Atmospheric Moisture Distribution and Transport over the Tibetan Plateau and the Impacts of the South Asian Summer Monsoon

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ABSTRACT

In this study, by using the ECMWF ERA-Interim reanalysis data from 1979 to 2010, the spatial distribution and transport of total atmospheric moisture over the Tibetan Plateau (TP) are analyzed, together with the associated impacts of the South Asian summer monsoon (SASM). Acting as a moisture sink in summer, the TP has a net moisture flux of 2.59×10^7 kg s^{-1} during 1979–2010, with moisture supplies mainly from the southern boundary along the latitude belts over the Bay of Bengal and the Arabian Sea. The total atmospheric moisture over the TP exhibits significant differences in both spatial distribution and transport between the monsoon active and break periods and between strong and weak monsoon years. Large positive (negative) moisture anomalies occur over the southwest edge of the TP and the Arabian Sea, mainly due to transport of easterly (westerly) anomalies during the monsoon active (break) period. For the whole TP region, the total moisture supply is more strengthened than the climatological mean during the monsoon active period, which is mainly contributed by the transport of moisture from the south edge of the TP. During the monsoon break period, however, the total moisture supply to the TP is slightly weakened. In addition, the TP moisture sink is also strengthened (weakened) in the strong (weak) monsoon years, mainly attributed by the moisture transport in the west-east directions. Our results suggest that the SASM has exerted great impacts on the total atmospheric moisture and its transport over the TP through adjusting the moisture spatial distribution.

Key words: Tibetan Plateau, moisture transport, South Asian summer monsoon

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1. Introduction

The Tibetan Plateau (TP) is one of the most important geographic features on earth and exerts great influences on the weather and climate systems over Asia through distinguished thermal and dynamical processes (e.g., Ye and Gao, 1979; Tao et al., 1999; Duan and Wu, 2005; Liu et al., 2007; Wu et al., 2012). As the origin of major Asian rivers, the TP also plays the role of the "Asian water tower", affecting the water sustainability for nearly 40% of the world's population (Ding et al., 2008; Xu et al., 2008). Therefore, the distribution and transport of moisture over the TP are essential for the water vapor budgets and hydrology cycles over Asia (e.g., Fekete et al., 1999, 2000; Xu et al., 2008). For example, anomalies in moisture transport over the TP could affect greatly the frequency and intensity of floods or droughts in the vast majority of its downstream areas, i.e., the Yangtze and Yellow River basins, South China, and other countries in East and Southeast Asia (Xu et al., 2002; Dong et al., 2007; Sato and Kimura, 2007; Wang et al., 2008; Bao et al., 2010).

Studies have revealed that the main sources of

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moisture supply to the TP are the Arabian Sea, the Bay of Bengal, the South China Sea, and the midlatitude westerlies (Simmonds et al., 1999). Xu et al. (2008) further pointed out that the moisture from the Bay of Bengal can be transported to the South China Sea. Chen et al. (2012) argued that the dominant source of moisture supply to the TP is the Arabian Sea, while the Bay of Bengal plays a secondary role. All these studies indicated that the evolution of the South Asian summer monsoon (SASM) can be vital to the supply of moisture to the TP and its transport over that region. In fact, a close relationship between the moisture conditions and precipitation in the TP and the SASM has previously been suggested by Gao et al. (1985) and Yao et al. (2009).

It is known that the SASM exhibits a wide spectrum of variability, on timescales from days to years (e.g., Li and Yanai, 1996; Webster et al., 1998; Hsu et al., 1999; Goswami et al., 2001, 2003; Gadgil, 2003; Zhou et al., 2008). Over timescales of days, the important phenomena may be the active and break spells of convection and rainfall over the monsoon regions, which are important for sowing, harvesting of crops, and water management (Gadgil et al., 1999; Gadgil and Rao, 2000; Sajani et al., 2007; Zhou et al., 2012). The active and break spells of the SASM are always associated with the precipitation maxima and minima over South Asia and the shifts in the location of the monsoon trough in India (Webster et al., 1998; Krishnamurthy and Shukla, 2000; Ding and Sikka, 2006). Over timescales of years, there are strong and weak monsoon years, based on the monsoon rainfall intensity or the corresponding circulation indices (Webster and Yang, 1992; Li and Yanai, 1996). Studies showed that the strong monsoon years are associated with warm sea surface temperatures (SSTs), enhanced convection over the South Pacific convergence zone (Meehl, 1987), and enhanced summer trade winds (Webster and Yang, 1992), while opposite conditions occur in the weak monsoon years. Whether and how this vigorous intraseasonal and interannual oscillations of the SASM affect the moisture transport and its budget over the TP have seldom been studied.

