



# Changes in the moisture contribution over global arid regions

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## Abstract

Arid regions have deficient precipitation, understanding the sources and transportation of moisture for precipitation are crucial. This study examined the major moisture contributions for global six arid regions, which are classified as inland arid region (China–Mongolia) and coastal arid regions (North Africa, West Asia, West United States, South Africa, South Africa and Australia). Results indicated that, the moisture for precipitation in coastal arid regions originates mostly from the ocean, which is influenced by the general circulation, particularly by the sinking branch of the Hadley cell. For inland arid region (China–Mongolia), the surrounding mountains supply more than 150 mm of moisture in wet months due to the ablation of glacial and snow melting. In arid regions, the moisture for precipitation is mostly contributed by advection of large-scale circulation, while the contribution of local moisture recycling is secondary. The moisture available for precipitation in wet and dry months depends on the general circulation. Moisture transportation in wet months is 10 times more than that in dry months, and the moisture sources differ greatly in wet and dry months. In both wet and dry months, the external moisture transported into arid regions has significantly decreasing trend during the period 1990–2019. The decreasing trend of precipitation recycling ratio in arid regions are greater than that in the globe. The decreased precipitation and moisture in arid regions suggest a potential drying trend.

**Keywords** Moisture source · Precipitation · Arid regions · Water accounting model

## 1 Introduction

Over land, 35% of precipitation originates from marine evaporation driven by winds, and 65% from evaporation from the land (Chahine 1992). Sources of water contributing to moisture in a column of air can be divided into two types: local evaporation and advection of moisture by wind from distant sources. Studies have investigated the role of vapor advection and local evaporation in atmospheric water cycling (Eltahir and Bras 1996; Trenberth 1999; Wang and Guo 2012; Guo and Wang 2014). Locally evaporated water is unlikely to precipitate over the same exact location (Eltahir and Bras 1996) but may affect a remote region. Moisture sources and transport paths are prerequisites for precipitation (Krug et al. 2022; Gustafsson et al. 2010). Research on

moisture sources for precipitation is important for understanding water cycling and precipitation (Arias et al. 2015; Gimeno et al. 2012; Ralph et al. 2006; Stohl and James 2004).

Drought is generally characterized by persistent deficit of precipitation, that is, a shortage of vapor transportation and convergence, as a consequence, the vapor characteristics in arid regions have attracted much attention (Barriopedro et al. 2012; Xu et al. 2016a; Li et al. 2018; Li and Wang 2020a, b). In general, the moisture for precipitation comes from external transportation and local moisture recycle. The moisture transported from external is an essential element for precipitation. In arid regions, moisture from local evaporation accounts for a small proportion of precipitation because of the low precipitation recycling ratio (PRR) (Dirmeyer et al. 2009; Li et al. 2018). According to the location relative to the ocean, global arid regions can be simply divided into the inland and coastal arid regions. In the arid region of China–Mongolia (CM) located in the central part of the Eurasian mainland, which is affected by the westerly system, moisture from outside the region cannot reach the area easily. In summer, moisture is transported from the area to the

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west of the CM arid region (Wang et al. 2007). In winter, the moisture in the arid region of Central Asia is derived from zonal transport (Xu et al. 2016b). In North Africa, precipitation is considerably affected by the moisture from the Atlantic (Li 2017). These studies suggested the vapor transportation channels by moisture flux, but further study is required to identify the moisture sources quantitatively.

The planet is undergoing global warming (Houghton 2015), and the Intergovernmental Panel on Climate Change (IPCC) reports (the latest one, WGI AR6 2021) note that the observed temperatures over land have increased by 1.61 °C between the periods 1850–1900 and 2011–2020. Studies showed that atmospheric vapor and precipitation increased globally in the past 20 years (1991–2010) in the context of global warming (Willett et al. 2008; Smith et al. 2012). However, under the assumption that relative humidity remains constant, specific humidity will increase against the background of global warming, leading to the wetter conditions in wet regions and drought in arid regions (Held and Soden 2006; Skliris et al. 2016). In general, precipitation in arid regions has shown a decrease from 1900 to 1994 (Hulme 1996). In southeastern Australia, a drought lasted from 1997 to 2011 (McGrath et al. 2012), and NA experienced a drought in the later twentieth century (Qian et al. 2017). In the arid region of northwest China, the amount of precipitation has increased in the recent years, changing its conditions from warm-dry to warm-wet (Shi and Shen 2003; Wang et al. 2021a). Moisture from either internal or external sources is available to produce precipitation variations over arid regions. However, the impact of local evaporative moisture, i.e., the local water cycle, on precipitation is limited in arid regions because of low precipitation and low soil moisture. There are still challenges in understanding the sources and changes in the moisture for precipitation in arid regions.

Prevalent moisture recycling approaches contain Bulk Models, General Circulation Models (GCMs) with tagged water, Lagrangian methods, and isotopic analysis (Bati-beniz et al. 2020; Gimeno et al. 2012). Bulk Models are well known for computational simplicity and flexibility (Bosilovich and Chern 2006). They are commonly based on the basic atmospheric moisture balance equation and well-mixed assumption, according to which advected and local evaporated moisture is well mixed so that each water molecule has the same probability to be precipitated. Many Bulk Models are available, and examples are those proposed by Brubaker et al. (1993), Burde and Zangvil (2001), Yoshimura et al. (2003), and Dominguez et al. (2006). The Water Accounting Model (WAM) proposed by van der Ent et al. (2010) and van der Ent and Savenije (2011) is one of the representatives of modern Bulk Models. The WAM is a Eulerian model of moisture recycling, and it can quantify moisture source–sink relations between evaporation and precipitation by tracking moisture forward or backward in time. It has been applied to

the analysis of moisture of precipitation by backward tracking (van der Ent and Savenije 2013; Zhang and Li 2014, Zhang et al. 2017a).

In this study, moisture sources for precipitation in global arid regions were investigated using the WAM and changes in moisture sources during 1990–2019 were identified in an attempt to answer the following questions: Where does the moisture for precipitation in arid regions originate from? What changes does the source of moisture undergo over time? Answering these questions will improve our understanding of precipitation formation and water recycle characteristics over arid regions.

The next section describes the numerical implementation for the WAM and datasets used in this study. Section 3 presents an analysis of the characteristics of precipitation and precipitation recycling. In Sect. 4, the distribution of the moisture sources for precipitation over arid regions in wet and dry months, including the trend of moisture contribution over 1990–2019, are presented. Section 5 provides an analysis of the variation in precipitation and PRR in recent decades. The conclusions are given in Sect. 6.

