Analysis and Research of Precipitation in Qinghai-Tibet Plateau Based on WAM-2layers Calculation Model

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Keywords: WAM-2layers, Qinghai-Tibet Plateau Region, Climate Change, Water Cycle.

Abstract: Moisture, as a key component of the atmospheric branch of global water cycle, are an important basis for precipitation formation. The warming rate of the Qinghai-Tibet Plateau in recent 40 years has been two times of the global concurrent warming rate, and the water cycle and water resource allocation in the region also vary with the temperature rise. Therefore, to study influences of changes in the water cycle structure in the permafrost region on the regional precipitation structure, the Water Accounting Model-2layers (WAM-2layers) was utilized to track moisture contributing to precipitation in the flood season (July and August) in the Qinghai-Tibet Plateau region from 2014 to 2016. By doing so, the research attempts to determine the main moisture sources and moisture cycling efficiency in the Qinghai-Tibet Plateau region. Main conclusions are summarized as follows: 1) due to the high elevation of the Qinghai-Tibet Plateau, precipitation in the region mainly concentrates in the south and the cumulative precipitation in the north is obviously lower than that in the south. Except for 2016, the cumulative precipitation in August was always higher than that in July in other years. 2) Due to the fact that the WAM-2layers model only analyzes precipitation caused by evaporation in the Qinghai-Tibet Plateau region, the proportion of internal water vapor contribution is only 25.5%, but the contribution of internal cycle water vapor is still the largest in the region. 3) Due to characteristic of WAM-2layers tracing evaporation source of regional precipitation, it is better at calculating regional precipitation recycling compared to other models. The precipitation formed by evaporation in the Qinghai-Tibet Plateau region accounts for 57.1% of the total precipitation, and the precipitation recycling ratio of the plateau itself is 25.5%.

1 INTRODUCTION

The Qinghai-Tibet Plateau at the average elevation above 4,000 m, is the source of seven Asian rivers, including the Yellow River, the Yangtze River, and the Ganges River and it breeds about 20% of global population. Therefore, it has huge influences on the utilization of local water resources, agricultural production, and socio-economic activities. Considering this, the Qinghai-Tibet Plateau is also termed as the world's third pole and the Asia's water tower(Xu et al, 2008; Gao et al., 2015;Lin et al., 2018). Due to the location of the plateau in the middle troposphere, its thermodynamic action is closely related to the intensity of Asian monsoon. The climate change in the region not only affects the climate pattern of China but also influences the atmospheric circulation in the Northern Hemisphere and the globe(Mann and Jones，2003; Jones et al，2001; Kutzbach et al，1993).

According to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the global land surface temperature in 2011 ~ 2020 had risen by 1.09°C above the pre-industrial level (Pascolini-Campbell, et al 2021). The global warming intensification has become an indisputable fact under the background of climate change. Such situation is particularly significant in permafrost regions including the Qinghai-Tibet Plateau in China. Previous research has pointed out that the warming rate of the Qinghai-Tibet Plateau in recent 40 years has been two times of the global concurrent warming rate (CHENG G D, et al.2019). The temperature rise has caused wide cryosphere variation in the region, in which the water cycle and water resource allocation in the region accompany the temperature rise. Therefore, to deeply study influences of variation of the water cycle structure in the permafrost region on the regional precipitation structure, the moisture sources and moisture

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recycling efficiency in the Qinghai-Tibet Plateau region need to be comprehensively analyzed.

Moisture, as a key component of the atmospheric branch of global water cycle, are an important basis for precipitation formation, so the variation of moisture sources and the precipitation recycling have become research hotspots at present. Aiming at the moisture sources and the precipitation recycling process in the Qinghai-Tibet Plateau, lots of researchers have proposed different ideas. In terms of moisture sources, Curio et al. (Curio et al, 2015) considered that the moisture recycling in the Qinghai-Tibet Plateau itself provides moisture more than the external moisture transfer to the regional summer precipitation. They also highlighted the influence of moisture recycling on precipitation in the plateau. Gao et al. (Gao et al, 2015) believed that relative to the recycling in the Qinghai-Tibet Plateau itself, large-scale circulation variation and moisture transfer outside the region are main causes for changes in the precipitation in the plateau. In terms of precipitation recycling, many researchers estimated the recycling rate of annual mean precipitation over the Qinghai-Tibet Plateau based on hydrologic budget or stable isotope and found that the recycling rate of annual mean precipitation over the region is as high as 50% ~ 80% (Kurita and Yamada, 2008; An et al, 2017). However, the estimate obtained by moisture tracking is below 30% (Zhang C et al, 2017; Li et al, 2019; Gao et al, 2020). At present, a consensus has not been reached with regard to the contribution of various moisture sources to moisture transfer in the Qinghai-Tibet Plateau.

