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Investigations on Moisture Transports, Budgets and Sources Responsible for the Decadal Variability of Precipitation in Southern China

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1. Introduction

Hydrological cycle plays an important role in the interaction processes among elements of climate systems. It also acts as a major source for energy and precipitation in the global climate system, so the hydrological cycle can exert great influences on climate system variabilities (Webster 1994). Hence, the hydrological cycle is the major concern in various international projects, such as the World Climate Research Program (WCRP), the Global Energy and Water Cycle Exchange Project (GEWEX) and the Climate Variability and Predictability (CLIVAR).

Moisture transports influencing China mainly include the following routes: southwesterly transport originating from the Somali Jet via the Arabian Sea-Indian Ocean-Bay of Bangle (BOB); southeasterly advection from the southern flange of the western Pacific subtropical high; cross-equatorial flow around 105°E via the South China Sea (SCS) and regions around; water vapor transport from mid-high latitudes. These moisture transports can be traced back to the western Pacific, South China Sea, Arabian Sea, and Indian Ocean (Ding 1994; Li 1999). Droughts and/or floods tend to occur in tandem with anomalous moisture transports and resultant moisture budgets from diverse sources (Xie *et al.* 2001; Sun and Ding 2002; Zhou *et al.* 2005; Liu *et al.* 2009). Under global warming, obvious decadal shifts of summertime precipitation in southern China have been reported. Accordingly, some studies investigated the precipitation variabilities in the Yangtze River Valley (YRV) (Xie *et al.* 2002; Zhuo *et al.* 2006) and South China (Lü *et al.* 1998; Shi and Ding 2000; Chang *et al.* 2006) from the perspective of moisture transport qualitatively via the Eulerian scheme. Additionally, many recent studies quantitatively analyzed the water source of precipitation in Europe and North America via the Lagrangian scheme (Stohl and James 2004; Brimelow and Reuter 2005; Roberge *et al.* 2009; Brubaker *et al.* 2001; Stohl *et al.* 2008). Such Lagrangian scheme were also employed in the investigations on heavy rainfall in southern Anhui (Su *et al.* 2010), enhanced precipitation in North China (Ma *et al.* 2008), extreme precipitation in eastern China during 2007 (Chen *et al.* 2011), and rainstorms occurring in the Huai-River (Jiang *et al.* 2011) during 2007. Similar studies paid particular attention to specific cases or precipitation processes of short duration. In a comprehensive way, Jiang *et al.*'s study (2013) traced enormous air particles to

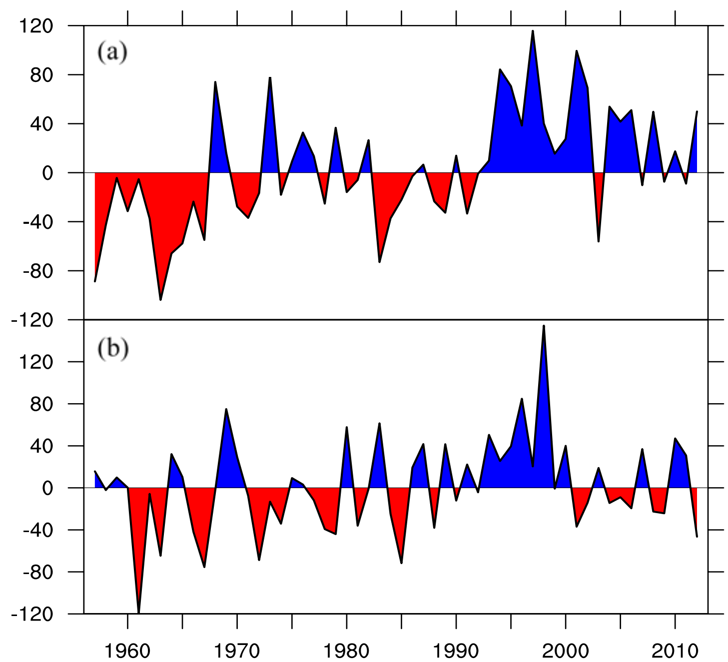

Fig. 1 Summer moisture budget anomalies (10^6kg/s) during 1957-2012 in South China (a) and the Yangtze River Valley (b).