## 2 Data and methodology

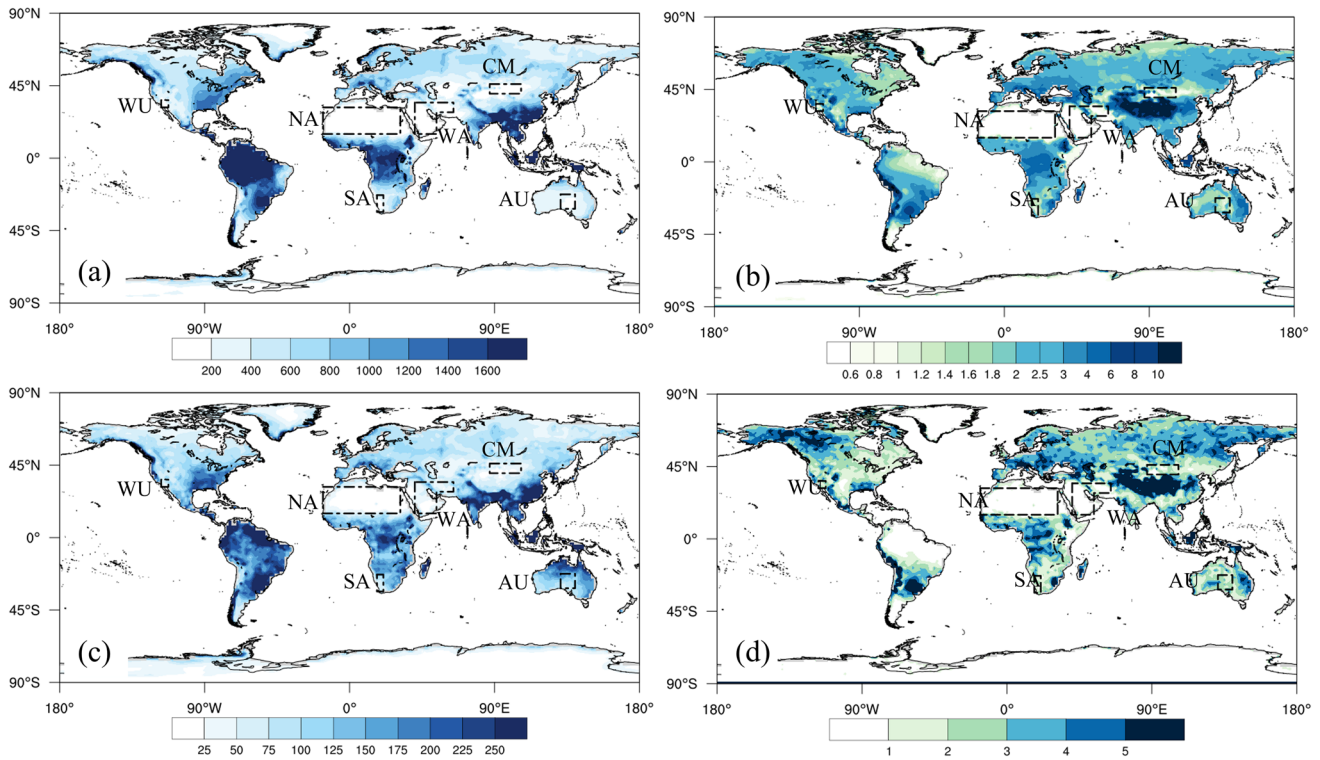
### 2.1 Arid region definition

Globally, arid region is identified with the criteria of the annual precipitation ( $P$ ) < 200-mm. Referring to the arid region distribution of Hulme and Marsh (1990) and Li et al. (2004) as an additional criterion, the arid regions study in this paper is shown in Fig. 1a. These six regions are China–Mongolia (CM), North Africa (NA), West Asia (WA), West United States (WU), South Africa (SA), and Australia (AU).

### 2.2 Data

In this study, the backward moisture tracking method based on the WAM is used to track the precipitation moisture in the arid regions. The model input is the reanalysis data of the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF, ERA5).

ERA5 is based on the ECMWF's Integrated Forecasting System (IFS) Cy41r2 and 4D-Var data assimilation method (Hersbach et al. 2020). The improvements in ERA5 include a revised data assimilation system and improved core dynamics and model physics (Hersbach and Dee 2016). The data variables include daily precipitation, evaporation, specific humidity, zonal and meridional winds at the lowest 23 pressure levels (200–1000 hPa), and surface pressure to calculate horizontal (vertically integrated) moisture fluxes



**Fig. 1** Distributions of **a** annual precipitation ( $P$ , mm), **b** precipitation recycling ratio (PRR, %), and the standard deviations of **c**  $P$  (mm) and **d** PRR (%) for the period of 1990–2019. The black outlined area delineates the six arid regions

and precipitable water. All data are available in a  $1.5^\circ$  latitude  $\times$   $1.5^\circ$  longitude grid for the period of 1990–2019.

In order to understand the characteristics of moisture sources at the seasonal scale, the dry (wet) months are defined as the months of the least (most) precipitation and its contiguous three months with the less (more) precipitation.

### 2.3 Methodology

Precipitation is considered to consist of two components:

$$P = P_r + P_a, \tag{1}$$

where  $P_r$  is regionally recycled precipitation calculated in the same way as performed by van der Ent (2014), and  $P_a$  is the precipitation originating from the moisture brought into the region by advection.

Regional precipitation recycling is the part of the precipitation in a region that originates from evaporation within the same region:

$$PRR = \frac{P_r}{P}. \tag{2}$$

The WAM is applied to track the origins of the moisture for arid region precipitation and the origination changes.

Furthermore, it is suitable on the spatial scale in these six arid regions. The basic equation of the WAM is the equation of atmospheric moisture balance:

$$\frac{\partial W}{\partial t} + \frac{\partial(Wu)}{\partial x} + \frac{\partial(Wv)}{\partial y} = E - P, \tag{3}$$

where  $u$  and  $v$  are the zonal  $x$  and meridional  $y$  wind velocities, respectively;  $E$  is evaporation;  $P$  is precipitation; and  $W$  represents the precipitable water contained in a column of atmosphere, as shown in Eq. (4):

$$W = -\frac{1}{g} \int_{P_s}^{200hPa} q dp, \tag{4}$$

where  $g$  is the acceleration of gravity,  $q$  is specific humidity, and  $P_s$  is surface pressure.

Moisture from a certain source region also follows a similar relationship:

$$\frac{\partial W_\Omega}{\partial t} + \frac{\partial W_\Omega u}{\partial x} + \frac{\partial W_\Omega v}{\partial y} = E_\Omega - P_\Omega, \tag{5}$$

where  $\Omega$  stands for the source region from where moisture is evaporated.

When precipitation reverses back to evaporative sources, a certain amount of moisture, which evaporated from the sources in the path, will fall in the target area. In each grid column, tagged moisture is well mixed with precipitable water. According to the well-mixed assumption,

$$\frac{W_{\Omega}}{W} = \frac{E_{\Omega}}{E}. \quad (6)$$

This ratio of that certain amount is  $r$ . For example, for the first source grid, an amount moisture  $E$  is evaporated into the air at this time step. At the same time, the mixed ratio is  $r$ , and then, only  $E \times r$  will finally fall into the target area. The direct contribution from the grid at this time step is  $E \times r$ . Tagged water will reduce the same amount of  $E \times r$  and will move on to the next source grids until all tagged water is depleted. Then, the total moisture contribution from each grid can be summed to produce a spatial distribution of moisture contributed to the precipitation in the target region. In the WAM backward-tracking method, for each grid, the contribution to precipitation in a study region is calculated as follows:

$$P_{con}(x, y) = \sum_t E(t, x, y) \frac{W_{\Omega}(t, x, y)}{W(t, x, y)}. \quad (7)$$

When the WAM is applied at a monthly scale, a large amount of tagged moisture may be left in the air after one month's tracking rather than allocated to the surface sources. In this case, backtracking will continue to run for another 30 days with no input of precipitation to ensure that 95% of the monthly precipitation moisture returned to the surface (Zhang et al. 2017a, b).

Due to the estimation of regional PRR is related to data's horizontal resolution (van der Ent et al. 2010), to avoid the biases caused by data's horizontal resolution, the calculation of PRR with WAM used only one dataset and regional PRR is averaged for all grid-cells over a specific region.

### 3 Spatial characteristics of precipitation and the recycling ratio

To understand characteristics of the moisture source for precipitation in arid regions, according to Eq. (2), the climatology of PRR distribution is shown in Fig. 1b. The global mean PRR is approximately 5%, and the PRR larger than 10% is mainly located in the Tibetan Plateau and Andes. PRR is the minimum (less than 3%) in arid regions, which is in agreement with the results of Li et al. (2018) and Su et al. (2014), and the interannual variabilities (standard deviation, STD) of  $P$  and PRR are low in all arid regions (Fig. 1c, d).

This finding implies that on average, the contribution of the local evaporation moisture to precipitation is minor and stable in arid regions.