Inspired by the above studies, the current research tracked moisture contributing to precipitation over the Qinghai-Tibet Plateau region in the flood season (July and August) from 2014 to 2016, attempting to ascertain main moisture sources and moisture cycling efficiency in the region. The remainder of the research is organized as follows: Section 2 introduces the data, research region, model, and methods. Section 3 provides main results and discussed these results. Section 4 draws the main conclusions.

2 DATA AND METHODS

2.1 Data and the Research Region

Data in the research include the precipitation, evaporation, and atmospheric data, which were used as the input data of the moisture tracking model. These data were derived from the ERA5 reanalysis dataset of the European Centre for Medium-Range Weather Forecasts (ECMWF), with the spatial resolution of 0.25° × 0.25°. The dataset was selected because it performs better among all reanalysis datasets for the atmospheric cycle budget (Trenberth et al,2011; Lorenz and Kunstmann, 2012). The ERA5 reanalysis dataset provided various data, including the horizontal radial wind, zonal wind, and specific humidity of 1-hour pattern; surface pressure of 1-hour pattern; a group of vertical moisture fluxes (water fluxes formed by vertical water, and north/east water vapor, liquid, and ice); and precipitation and evaporation of 1-hour pattern.

Apart from these, the auxiliary data included the shapefile format for country borders in the world on Natural Earth (https: //www.naturalearthdata.com/downloads), map of provincial administrative boundaries of China from a cloud platform of the Resource and Environment Science and Data Center (http: //www.resdc.cn/data.aspx?DATAID=200), and topographic data from the Global Land One-kilometer Base Elevation (GLOBE) (https: //www.ngdc.noaa.gov/mgg/topo/gltiles.html).

The research region is displayed in Fig. 1. The Qinghai-Tibet Plateau in the research region, located in the southwest of China (73°00′~104°47′ W, 26°00′~39°22′ N) is a plateau with the highest average elevation in the world and also the largest plateau in Asia. The region is rugged and mainly composed of the Himalaya, Kunlun, and Gangdisê Mountains. The region features unique and harsh climate conditions, which are mainly shown as the plateau climate and cold temperate climate. Whereas, due to the thin atmospheres, precipitation is little in the region. The summer mean precipitation differs across different geographical locations and elevations. At the mountain feet in the east and south of the Qinghai-Tibet Plateau, the summer mean precipitation is generally high and can reach 300 mm above, while little precipitation is received in the middle and west of the plateau, with the precipitation generally below 100 mm.

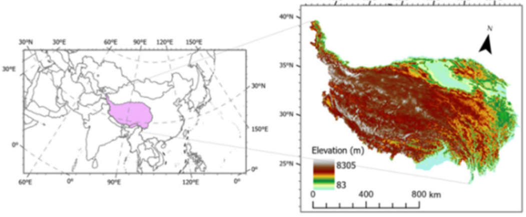

Figure 1: Study the district bitmap.

2.2 Methods and Model

1) Water Accounting Model-2layers

Water Accounting Model-2layers (WAM-2layers) is an off-line Eulerian numerical model for atmospheric moisture tracking (Van Der Ent,2014; Van Der Ent et al, 2010) that is commonly used for tracking the labeled water and backtracking the evaporation entering the air, thus quantifying the sink-source relationship of water . WAM2-layers is an update version of the original WAM model and it overcomes defects of the original WAM model in moisture tracking in regions with high vertical wind shear by dividing the vertical direction into two layers. The model has been widely applied to much research (Keys et al., 2017; van der Ent and Tuinenburg, 2017; Guo et al., 2019). Compared with the existing moisture tracking approaches using the Lagrange method, such as FLEXPART and HYSPLIT (Chu et al., 2017; Sodemann et al., 2008; Sun and Wang, 2014), what is tracked by WAM2-layers is actual surface precipitation water, while that tracked by the Lagrange method is water release in the air, rather than actual precipitation observed on the ground (Huang and Cui, 2015a). Apart from this, evaporation sources can be tracked for all precipitation water in WAM-2layers (Zhang et al., 2017a). The above characteristics render WAM-layers more suitable for researching the surface precipitation. The involved equation is