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provide climatological features of moisture transport from various sources to the mid-low reaches of the Yangtze River during Mei-Yu period in the past three decades. Pertinent results render a quantitative comparison between the water source of the Mei-Yu period in the YRV and precipitation periods in the northern part of the Huai-River (Yang *et al.* 2014).

2. Variability of atmospheric hydrological cycle in Asian monsoonal region

Changes in precipitation are closely associated with the variability of atmospheric hydrological cycle, in which the moisture budget change is one of the most direct contributors. Figure 1 displays the moisture budget variation derived by the NCEP/NCAR reanalysis in South China (a) and the YRV (b). Figure 1 shows generally in-phase evolution features between the moisture budget and precipitation in both regions, with respective correlation coefficients of 0.59 and 0.66 at the 0.01 significance level. On decadal-interdecdal scales, moisture budgets in South China experienced a phase transition from positive phase to negative phase in the mid-1970s, and a reverse process in the early 1990s. As indicated in Figure 1b, the moisture balance in the YRV is under positive phase during 1980s-1990s, followed by a negative phase after 2000. Such variations in moisture budget are in good agreement with the precipitation changes temporally, with the positive balance corresponding to above-normal precipitation and the negative value corresponding to below-normal precipitation. So, anomalies in precipitation of southern China may be related with the moisture balance shifts.

To evaluate the relative contributions of water supply from each side to moisture budget changes, Figure 2 presents the temporal evolution of meridional and zonal moisture budgets in both regions. Clearly, no matter for South China and the YRV, an anti-phase relationship exists between zonal and meridional moisture budgets, *i.e.* positive moisture residual from zonal sides accompanied by deficient moisture on meridional sides, and vice versa. In Fig. 2, variations of meridional moisture budgets in both regions match reasonably well with the total moisture budgets. Of particular note is that the meridional moisture budget turned into a regime with significantly positive balance in the early 1990s (Fig. 2b) and the meridional component for the YRV stepped into a deficient period (Fig. 2d). These transitions are explicitly consistent with the total moisture budget in both regions, indicating that the total moisture budgets in these regions are largely controlled by the meridional components.