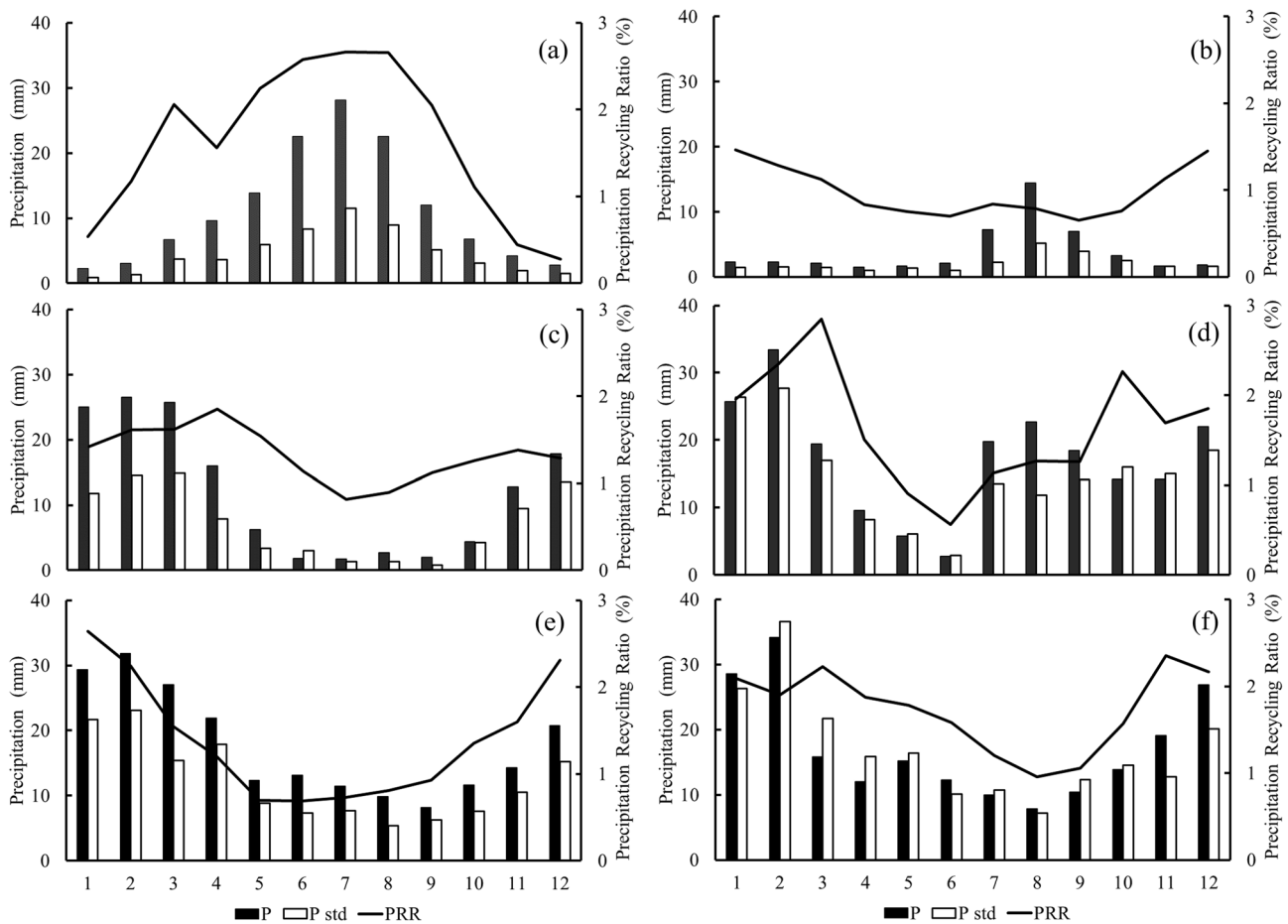
The monthly  $P$ , PRR, and STD in Fig. 2 indicate that there are relatively concentrated precipitation months like monsoon precipitation in CM and NA in the Northern Hemisphere (Fig. 2a, b) and in SA and AU in the Southern Hemisphere (Fig. 2e, f), where the most significant amounts of precipitation and its variability are concentrated in warm months. Conversely, the maximum  $P$  and STD occur in spring and winter—the cold months in WA and WU (Fig. 2c, d), and in these months, PRR is stronger than that in warm months. In wet months, although the local moisture recycles (PRR) is stronger than that in dry months in most arid regions, the maximum PRR is still less than 3% in all arid regions, which is much low than the global continental precipitation recycling ratio (36%) (van der Ent et al. 2014). Although an arid environment induces strong potential evaporation, actual evaporation is small due to deficient precipitation, thus, the contribution of local evaporation to precipitation in arid region is inevitably weak. This also illustrates that proportion of local moisture in precipitation is small in arid region, the precipitation in arid region might still be dominated by large scale circulation.

### 4 Moisture origins and changes in their moisture contributions in arid regions

The PRR induced by local evaporation has limited impact on precipitation in the arid regions, to understand the characteristics of relative contribution of moisture transportation of large scale and local moisture recycle to precipitation, it is necessary to further discuss arid region moisture and its changes from the perspective of moisture source.

To identify moisture origins source for arid regions, the moisture contributions to precipitation in arid regions in wet and dry periods are calculated using the backward-tracking WAM according to Eq. (7). The moisture contribution of each grid in every time step was recorded, and the moisture contribution in each arid region is analyzed separately. To compare the differences of sources at seasonal scale, the accumulated moisture contributions to precipitation in wet and dry months in all arid regions are calculated.

Figure 3 shows that the accumulated moisture contribution (of more than 150 mm) to precipitation in CM in wet months (June–August, JJA) originates from the Tianshan Mountains to the west of the CM (Fig. 3a), and only a small part of moisture (approximately 30 mm) originates from Central Eurasia. Most of the moisture contribution to summer precipitation is attributed to glacial ablation on the mountains. It is worth noting that the Tianshan Mountain on the southwestern CM is a prominent water supplement



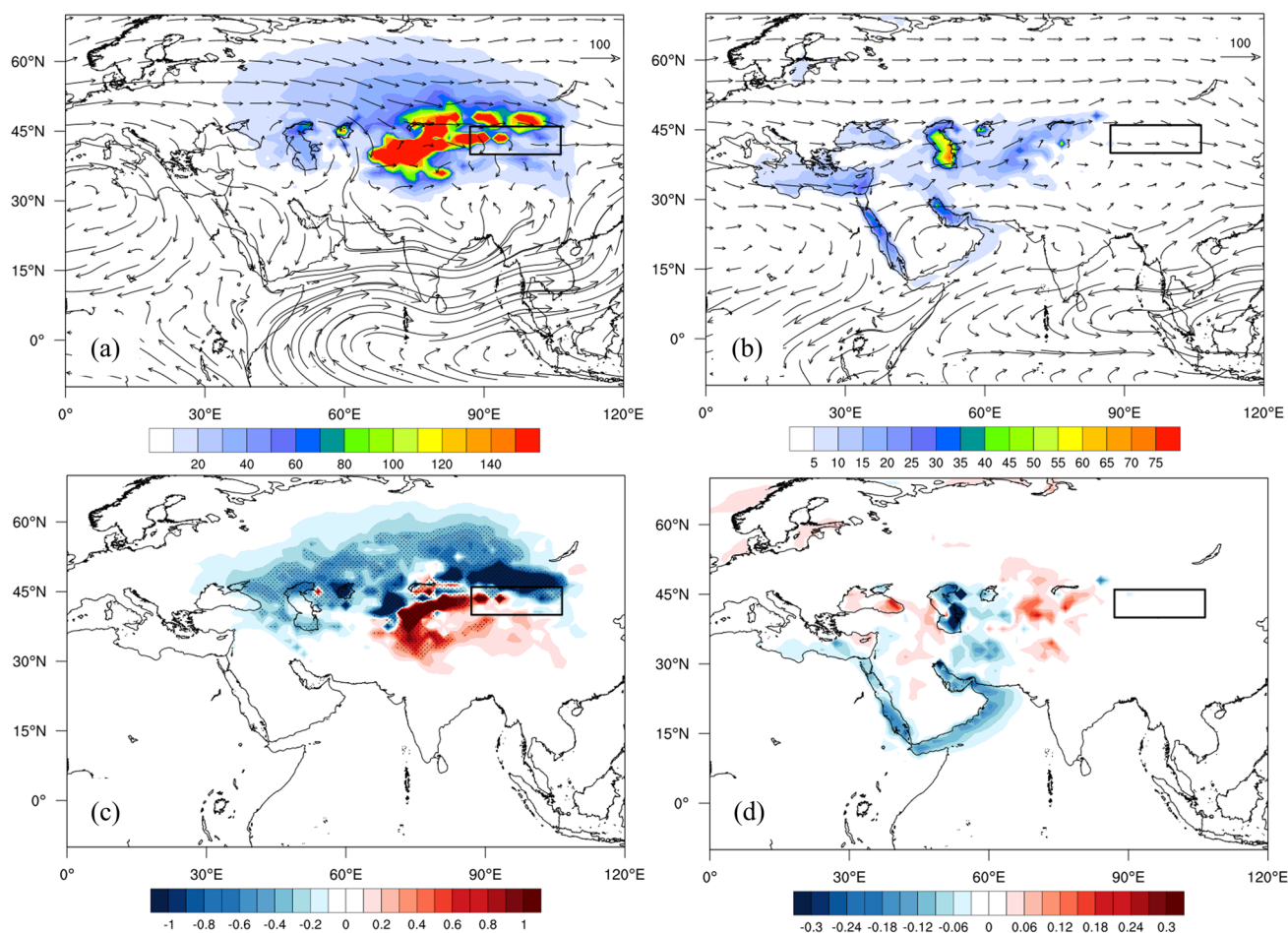
**Fig. 2** Monthly precipitation (black bar; P, mm), standard deviation of precipitation (white bar; STD, mm) and precipitation recycling ratio (line; PRR, %) over **a** China–Mongolia (CM), **b** North Africa