From the above discussion, it is clear that moisture distribution and transport over the TP, which are possibly affected by the SASM evolution, have significant impacts on the occurrence and intensity of drought and flood in the downstream rivers. In this study, we will examine the horizontal distribution of total moisture and its transport over the whole TP air column, from the point of view of climate mean, and investigate the possible influences of the SASM intraseasonal and interannual oscillations on the moisture distribution and transport over the TP. Our results will be beneficial for further understanding of the effects of the SASM evolution on the distribution of moisture over the TP and related variations, and the role of the TP as the “Asian water tower”.

2. Data and methodology

To depict the summer atmospheric circulation, we use the daily data of geopotential height, temperature, specific humidity, and wind speed from the ECMWF ERA-Interim dataset. The climate means are obtained by averaging the above variables over the 32-yr period from 1979 to 2010. Note that the TP region is represented by the 3000-m topographic contour (see the thick dashed line in Fig. 2a and other figures in this paper), and all the averages over the whole TP region are obtained by performing arithmetical mean over this 3000-m contour enclosed area.

In order to quantify the variability of the SASM, the monsoon index of Wang et al. (2001) was adopted in this study. The index is defined as the difference of 850-hPa zonal winds between a southern region of 5°–15°N, 40°–80°E and a northern region of 20°–30°N, 70°–90°E. This index can reflect the convective latent heating over the Bay of Bengal, which is most important during the monsoon evolution. In addition, the Webster and Yang (1992) index was also applied for comparison, which is defined as the vertical shear of zone wind between 850 and 200 hPa, averaged over the region of 0°–20°N, 40°–110°E.

3. Climatology of summer moisture distribution and transport over the TP

For better understanding of the moisture condi-

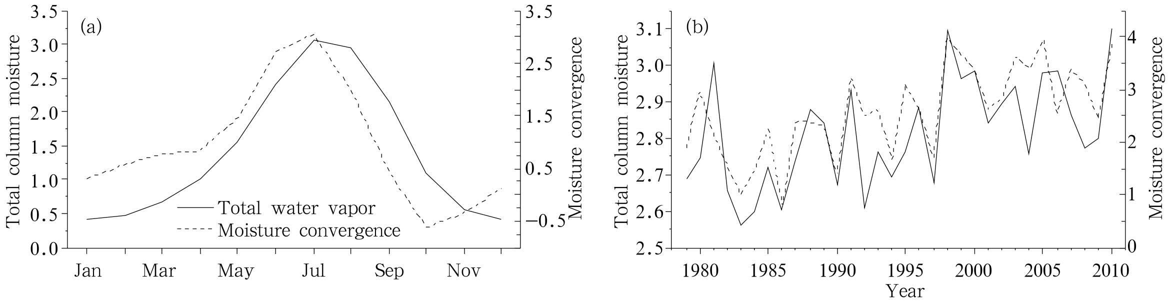

Fig. 1. (a) Seasonal variations of total water vapor (solid curve; 10^{13} kg) and moisture convergence (dotted curve; 10^{7} kg s^{-1}) over the whole TP region (see definition in Section 2), integrated for the whole air column and averaged for 1979–2010. (b) As in (a), but for the annual variation and averaged for the summers of 1979–2010.