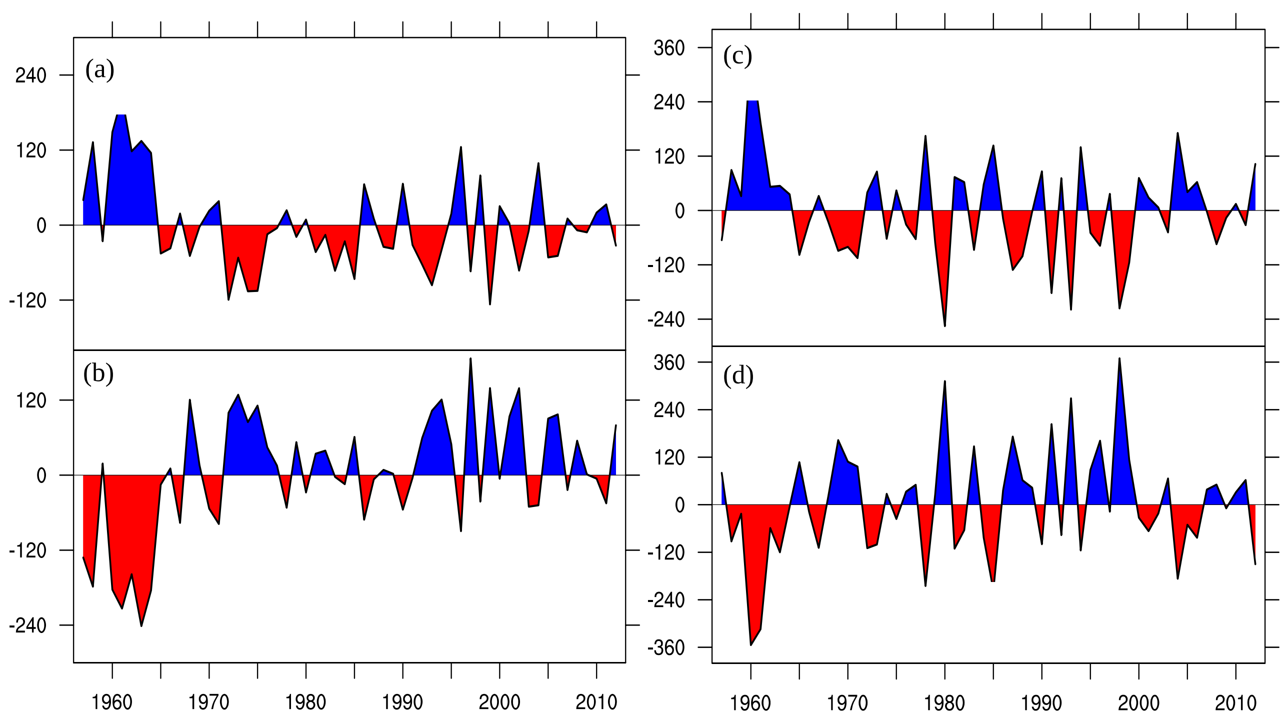

Fig. 2 Anomalies of zonal (a) and meridional (b) moisture budgets (10^6kg/s) in South China during 1957-2012. (c) and (d) same as (a) and (b), but for the Yangtze River Valley.

In this study, particular attention is paid to moisture budget variations from four sides in both two regions during the latest precipitation transition. As shown in Fig. 3a, after 1990s (difference between 1993-2012 and 1981-1992), moisture inflows increased by 77.1 * 10^6kg/s and 21.3 * 10^6kg/s via southern side and western side respectively. While, losses of moisture increased by 38.9 * 10^6kg/s and 6.5 * 10^6kg/s via the northern side and the eastern side respectively. Consequently, the positive moisture balance in South China after 1990 was mainly contributed by the increased meridional inflow from the southern side, and secondly contributed by the increased zonal inflow from the western side. For the YRV after 2000s (Fig. 3b, difference between 2000-2012 and 1981-1999), the moisture inflow via southern side decreased by 62.4 * 10^6kg/s, while the moisture inflow increased by 3.7 * 10^6kg/s from the western side. The loss of moisture via northern side increased by 11.1 * 10^6kg/s, while the outflow via the eastern side decreased by 49.1 * 10^6kg/s. Accordingly, the moisture deficiency in the YRV after 2000 mainly resulted from sharply decreased inflow via southern side. Increased outflow via northern side provide the secondary contribution to the dry condition.

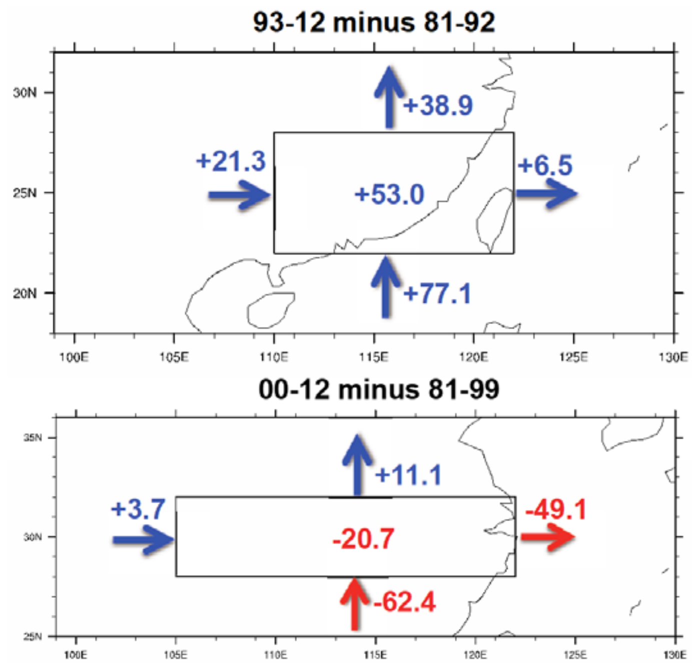

Fig. 3 Moisture budget changes from four sides for South China around 1992/1993 (top) and the Yangtze River Valley around 1999/2000 (bottom). Directions of the arrows indicate the inflow and outflow; blue (red) denote moisture increase (decrease).