(NA), **c** West Asia (WA), **d** West United States (WU), **e** South Africa (SA), and **f** Australia (AU)

(Immerzeel and Bierkens 2012; Chen et al. 2016) where the glacier number density is greater than 150 glaciers per 1000 square kilometers (Ren et al. 2007). The glaciers melt during JJA over Tianshan Mountains and then results in the maximum moisture (Yao et al. 2013), and transporting into CM by westerly (Fig. 3a). In additional, glaciers and snow melting over Tianshan mountains forms the runoff into inland river, the evapotranspiration from irrigates and oases involves precipitation over CM by local recycle. In dry months (November–January, NDJ) when precipitation in CM is the least, most of the moisture comes from upwind regions, especially the Caspian Sea, which provides more than 50 mm of moisture. Moisture from some water sources even traverses the Black Sea, Mediterranean Sea, and Persian Gulf, providing ~20 mm moisture volume (Fig. 3b). The moisture for precipitation in CM is mainly transported over a long distance in dry months. Comparing the moisture contribution sources for precipitation in CM between wet and dry months, the evaporation with glaciers and snow melting in surrounding mountains provide moisture to form

precipitation in the CM in JJA when the temperature is high. This coincides with the suggestion of Shen and Wang (2002) that the melting of glaciers is linked to precipitation in the surrounding arid regions. Moreover, in low-precipitation months, moisture is transported over a long distance from the upwind region. CM is an inland arid region, where it is far away from ocean, although the moisture which forms precipitation comes from glacial ablation in the surrounding mountains, but the moisture for precipitation in arid region still transported by large-scale westerly.

The moisture contribution source for CM precipitation has changed significantly in the last 30 years. Moisture (more than 1.0 mm/a) originating from the Tianshan Mountains increases in JJA, the moisture supply extends to the north and west regions of CM shows a decreasing trend of -0.5 mm/a, and in DJF, the Caspian Sea and Persian Gulf provide less moisture (Fig. 3c, d). These results consist with the phenomenon of significant wet trend and the moisture increase in Tianshan during ablation season (Guan et al. 2022; Yao et al. 2016), and the glaciers recession here has



**Fig. 3** Moisture contributions to the precipitation (mm; first row) and the trend of the moisture contribution (mm; second row) from 1990 to 2019 over CM in **a, c** wet months (July–August, JJA) and **(b, d)** dry months (December–February, DJF). The vectors represent the clima-

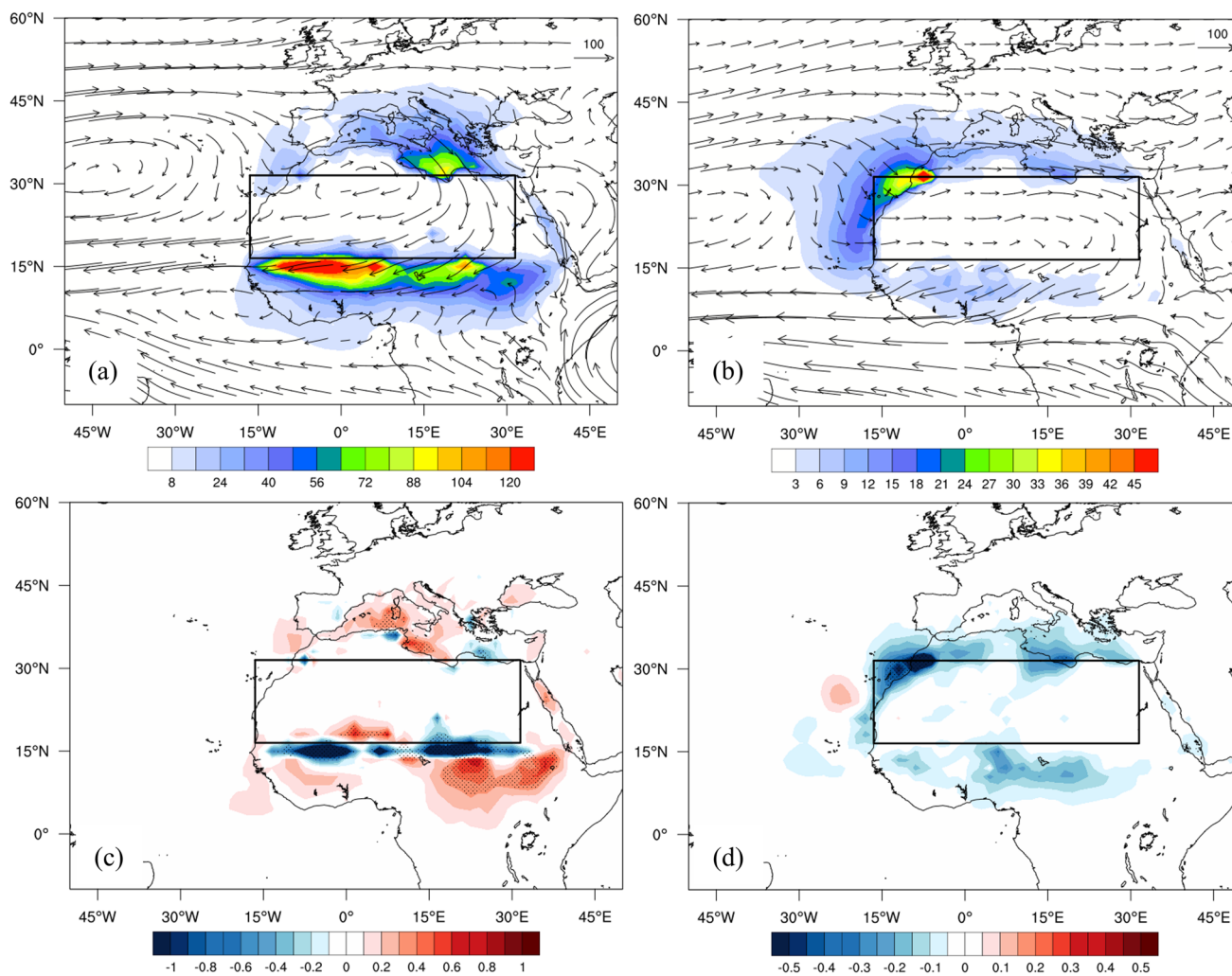
tological water vapor flux ( $\text{kg/m s}$ ). The black outlined area delineates the targeted area. The dots indicate a trend at the 90% significance level based on the Student's *t*-test

been observed by remote sensing observation (Narama et al. 2010) and glaciers losing rate accelerated in recent years as the air temperature rising (Liu and Liu 2016).