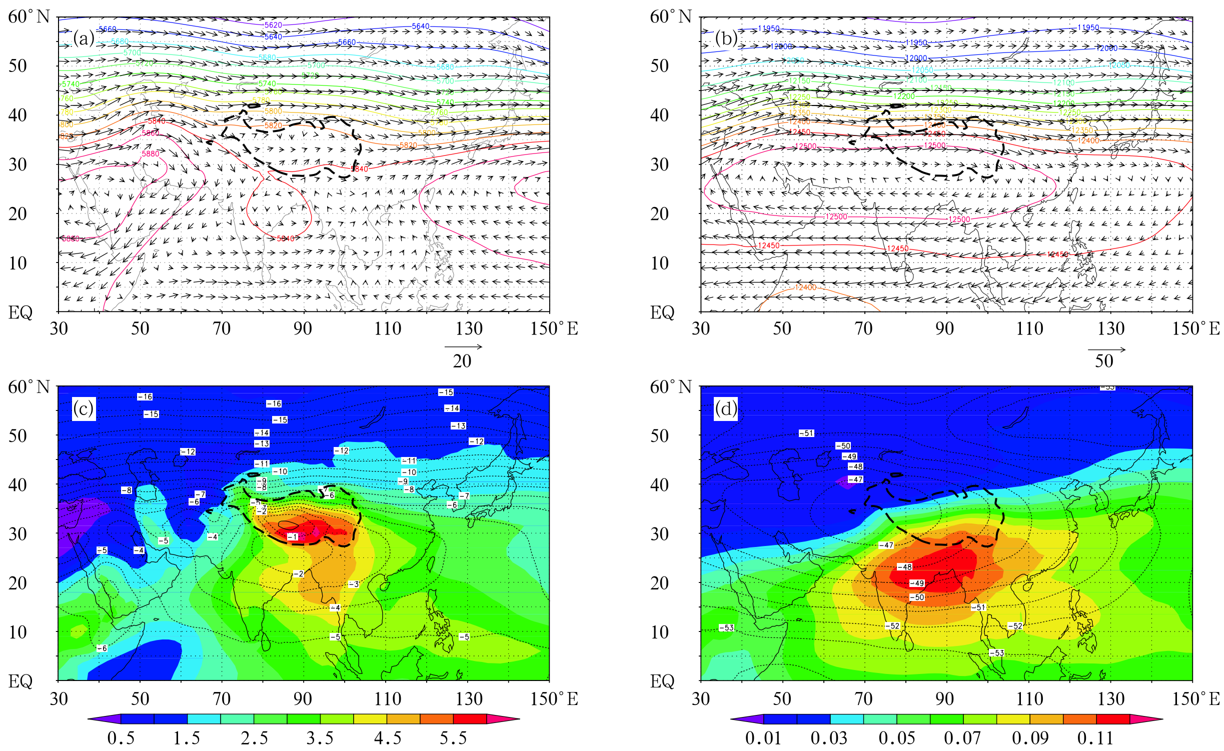

Fig. 2. Horizontal distributions of geopotential height (contour; gpm) and wind vector (m s^{-1}) at (a) 500 hPa and (b) 200 hPa, temperature (contour; ℃) and specific humidity (shaded; g kg^{-1}) at (c) 500 hPa and (d) 200 hPa in summers of 1979–2010. The geopotential height has a contour interval of 20 m at 500 hPa and 50 m at 200 hPa. The contour interval of temperature is 1℃.

tions over the TP, seasonal variations of climatological total atmospheric moisture and its convergence are firstly presented in Fig. 1a, integrated for the whole air column and averaged for 1979–2010. High values of column integrated total water vapor appear over the whole TP from late spring (May) to early autumn (September), and reach the maximum in summer, with the highest value of 3.1×10^{13} kg in July. The moisture convergence exhibits a similar variation as that of water vapor, with large values occuring in summer. From Fig. 1, it is clearly seen that summer moisture over the TP is the largest in the seasonal variation, containing more than 50% of the annual total atmospheric moisture. In addition, consistent with previous studies (e.g., Xu et al., 2008), the TP is a moisture sink as the moisture convergence values are positive throughout the year.

Figure 1b further shows the interannual variation of moisture and its convergence in summers from 1979 to 2010. For the whole TP region, the summer-mean water vapor and its convergence exhibit strong interannual variations, which may be affected by climate factors such as the El Niño–Southern Oscillation (e.g., Li et al., 2011, 2012; Li and Zhou, 2012) and the SASM. In addition, an increasing trend has been found in the total water vapor over the whole TP region from 1979 to 2010, mainly caused by the increasing moisture convergence during the last 32 years. Due to the dominant roles of summer water vapor and its convergence, the distribution and transport of summer moisture and its transport over the TP are discussed in the following, together with the possibly associated influences of the SASM.