$$\frac{\partial M_b}{\partial t} = \frac{\partial (M_b u)}{\partial x} + \frac{\partial (M_b v)}{\partial y} + E_b + P_b + \varepsilon_b \pm F_{V,b}$$

where M_b is the labeled atmospheric water vapor in the lower atmosphere; t is time; u and v separately represent zonal (x) and meridional (y) wind components. E_b and P_b separately denote evaporation entering and precipitation departing from the lower atmosphere; ε_b is the residual error; F_v, b is the vertical water transport between the lower atmosphere and the top of atmosphere.

As the backtracking begins, precipitation enters water layers of the atmosphere while evaporation exists from water layers. The precipitation water entering the water layers is called the labeled water, which is well mixed with water in the upper and lower two water layers. As the integral operation of the model continues with time, the moisture (including labeled water) have horizontal and vertical motion in grid cells driven by prevailing wind. At each time step, if the evaporation on the surface grids is e and the mixing ratio in the lower layer is r, then the grid contributes e×r moisture, which finally fall in the target region as precipitation. Meanwhile, the same amount of labeled water (e×r) also reduces in the lower layer. The process continues until all labeled water is consumed in the air. More details can refer to previous research (Van Der Ent,2014).

2) Moisture contribution rate and precipitation recycling ratio

The moisture contribution rate is defined as a ratio of the tracked total vapor waters (Elocal) in a region to the total precipitation in a basin (P=Plocal+Padvected). Apart from the moisture contribution rate, the variable that also needs to quantify is the precipitation recycling ratio of the Qinghai-Tibet Plateau region. The precipitation recycling ratio in a basin refers to the ratio of the precipitation formed by local evaporation in the basin (Plocal) to the total precipitation in the basin. Here, it is assumed that all evaporation in the basin will induce precipitation in the region. Therefore, the precipitation recycling ratio is defined as

$$\rho_r = \frac{\int_A E_{\text{local}} dA}{\int_A PdA}$$

where A is the area of the research region.

3 RESTLTS AND DISCUSSION

3.1 Precipitation Over the Qinghai-Tibet Plateau in July and August and Distribution of Moisture Contribution

Figures 2a ~ 2f separately show the event-based cumulative precipitation over the Qinghai-Tibet Plateau in July and August from 2014 to 2016. It is clearly shown in each figure that the precipitation in the region mainly concentrates in the south, while the cumulative precipitation in the north of the plateau is obviously lower than that in the south. Such phenomenon occurs because the northwest of the Qinghai-Tibet Plateau is so high that moisture are blocked by mountains, fail to pass through the plateau, and can only form precipitation in the south of the region. Fig. 2f taken in August, 2016 shows an interesting phenomenon: although some moisture were blocked by mountains on the plateau and the region of the highest cumulative precipitation was still the south of the plateau, a considerable amount of moisture passed through mountains and formed precipitation in the north. As a result, the cumulative precipitation in the month exhibited most uniform spatial distribution among all months studied. Table

1 lists statistical results of sums of event-based cumulative precipitation and moisture contributions in the Qinghai-Tibet Plateau region. It can be seen from the table that the event-based cumulative precipitation was lowest (946,183.75 mm) in July, 2015 while highest (1,391,220.875 mm) in July, 2016. Over the three years, precipitation in August was always higher than that in July in 2014 and 2015; however, precipitation in July was higher than that in August in 2016. Over the three years, the region received the maximum (2,357,069.75 mm) and minimum cumulative precipitation (2,083,921.5 mm) separately in 2016 and 2015.

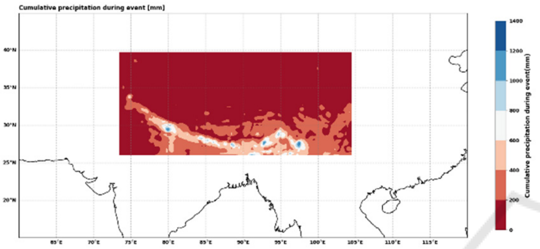

Figure 2a: Distribution map of cumulative precipitation over the Tibetan Plateau in 2014/07.