NA is a well-known arid region in the world including the Sahara Desert. As NA is lies on the sinking branch of the Hadley cell, precipitation over there is deficient, even though it is close to the Mediterranean Ocean and Atlantic Ocean. In the wet months (July–September, JAS), northern NA is the anticyclone center, and  $> 120$  mm moisture for precipitation comes from the south of NA at  $15^\circ\text{N}$ , where the Intertropical Convergence Zone is located. The Mediterranean Sea, which is upwind NA, contributes approximately 80 mm of moisture for precipitation (Fig. 4a). However, as the Hadley cell weakens and moves southward, the ocean to the northwest of NA supplies moisture during the dry months (March–May, MAM), the source of moisture can extend from the eastern Atlantic Ocean to the central Atlantic Ocean ( $15^\circ\text{W}$ – $40^\circ\text{W}$ ), providing  $> 20$  mm of moisture (Fig. 4b). Comparing Fig. 4a

and Fig. 4b, the opposite changes of moisture flux appear in  $5^\circ$ – $15^\circ\text{N}$ , which is the North African monsoon zone (Raj et al. 2019), this illustrates that NA precipitation is also influenced by the monsoon. According to the trend distribution, in the last 30 years' wet months, the land surface in the southern part of the study region provides less moisture, but the Mediterranean Sea, Central Africa, Ethiopia, and south of Sudan provide slightly more moisture in wet months. The moisture transported to NA in dry months has decreased in the last 30 years (Fig. 4c, d).

Similar to NA, the sinking branch of the Hadley cell leads to an anticyclonic circulation on the surface in WA, causing less precipitation in WA. In wet months (January–March, JFM), an anticyclone located to the south of WA, under the influence of southwesterly and westerly flows  $> 180$  mm of moisture originates from the Red Sea (Fig. 5a). Furthermore,  $\sim 40$  mm of moisture originates from the Gulf of Aden and Mediterranean Sea. Compared to the wet months, the



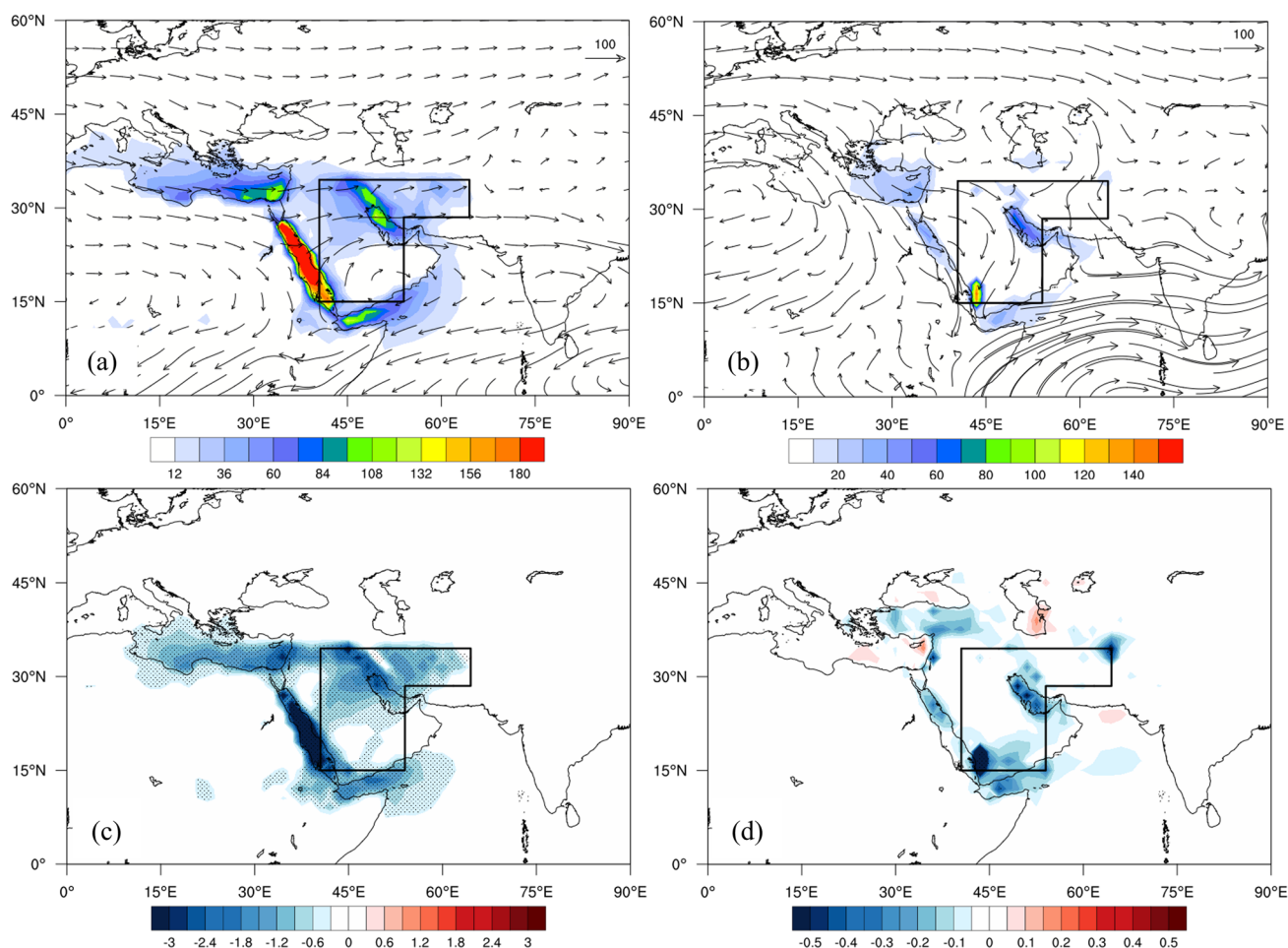
**Fig. 4** As in Fig. 3 but for NA in **a, c** wet months (July–September, JAS) and **b, d** dry months (March–May, MAM)

dry months (JJA) witness less moisture transport for precipitation into WA because of the anticyclones that dominate over the north of WA and the strong Indian monsoon. Figure 5c, d show that in both wet and dry months, the contribution of moisture has decreased in the last 30 years at rates of  $-3$  mm/a in wet months and  $-0.2$  mm/a in dry months. In winter, most of the moisture for precipitation in CM and WA originates from the Red Sea and the Persian Gulf, but the amount of precipitation is significantly different. Because of the obstruction by terrain and long-distance transportation, only a small part of moisture enters CM with the westerly wind.

WU is a special arid region that is influenced by both the sinking branch of the Hadley cell and Cordillera Mountains geomorphic pattern (Tannehill 1947), even though the moisture of the precipitation comes from the Pacific Ocean and the moisture is limited (Fig. 6). Compared with dry months (April–June, AMJ), the center of subtropical high

moves southeast in wet months (DJF) results in the transport of more than 30 mm of moisture from the Eastern Pacific Ocean. In dry months, approximately 12 mm of moisture comes from the north of WU and the Pacific Ocean. In both wet and dry months, the moisture for precipitation over WU has decreased in the recent 30 years. Studies attributed the decrease of precipitation to the lower land surface fluxes of water and energy (Hu and Feng 2004); and the Atlantic sea surface temperature rising reduces the precipitation in the southwest United States (Lee et al. 2018).

SA and AU are located at around  $30^{\circ}\text{S}$ , in the sinking branch of the Hadley cell as in the case of most arid regions in the Northern Hemisphere (Held and Soden, 2006). The proximity to the sinking branch poses challenges to precipitation. The moisture contribution in wet months (JFM) of approximately 120 mm of moisture comes from the northern part of the arid SA region because of the combined action of the northern cyclone and southern anticyclone (Fig. 7a).



**Fig. 5** As in Fig. 3, but for the WA in **a, c** wet months (January–March, JFM), **b, d** dry months (June–August, JJA)

In dry months (JAS), the arid region is affected by an anticyclone and less than 20 mm of moisture is carried by the westerly flow (Fig. 7b). An evident characteristic of moisture contribution is that it increases in wet months but decreases in dry months to the north of SA.