3. Quantitative evaluations of relative moisture contributions from different sources

As displayed in Fig. 4a, during the regime with deficient precipitation in South China (1981-1992), seven routes can be detected. If clustered by above-mentioned five sources, two routes are associated with the channel from the Arabian Sea-Indian Peninsula-BOB, and their combined contribution reaches 34.7%; another two routes are linked with the channel from Indo-China Peninsula-SCS and around, and they contribute 36.8% to total moisture transport; three routes originate from the western Pacific with their joint contribution about 28.5%. During the regime with abundant precipitation in South China (1993-2012), 5 routes can be identified (Fig. 4b).

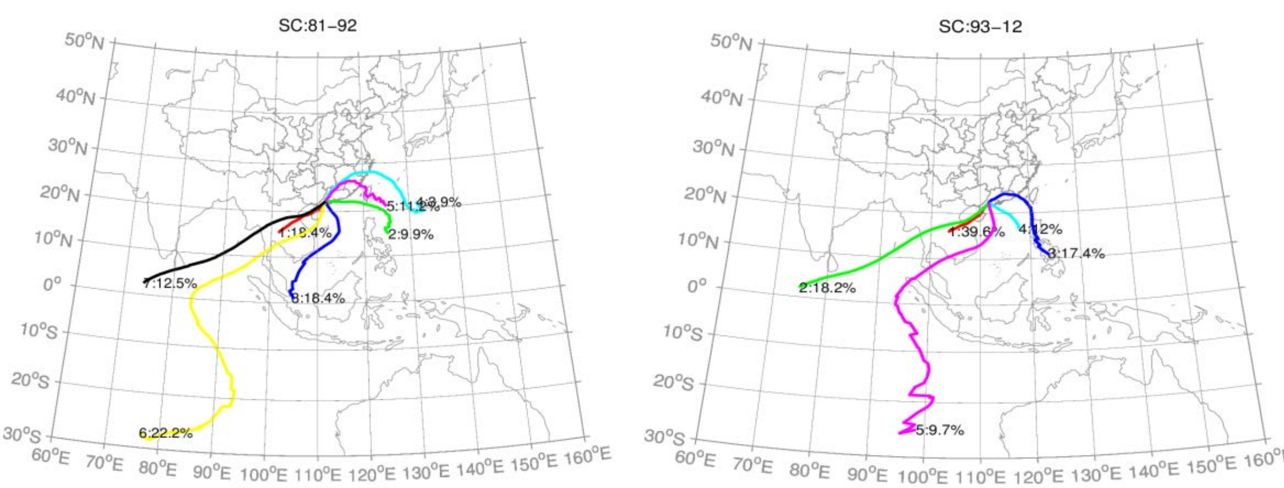

Fig. 4 Moisture transport paths during deficiency regime (left, 1981-1992) and abundance regime (right, 1993-2012) in South China and their contributions labeled on them.

Two belong to the channel from the Arabian Sea-Indian Peninsula-BOB, and their total contribution is 27.9; another two come across Indo-China towards the SCS and around with their joint contribution about 51.6%; the other one originate from the western Pacific, and it provides about 17.4% of total moisture.

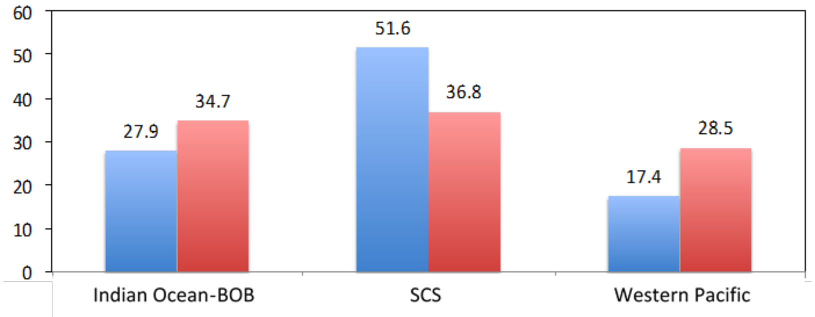

Fig. 5 Moisture contributions from diverse sources during different precipitation regimes in South China.