Figure 2 shows the large-scale atmospheric circulations (geopotential height and wind speed fields) and the thermal and moisture conditions over the South Asian region at 500 and 200 hPa, averaged for the summers of 1979–2010. A low pressure system covering the whole TP persists there with weak southwesterlies at 500 hPa; this low system extends southward to India and forms a cyclone over northeastern India (Fig. 2a). A convergence zone forms in the central TP at around 30°N, where the maxima of temperature and moisture exist (see Fig. 2c). Correspondingly, an anticyclone occurs in the upper troposphere over the TP region, with strong easterly winds in the south edge of the TP and westerly winds in the northern TP (Fig. 2b). In the lower troposphere, the air mass over the TP is much warmer and more humid than the air of the surroundings due to the elevated topography being a heat source and the Bay of Bengal being a moisture source (Fig. 2c), with the maxima located over the southern TP. In the upper troposphere, the maximum center of the warm and moist air mass moves southward to the latitude belt of the northern Bay of Bengal (Fig. 2d), where the topographic effect is reduced. From Figs. 2c and 2d, it can be clearly seen that strong inhomogeneous distributions exist in air temperature and moisture over the TP, which could have resulted in the spatial inhomogeneity of atmospheric moisture transport there.

Figure 3 presents the climatological distribution and transport of total atmospheric moisture over the South Asian region in summer, integrated for the unit air column and averaged for 1979–2010. High moisture is found over north of the Bay of Bengal and south edge of the TP, with a maximum value of more than 60 kg m^{-2} centered around 20°N, 90°E (Fig. 3a). In comparison, the total atmospheric moisture over the TP region is much smaller than the surroundings due to the elevated topography, with the value less than 20 kg m^{-2}. In terms of climatological mean, the total atmospheric moisture over the TP exhibits a horizontal inhomogeneity, with high values over the southeast and low values over the northwest. A strong cyclone exists over north of the Bay of Bengal and northeast-

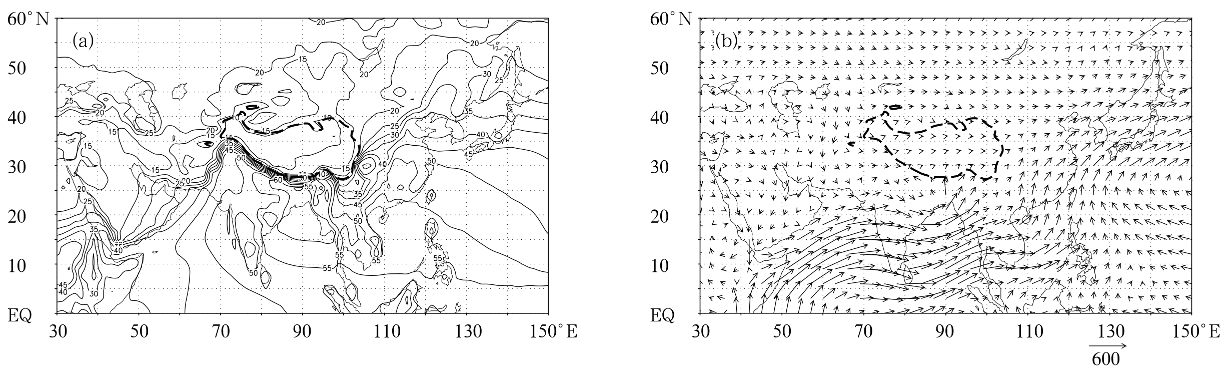

Fig. 3. Spatial distributions of total atmospheric moisture (a; kg m^{-2}) and its flux (b; kg m^{-1} s^{-1}) over the South Asian region in summer, integrated for the unit air column and averaged for 1979–2010.

ern India (Fig. 3b), which could transport the warm and moist air northward, resulting in the highest moisture over the south and southeastern edge of the TP (Figs. 3a and 3b). Over the TP region, the total atmospheric moisture is mainly transported from the west and south to the east and north, which could result in a net moisture sink there (refer to the moisture fluxes discussed later). It is clear from Fig. 3b that the water supply to the TP is mainly from the Arabian Sea and the Bay of Bengal, which is much stronger than that from the westerly originated from the Eurasian Continent northwest of the TP; this finding is consistent with previous results (e.g., Xu et al., 2008; Chen et al., 2012).

4. Evolution of the SASM

To investigate the possible influences of the SASM on the horizontal distribution and transport of atmospheric moisture, the SASM evolution, characterized by the large-scale circulation in the lower troposphere over the South Asian region (e.g., Webster and Yang, 1992; Webster et al., 1998; Goswami et al., 2003), is examined.