Figure 8 shows that the southern Indian Ocean and northern land region are the main sources of moisture in AU, which is mainly affected by the subtropical high. Because of the influence of the northwesterly of monsoon flows, northern Australia is humid and rainy in summer. Hence, this region supplies a large amount, i.e., more than 50 mm, of moisture to the study area in wet months (DJF), and the northern cyclonic circulation supplies more moisture. In dry months, the anticyclonic circulation moves northward and WA is affected by the West Australian cold current. Only a small amount of moisture is transported from the Indian Ocean by the westerly flow (Fig. 8b). In the last 30 years, moisture contribution in DJF has decreased at  $-0.8$  mm/a in the main source areas, but it increased at  $0.4$  mm/a to the northwestern part of the study

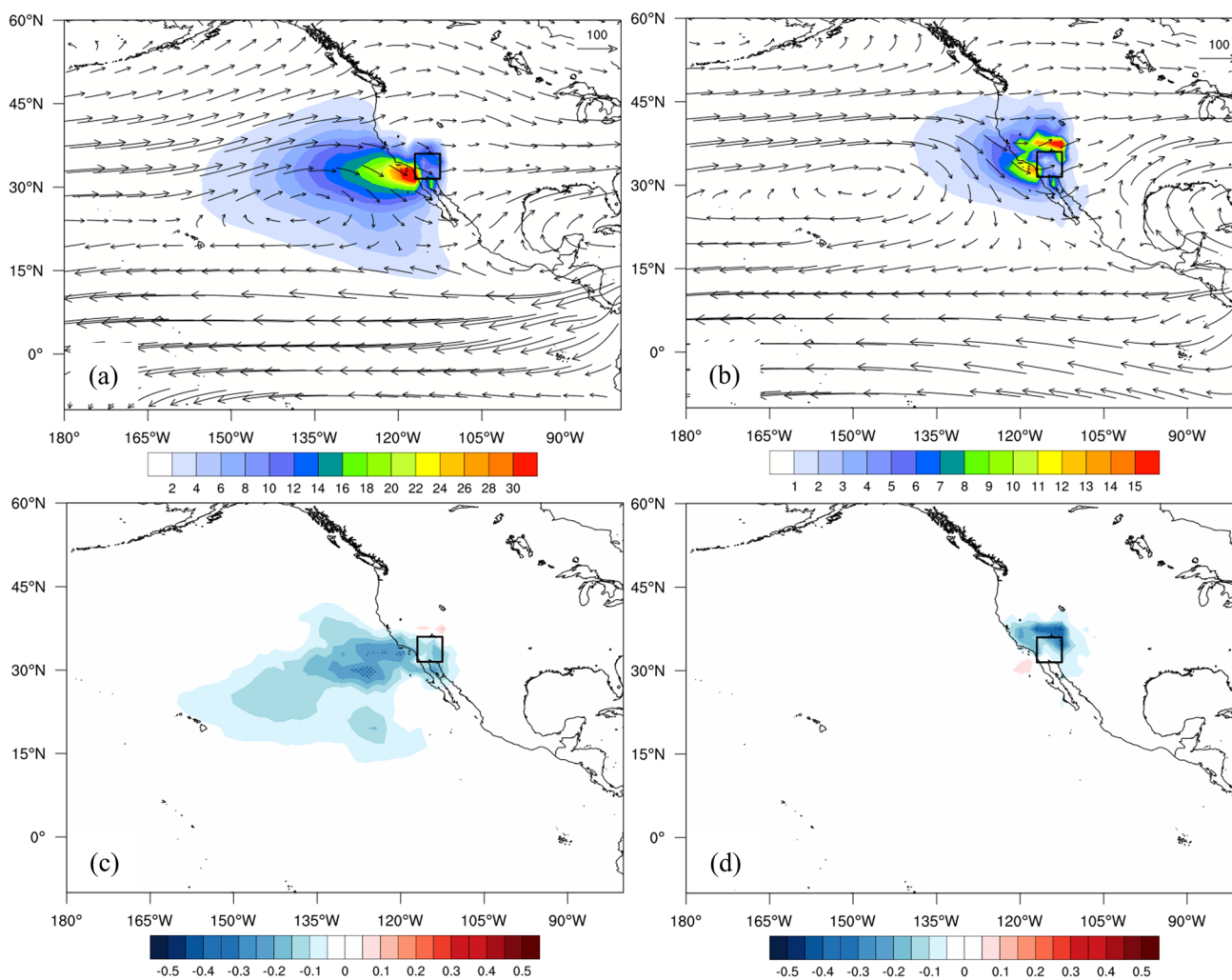
region. Further, the decrease of the moisture supply near the coastal region in dry months is a prominent feature (Fig. 8c, d).

The average moisture source distributions of the six arid regions during wet and dry periods in the last 30 years show a significant difference in moisture sources. The main source of moisture for precipitation is the transport of external moisture, and the contribution of local evaporation in these arid regions to local precipitation is less than that of external sources, even in CM arid region, where it locates inland and far away from ocean, PRR increasing in past decades, the moisture transportation still depend on large scale circulation, the contribution of local moisture (PRR) also comes from margin of arid region, it does not comes arid region itself.

## 5 Evolution of P and PRR in the last 30 years

To understand the changes in the water cycle in the last 30 years, the variabilities of P and PRR are investigated. The interannual temporal variabilities of P and PRR over the



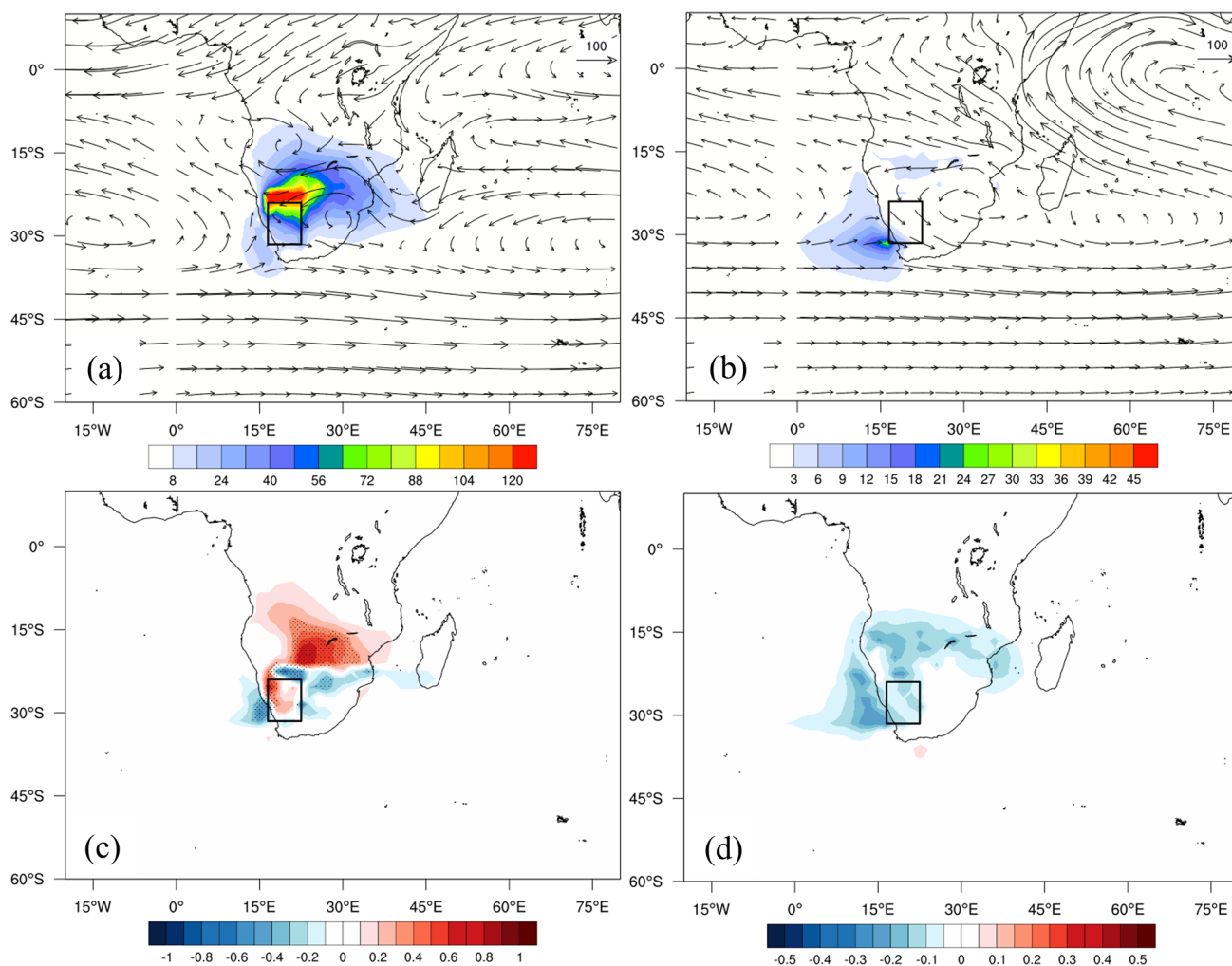


**Fig. 6** As in Fig. 3, but for the WU in **a, c** wet months (December–February, DJF), **b, d** dry months (April–June, AMJ)

period of 1990–2019 for the global land and six arid regions are shown in Fig. 9.