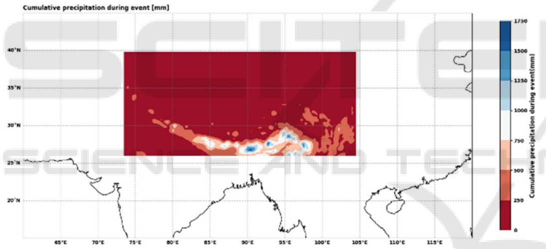

Figure 2b: Distribution map of cumulative precipitation over the Tibetan Plateau in 2014/08.

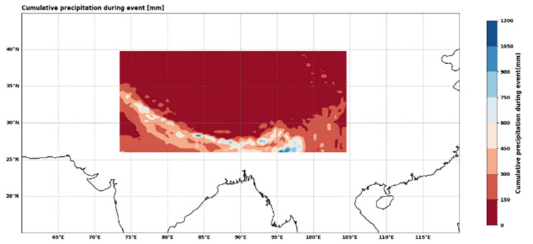

Figure 2c: Distribution map of cumulative precipitation over the Tibetan Plateau in 2015/07.

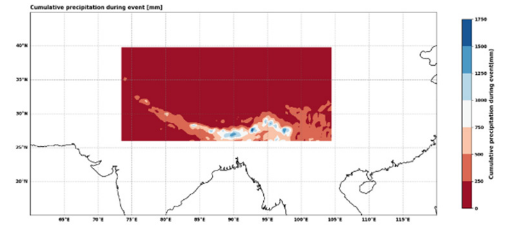

Figure 2d: Distribution map of cumulative precipitation over the Tibetan Plateau in 2015/08.

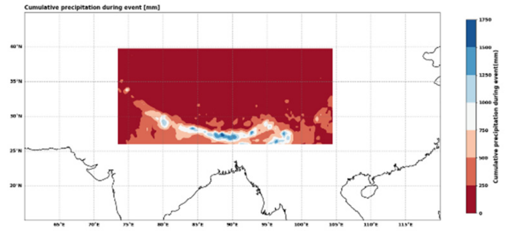

Figure 2e. Distribution map of cumulative precipitation over the Tibetan Plateau in 2016/07.

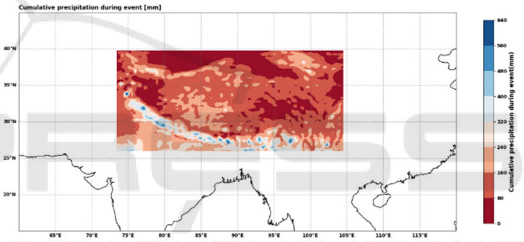

Figure 2f: Distribution map of cumulative precipitation over the Tibe tan Plateau in 2016/08.

Table 1: Summary of contribution of moisture sources to precipitation in the source area.

Date		2014		2015		2016	
		July	August	July	August	July	August
Total precipitation(mm)		2277283		2083922		2357070	
Precipitation(mm)		1118405	1158878	946184	1137738	1391221	965849
Moisture Contribution(mm)	Northwest of Eurasia	41462	56912	34087	55726	71750	26020
	Indian Ocean	224234	213892	129778	242648	334765	112079
	South China Sea-Bay of Bengal	62115	39893	27137	45611	45110	56721
	Northeast of Eurasia	3398	13013	24590	6152	4491	7718
	Qinghai-Tibet Plateau region	273094	280109	269063	283729	283729	297108
	Pacific Ocean and others	41036	56490	33764	54930	71168	27103
	Monthly total	645339	660309	518419	688799	811014	526749