For quantifying the summer monsoon interseasonal and interannual oscillations, the monsoon index of Wang et al. (2001) (SASMI) is calculated. The "active" periods defined here are days with the monsoon index over 1σ, and the "break" periods are days with the index less than -1σ. Variations of the number of active and break days during the summer monsoon for the period 1979–2010 are shown in Figs. 4a and 4b, respectively. In general, the mean durations of monsoon active and break periods are almost the same for every summer of 1979–2010, with the number of days being 13 and 12 for the active and break periods, respectively. Duration of the monsoon active period shows similar anual variability as that of the monsoon break period, with a standard deviation of 6.5. In fact, our results are consistent with those of Rajeevan et al. (2010), who identified the active and break periods from the precipitation over the Indian region. Therefore, given the same mean duration and similar variability of monsoon active and break periods during 1979–2010, all the variables are averaged over the active and break periods, from which the climate mean is subtracted and anomalies are obtained. To further illustrate anual variations of the SASM, the time series of SASMI during 1979–2010 is presented in Fig. 5, with one standard deviation of ±1.4 m s^{-1} superimposed. Similar to the definition of monsoon active/break period, the strong (weak) monsoon year is defined as the year when the monsoon index is larger than 1σ (smaller than -1σ). Our definition of strong/weak monsoon year is the same as that by Li et al. (2011) and by Li and Yanai (1996). Using this definition, five strong monsoon years of 1985, 1994, 1999, 2000, and 2001 and five weak monsoon years of 1979, 1983, 1987, 1992, and 1997 are identified. In the following, the anomalies are obtained by averaging those variables for all the strong/weak monsoon years and then subtracting their climate mean.

5. Possible impacts of the SASM on the moisture transport over the TP

5.1 Moisture distribution and transport related to the active and break SASM

Figure 6 shows distributions of anomalies of the

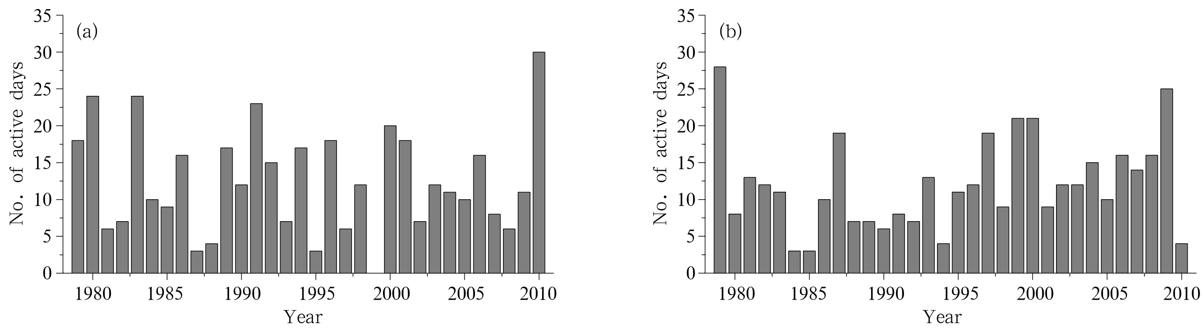

Fig. 4. Variation of number of (a) active and (b) break days during the summer monsoon for the period 1979–2010.

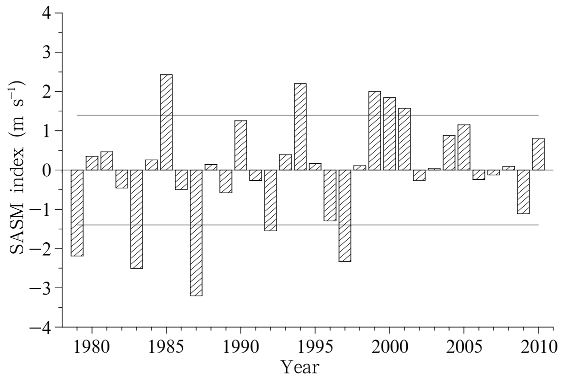

Fig. 5. Time series of the SASM index (SASMI) from 1979 to 2010. The horizontal lines represent the associated one standard deviation ($\pm 1\sigma$).