IPCC (AR6 2021) shows that the water cycle has become more intense, and that the global annual precipitation has likely increased since 1950. However, some studies show a significant decline in precipitation over global land from the 1980s to the 2000s (Hersbach et al. 2020). Additionally, the continental recycling ratio decreased (Findell et al. 2019) and the precipitation of oceanic origin has increased (Gimeno et al. 2020). Figure 9 shows that global land P, as well as PRR, has decreased in the last three decades. It indicates that the evaporation over the continent is less than the precipitation in the ocean due to soil moisture limitation. In all six arid regions, precipitation decreases, which is consistent with the “wet gets wetter, dry gets drier” tendency (Held and Soden 2006; Han et al. 2019). Except for NA (with the least precipitation), P in arid regions decreases faster than the global mean P in the recent decades, showing

a tendency of these arid regions to be drier. Precipitation in CM decreases at a rate of  $-0.76$  mm/a, although the melting of snow and ice in the Tianshan Mountains has intensified because of global warming (Shi and Huang 2000). The glacier and snow melting has caused an increase in moisture in wet months, but the contributions of other moisture sources have decreased significantly. CM includes part of northwest China and southwestern Mongolian. Studies suggested that the arid region of northwestern China gets wetting from 1961 to 2010 (Shi et al. 2014), and precipitation at more than 90% of the stations increases significantly in winter and spring during 1961–2018 (Wang et al. 2021a, b). However, the annual precipitation has weak decreasing trend over northwest China during 1960–2018 (Mao et al. 2021). This slight difference should be caused by different study period and research regions. PRR ranges from 1.09 to 2.3%, changing slightly by  $-0.008\%$  (Table 1) that possibly because the local evaporation in CM has no significant



**Fig. 7** As in Fig. 3, but for the SA in **a, c** wet months (January–March, JFM), **b, d** dry months (July–September, JAS)

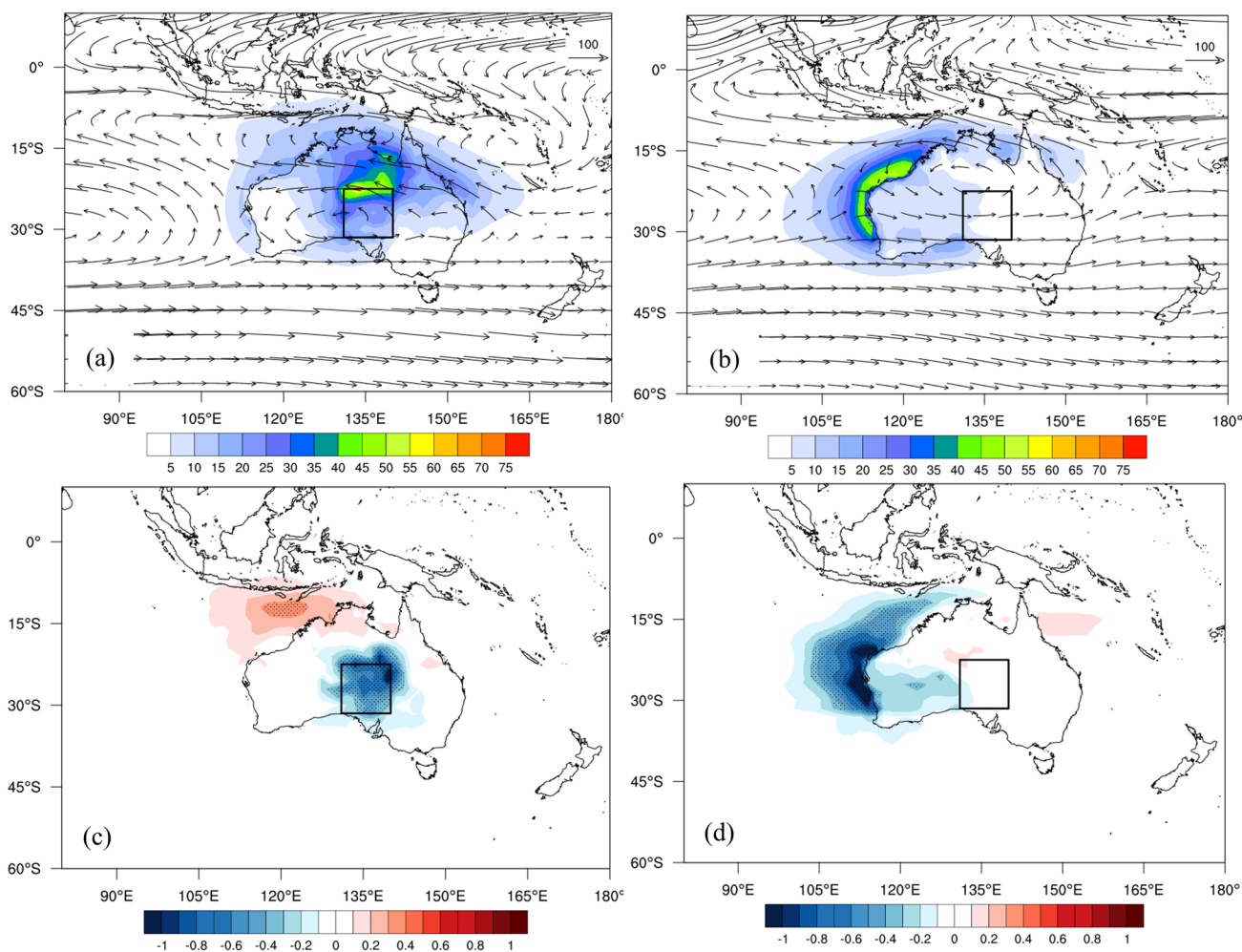
effect on precipitation and more moisture originates from surrounding mountain sources.

The precipitation and PRR changes in coastal arid regions are almost consistent with the inland arid region. NA has the least precipitation and weakest precipitation recycling, and the annual precipitation in NA decreases, but in wet months, moisture contribution tends to increase. Moisture sources provide less moisture and may lead to the intensification of drought in dry months. Meanwhile, the PRR of NA, which is the lowest among the six arid regions, decreases probably because of the minimal precipitation in this region. In WA and WU, P decreases the most significantly by  $-1.03$  and  $-1.31$  mm/a, respectively, and the contributions of the internal and external sources of moisture for precipitation show downward trends. Annual precipitation has decreased significantly since 2000, and although heavy precipitation occurred in 2010 and 2016, the overall precipitation showed a weakening trend in AU. For the global land, P and PRR both decreased in the last 30 years. The precipitation over

land shows a clear interdecadal variation that more precipitation occurred in the first decade (1990–1999) and less in the second decade (2000–2009), and in the most recent decade (2010–2019), precipitation increased slightly. In arid regions, the annual P and PRR decreased synchronously in the last 30 years, implying that the arid regions will become much drier and that less moisture can evaporate for the precipitation.