From Fig. 5, the moisture transport from Indo-China Peninsula to the SCS and around contribute most to precipitation in South China. The second largest contribution comes from the source of Arabian Sea-Indian Peninsula-BOB, followed by the contribution from source in western Pacific.

By comparing relative contributions from diverse sources during different regimes, it can be found that climatologically, moisture transport from the Indo-China Peninsula to the SCS and around, western Pacific, and Arabian Sea-Indian Peninsula-BOB contribute larger to precipitation anomaly in South China. After the transition from deficiency (red) to abundance (blue) condition after early 1990s, contribution of moisture steered from the Indo-China Peninsula to the SCS and around increased by 14.8%, while the contributions from the western Pacific and Arabian Sea- Indian Peninsula-BOB decreased by 11.1% and 6.8% respectively.

As displayed in Figure 6a, during abundant precipitation regime in the YRV (1981-1999), seven routes can also be detected. Based on the above classification, one route is associated with the channel from the Arabian Sea-Indian Peninsula-BOB with its contribution of 26.5%; two routes linked with the channel from Indo-China Peninsula-SCS contribute 32.3% to total moisture transport; three routes originated from western Pacific jointly contribute about 27.6%; the contribution from local moisture is 13.6%. During the regime with deficient precipitation in the YRV (2000-2012), 7 routes can be identified (Figure 6b). Three originate from Indian Ocean-BOB, and their total contribution is 39.6%; another comes across Indo-China towards the SCS and around with its contribution about 29.2%; two originate from the western Pacific, and they provides about 22.2% of total moisture; the moisture transport from north route account for 7.9%.

Based on total contributions from diverse sources during different regimes as revealed in Fig. 3, it can be concluded that climatologically the largest contribution to precipitation in the YRV is yielded via the transport from the Arabian Sea-Indian Peninsula-BOB. The contribution of moisture transport from the SCS and around

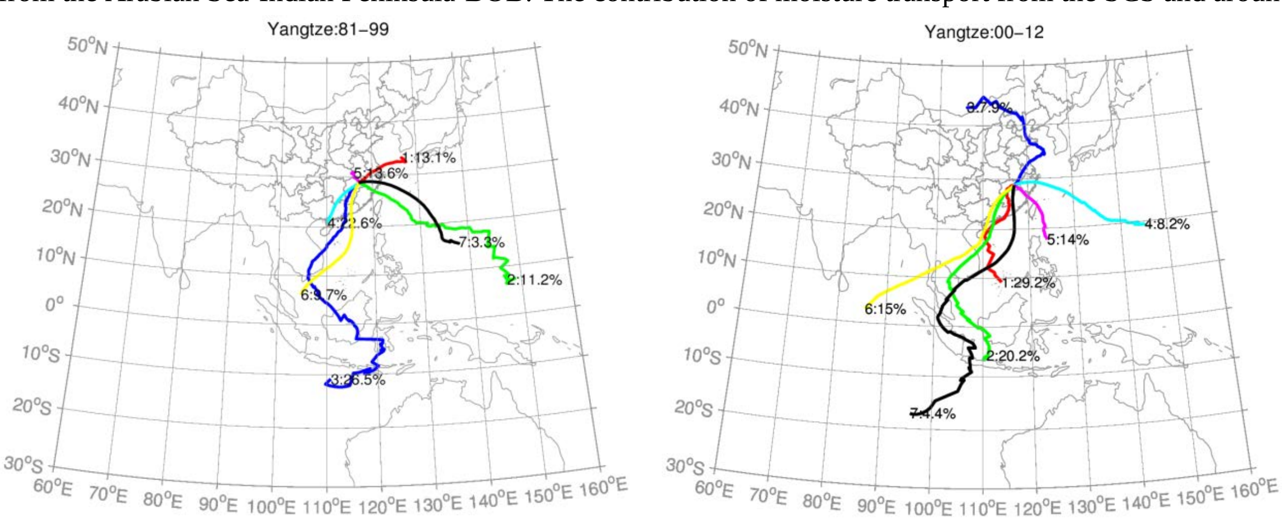

Fig. 6 Moisture transport paths during deficiency regime (left, 1981-1999) and abundance regime (right, 2000-2012) in the Yangtze River Valley and their contributions labeled on them.

ranks second, followed by source in western Pacific. The moisture from the north contributes least to precipitation in the YRV.