When calculating moisture contributions, the research region was divided into six subregions, for the convenience of better analyzing moisture contributions of different subregions to precipitation in the Qinghai-Tibet Plateau region. The six subregions included: 1) the Qinghai-Tibet Plateau region; 2) the northwest of Eurasia; 3) the northeast of Eurasia; 4) the Indian Ocean; 5) South China Sea-Bay of Bengal; and 6) the Pacific Ocean and others. It can be clearly seen from Figs. 3a ~ 3f that two subregions greatly influencing the precipitation in the research region are separately the plateau itself and the Indian Ocean. In the region, the value of moisture contributions of internal cycle in the Qinghai-Tibet Plateau region is significantly higher than other regions and the internal cycle provides lots of moisture, which remarkably affect the local precipitation. The moisture brought by the southwest monsoon from the Indian Ocean in July and August also remarkably affect precipitation in the Qinghai-Tibet Plateau region in the southwest of China. As displayed in the figure, although the value of moisture contributions provided by the Indian Ocean is not higher than the internal cycle in the Qinghai-Tibet Plateau region, the number of moisture is much larger than that provided by the Qinghai-Tibet Plateau region. Additionally, Fig. 3f shows that the cause for the precipitation anomaly in the north of the Qinghai-Tibet Plateau in August, 2016 is probably because moisture in the Pacific Ocean and other regions entered the plateau from the east in the month. Table 1 also shows statistical results of total moisture contributions in various months. Same as event-based cumulative precipitation, total moisture contribution in August was greater than that in July in 2014 and 2015; while total moisture contribution in July was larger than that in August, 2016. July, 2015 and August, 2016 are separately two months of minimum and maximum moisture contributions, which are separately 518,419.17 and 811,013.93 mm.

Comparing WAM-2layers model's tracking of water vapor in Qinghai-Tibet Plateau with other models using WRF or other methods for water vapor tracking(Curio et al, 2015; Gao et al, 2015), it was found that internal water vapor contribution in Qinghai-Tibet Plateau region analyzed using WAM-2layers is smaller than that of other methods. This may be because WAM-2layers model tracks precipitation back to its evaporation source, and since evaporation precipitation accounts for only about 57% of precipitation in Qinghai-Tibet Plateau region, 43% of non-evaporation precipitation is not tracked, ultimately resulting in smaller internal water vapor contribution analyzed by WAM-2layers model compared to other models.

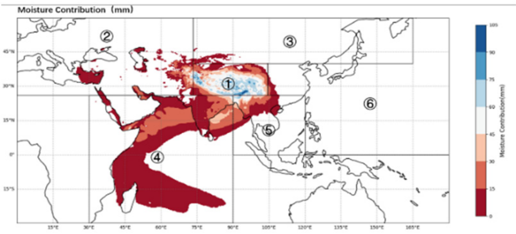

Figure 3a: 2014/07 Moisture contribution distribution map for each region.

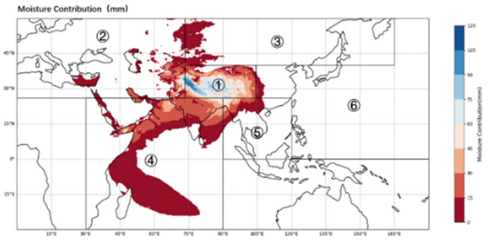

Figure 3b: 2014/08 Moisture contribution distribution map for each region.

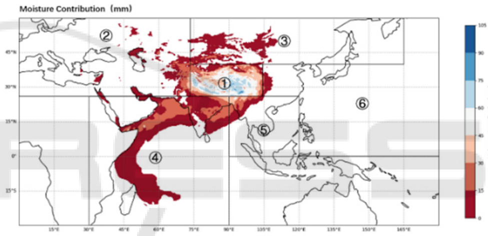

Figure 3c: 2015/07 Moisture contribution distribution map for each region.

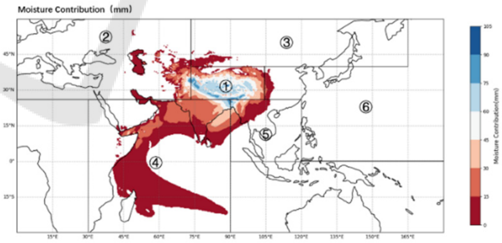

Figure 3d: 2015/08 Moisture contribution distribution map for each region.

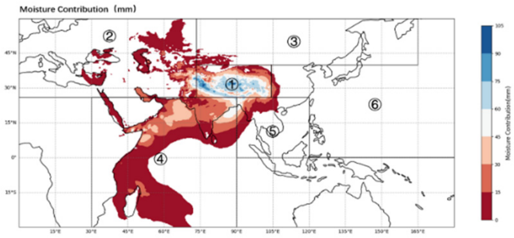

Figure 3e: 2016/07 Moisture contribution distribution map for each region.

