the core region is mostly determined by

the AR-produced moisture convergence. In contrast, for non-AR-group, the divergence of moisture transport ($\nabla \cdot \text{IVT} > 0$) in the core region is unfavorable to in situ precipitation. Non-AR-group's precipitation in the core region is attributed to evaporation from the earth surface.

We further investigated the AR influence on total and extreme precipitation during ENSO winters. During El Niño winters, the total precipitation anomalies show a tripolar pattern of a positive center over East Asia and its coastal waters, a negative one over the central Pacific and another positive one over the eastern Pacific and the coastal areas of California. The AR frequency is increased in the core region, and decreased over the middle basin between 40° and 50°N. AR-group contributes nearly 60% of the positive precipitation anomalies in the core region. Besides, almost half of negative ones over the middle basin between 40° and 55°N is attributed to AR-group. During El Niño winters, the anomalous patterns in total extreme precipitation, along with its total days are mostly determined by AR-group. During La Niña winters, AR-group's contribution (about 50% of the negative precipitation anomalies) is robust only around the core region.

During El Niño winters, anomalous moisture sinks over the western and the eastern Pacific are conducive to the increased

FIG. 12. (a) Climatological winter accumulated GPCP precipitation (mm winter^{-1} ; ≥ 95 th percentile daily precipitation), (d) total days (day winter^{-1}), and (g) IVT (vector; $10^5 \text{ kg m}^{-1} \text{ winter}^{-1}$) and $\nabla \cdot \text{IVT}$ (shaded; mm winter^{-1}) of 2-day EPEs for winters during 1996–2018. (b), (e), (h) As in (a), (d), (g), but for AR-group. (c) Ratio of (b) to (a), (f) ratio of (e) to (d), and (i) ratio of (h) to (g).

in situ precipitation. Meanwhile, anomalous moisture source over the central basin contributes to the decreased in situ precipitation. Similar relation is also seen during La Niña winters. ARs play a more essential role in the total moisture source and sink anomalies during El Niño winters than during La Niña winters. AR-group contributes around 35% of accumulated anomalous moisture sink in the core region. It also decides nearly 40% of anomalous moisture source over the middle basin between 35° and 50°N.

Based on a time-scale decomposition, it is showed that, the total IVT and $\nabla \cdot \text{IVT}$ anomalies are primarily decided by changes in wind fields (dynamic process) and second by changes in moisture (thermodynamic process), whether in AR-group or non-AR-group. In addition, changes in moisture act to slightly weaken the dynamic process and to cause asymmetric features of IVT and $\nabla \cdot \text{IVT}$ anomalies between El Niño and La Niña but with limited effects. The nonlinear process is much smaller than above processes.

b. Discussion

Previous studies showed that ENSO-related precipitation anomalies vary widely from episode to episode (e.g., Ropelewski and Halpert 1987; D. Chen et al. 2019). Therefore, dataset with

longer period and more ENSO cases are needed to confirm the ARs' influence. On the other hand, the ARs' influence on precipitation anomalies is also different during central Pacific (CP) and eastern Pacific (EP) El Niño events (Kim and Alexander 2015; Kim et al. 2017). Thus, the ARs' impact on moisture transport and precipitation in the pan-North Pacific region should be investigated further via separating CP and EP El Niño events.

We only focus on the influence of winter ARs over the pan-North Pacific region. ARs are global phenomena with a large impact on regional hydrological events in many locations (Guan and Waliser 2015; Mundhenk et al. 2016). In addition, water vapor increases and circulation patterns change in a warming climate. These changes may influence ARs (Payne and Magnúsdóttir 2015; Hagos et al. 2016; Tan et al. 2020). Above issues require further exploration in the future.

Acknowledgments. The authors wish to thank Guan and Waliser for providing the source code of the AR detection algorithm. We also thank the reviewers for their useful comments, which helped to improve this manuscript. The ERA-Interim daily data are downloaded from <http://apps.ecmwf.int/datasets/>. The GPCP daily data are downloaded from

FIG. 13. (a) Composite anomalies in accumulated GPCP precipitation (mm winter^{-1}), (c) total days (day winter^{-1}), and (e) accumulated IVT (vector; $10^3 \text{ kg m}^{-1} \text{ winter}^{-1}$) and $\nabla \cdot \text{IVT}$ (shaded; mm winter^{-1}) of 2-day EPEs for the four El Niño winters during 1996–2018. (b), (d), (f) As in (a), (c), (e), but for AR-group. The left (/) and right (\) oblique lines denote the areas exceeding 95% and 90% significance levels, respectively.

http://eagle1.umd.edu/GPCP_CDR/Daily_Data. The Niño-3.4 index is downloaded from <http://www.cpc.ncep.noaa.gov/data/indices/>. This work was jointly supported by the National Natural Science foundation of China under Grants 41621005, the National Key R&D Program of China (Grants 2018YFC1505903), and the Special Fund for Meteorology Research in the Public Interest (Grant GYHY201106017).

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