## 6 Conclusions

This study investigated and quantified the moisture contribution of the precipitation for the six arid regions over the global from 1990 to 2019. By applying the WAM with ERA5 datasets, the origins of the moisture of the precipitation over the target arid regions in wet and dry periods are tracked, and the changes in moisture contributions were analyzed. Changes in precipitation and precipitation recycling



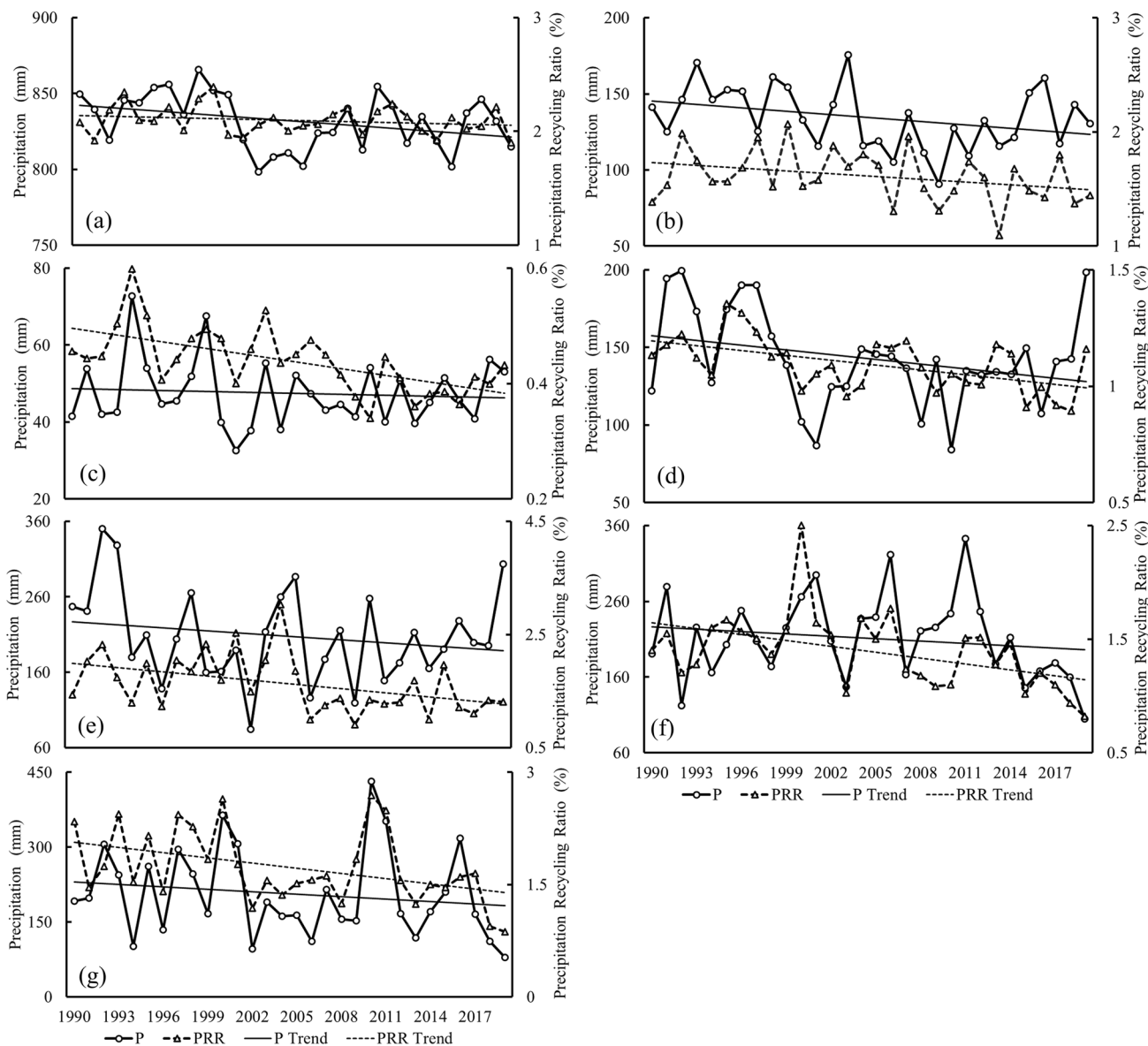
**Fig. 8** As in Fig. 3, but for the AU in **a, c** wet months (December–February, DJF), **b, d** dry months (July–September, JAS)

over the arid regions during the last 30 years are also examined. The following conclusions are drawn.

The results of backward tracking moisture for precipitation in the global arid regions indicate that there are significant differences in the distributions of moisture contribution sources in wet and dry months. Note that the moisture sources for CM in wet months are located on land—i.e., the moisture over the surrounding mountains, where the glaciers and snow melts and retreats at an accelerated rate (Yao et al. 2004), is transported by large scale circulation into the CM (more than 1 mm/a), but the contributions of other moisture sources are decreasing. Less than 50 mm of moisture travels from the distant Red Sea and Mediterranean Sea, and after long-distance transportation on the land surface, little moisture for precipitation eventually arrives in CM in dry months.

Most of the arid regions are located in subtropics, where the sinking branch of the Hadley cell plays an important role in subsidence of dry air. The general circulation

dominates moisture transport and influences precipitation. In wet months, the Mediterranean Sea is the main source for precipitation over NA, and the southwesterly flow across the Gulf of Guinea sends more moisture into NA, providing more than 120 mm of moisture. The upwind regions, i.e., the eastern Atlantic, provide approximately 30 mm of moisture in dry months. The Red Sea, Gulf of Aden, and Mediterranean Sea are the main sources of moisture for WA. The moisture supply in wet months is twice more than that in dry months. The moisture for precipitation in WU is held back by the Rocky Mountain. Additionally, because of the cold California Current, which affects moisture formation, the westerlies carry approximately 30 mm of vapor from the western Pacific Ocean in wet months. The moisture contribution source for WU can extend from the Pacific Ocean at 120° W to the central Pacific Ocean at 160° W. The northern part of the SA arid region on land provides approximately 120 mm of moisture in wet months. The Atlantic Ocean provides more than 24 mm of moisture to SA. The northern



**Fig. 9** Evolution of annual total precipitation (P, mm) and annual precipitation recycling ratio (PRR, %) over **a** the global land, **b** CM, **c** NA, **d** WA, **e** WU, **f** SA, and **g** AU from 1990 to 2019

**Table 1** Annual precipitation (P), precipitation recycling ratio (PRR), and their trends in the arid regions and global land during 1990–2019

	Land	CM	NA	WA	WU	SA	AU
P (mm)	832	134	48	142	207	216	206
P trend (mm/a)	-0.72*	-0.76*	-0.08	-1.03*	-1.31*	-1.04*	-1.63*
PRR (%)	2.10	1.61	0.45	1.09	1.63	1.40	1.73
PRR trend (%/a)	-0.003*	-0.008*	-0.004*	-0.007*	-0.025*	-0.017*	-0.023*

The values shown with \* are statistically significant at 90% confidence level

region of AU is the main source of moisture in wet months. The Indian Ocean and Pacific Ocean are the main sources of moisture in AU in summer. More than 50 mm of moisture comes from the Indian Ocean.

Under the global warming, moisture contributions to precipitation in arid regions are undergoing significant changes in increase/decrease rate and proportion of transportation on large scale and local recycle. The global land

precipitation shows a decreasing trend in the last 30 years at rate of  $-0.72$  mm/a, and the reduction in precipitation in arid regions leads to aggravated drought conditions as seen from the trend of “dry gets drier” as reported by Held and Soden (2006). The amount of local moisture contribution to precipitation in arid regions decreases significantly, although some studies show that as global warming increases, the water cycle strengthens (Zhang et al. 2019). Local moisture recycling has secondary impact on local precipitation, and most of the moisture for precipitation is supplied by advection transport into arid regions. The supply amount of moisture in areas outside the arid regions with sufficient water is the main factor affecting the intensity of precipitation.

It should be noted that the estimations in this study are based on ERA5 reanalysis. Although this dataset is reasonable to describe the moisture sources, the results should be verified with more datasets because of the uncertainty induced by model performance.

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**Data availability** The reanalysis data of ERA5 are from <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>.

## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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