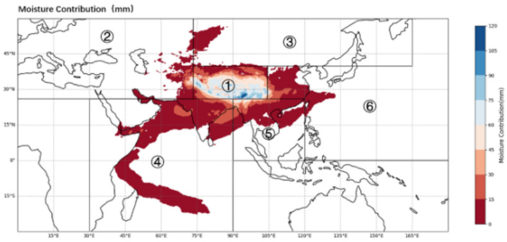

Figure 3f: 2016/08 Moisture contribution distribution map for each region.

3.2 Moisture Contribution Rate and Precipitation Recycling Efficiency in the Qinghai-Tibet Plateau in July and August

Figure 4 displays the moisture contribution rates of different moisture sources to precipitation in the Qinghai-Tibet Plateau region. As shown in the figure, the tracked evaporated moisture contribute as high as 57.1% to precipitation in the region. Moisture contributed by the Indian Ocean that is to the southwest of the region pass through the Indian Ocean and then are delivered along the east coast of Africa, finally passing through the Arabian sea and forming precipitation in the Qinghai-Tibet Plateau region. The precipitation provided by these moisture accounts for about 18.2% of total precipitation in the region. Moisture from the northwest are transported constantly by stationary flows in the Qinghai-Tibet Plateau, Central Asia and Southern Europe, which form precipitation accounting for about 4.2% of total precipitation over the plateau. The precipitation contributed by moisture from South China Sea and Bay of Bengal is same as that by moisture from northwest of Eurasia, both about 4.2%. The northeast of Eurasia that is to northeast of research region contributes lowest to precipitation in Qinghai-Tibet Plateau region, and moisture contributed thereby only account for 0.9% of total precipitation. Beyond above regions and internal cycle in Qinghai-Tibet Plateau contribute, moisture from other regions little to precipitation and they mainly come from inland China. In some months, a few moisture may come from Pacific Ocean and other regions, contribution of which amounts to 4.1% of total precipitation of region. For precipitation recycling of Qinghai-Tibet Plateau itself, only 25.5% of precipitation in region is from moisture evaporated in region itself. Conclusion basically agrees with other conclusions regarding regional precipitation recycling efficiency calculated using moisture tracking method.

Due to characteristic of WAM-2layers tracing evaporation source of regional precipitation, it is better at calculating regional precipitation recycling compared to other models. Comparing result with result analyzed using first generation WAM model, contribution of internal water vapor cycle increased by 7% compared to calculation result of first generation model. In addition to reasons for climate change in recent years, second generation model divides atmosphere into two layers, simplifying problem of gas flow in atmosphere, making calculation results more accurate.

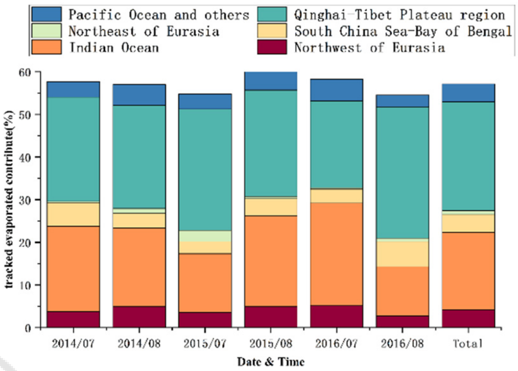

Figure 4: The tracked evaporated moisture contribute in each zone.

4 CONCLUSIONS

WAM-2layers was utilized to identify and quantify moisture sources for precipitation in the Qinghai-Tibet Plateau region in July and August from 2014 to 2016. The main conclusions are summarized as follows:

1) Due to the high elevation of the Qinghai-Tibet Plateau, precipitation mainly concentrates in the south of the region while the cumulative precipitation in the north is obviously lower than that in the south. Except for 2016, the cumulative precipitation in August was always higher than that in July in other years.

2) The value of moisture contributions of internal cycle in the Qinghai-Tibet Plateau region is significantly higher than those in other regions, and the internal cycle provides numerous moisture, which greatly influence the local precipitation. Moisture brought by the southwest monsoon from the Indian Ocean in July and August also greatly influence the precipitation over the Qinghai-Tibet Plateau in the southwest of China. The moisture contribution rates of the two are separately 25.5% and 18.2%.

3) Due to characteristic of WAM-2layers tracing evaporation source of regional precipitation, it is better at calculating regional precipitation recycling

compared to other models. The precipitation formed by evaporation in the Qinghai-Tibet Plateau region accounts for 57.1% of the total precipitation, and the precipitation recycling ratio of the plateau itself is 25.5%.

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