Figure 7 shows relative contributions from diverse sources during deficiency and abundance regimes. Larger contributions during abundant precipitation regime are mainly provided by sources in the Arabian Sea-Indian Peninsula-BOB, local source, and moisture from SCS and western Pacific. During the period with deficient precipitation in the YRV after 1990s, the contributions of moisture transport from local sources, western Pacific and sources from Indo-China to the SCS and around decreased by 13.6%, 5.4%, and 3.1% respectively. Increased contributions of 13.1% and 7.9% arise from the moisture transport from the Indian Ocean-BOB and northern China respectively.

After early 1990s, the anomalous westerly inhibited the eastward moisture transport, while the anomalous anticyclone over western Pacific-SCS promoted moisture from the SCS and around to advance towards South China. After late 1990s, the westerly moisture transport is conductive to moisture advection towards the YRV, while the anomalous cyclonic moisture transport is adverse to the moisture conveyed by cross-equatorial flow and from the SCS towards the YRV.

4. Conclusions

Based on daily rain gauge observations and NECP/NCAR reanalysis, changes in large-scale moisture transport and moisture budget in Asian monsoonal region under global warming are investigated. The influences of these changes on summer precipitation in southern China are further discussed, followed by quantitative estimation of contributions from diverse moisture sources to summer precipitation in southern China during different stages. Main conclusions are summarized as follows:

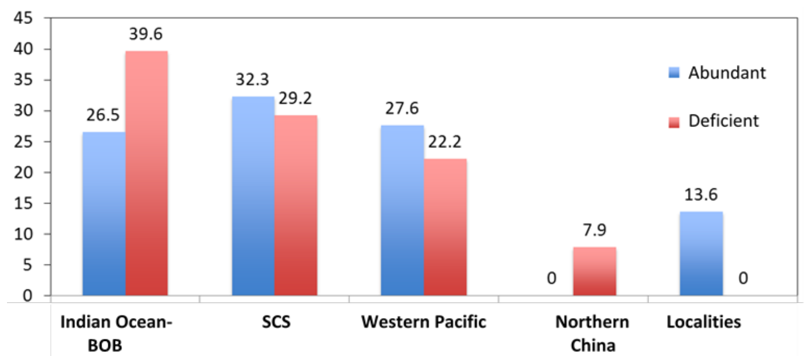

Fig. 7 Moisture contributions from diverse sources during different precipitation regimes in the Yangtze River.

(1) The northward moisture transport anomaly from lower-latitudes in Asian monsoonal region is responsible for variations of meridional and total moisture budget in South China and the YRV. For South China, before and after the regime shift around early 1990s, the anomalous moisture flux circulation in the SCS-western Pacific and the BOB remains consistent; while for the YRV, the anomalous moisture transport circulation behaves converse patterns after regime shift around late 1990s.

(2) By analyzing the model outputs of backward trajectory analyses, it can be found climatologically, the largest moisture contrition to precipitation in South China comes from the SCS and around, followed by the contribution from the sources in the Arabian Sea-Indian Peninsula-BOB and western Pacific consecutively. The largest moisture contribution to precipitation in the YRV is provided by the moisture source in the Indian Peninsula-BOB. The secondary and the third large contributions are from the SCS and western Pacific. The moisture from the north contributes least to precipitation in the YRV.

(3) Compared with deficiency period, the moisture contribution from the SCS and around increased by 14.8% during abundant regimes of precipitation in South China after early 1990s; respective contributions from the western Pacific and Indian Ocean-BOB decreased by 11.1% and 6.8%. After late 1990s, the YRV stepped into a deficiency regime. Moisture contributions from local source, western Pacific and the SCS to precipitation in the YRV decreased by 13.6%, 5.4%, and 3.1%; while increased contributions of 13.1% and 7.9% are detected in the sources of Indian Ocean-BOB and northern sources.

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