atmospheric variables at 500 hPa, which deviate from the climate mean of 1979–2010, during the SASM active and break periods. During the active period, the Indian low is much stronger due to the development of a stronger cyclone over the Arabian Sea, resulting in negative geopotential height anomalies over north of India and the whole Arabian Sea (Fig. 6a). Warm air persists over almost the entire TP and Indian regions, while moist air appears mostly over the Arabian Sea, extending northeastward and resulting in little wetness over the western TP region. It is clear from Fig. 6e that a strong cyclone forms over the Arabian Sea, which transports the warm and wet air westward to

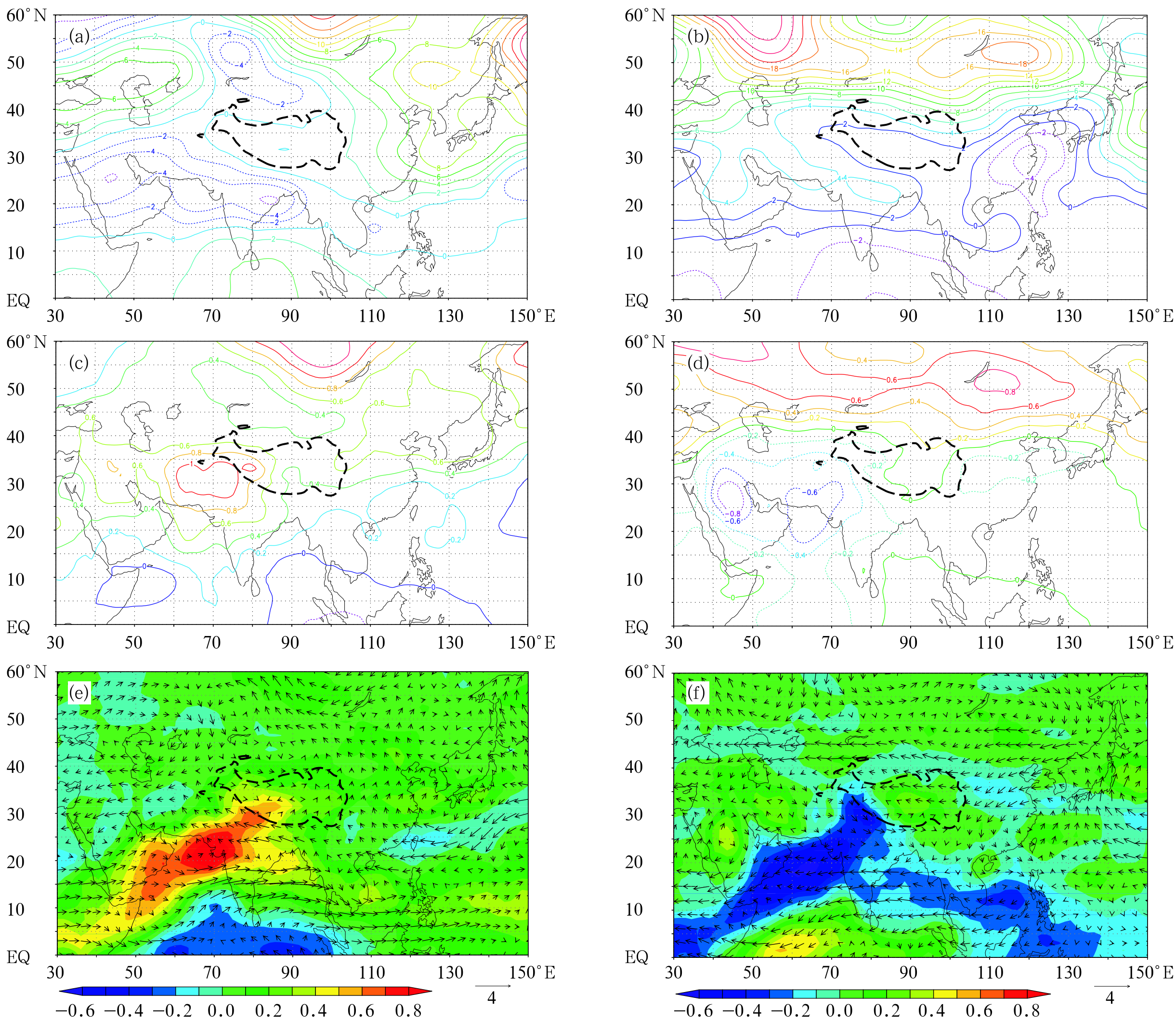

Fig. 6. Anomalies of (a, b) geopotential height, (c, d) temperature, and (e, f) wind vector overlapped with specific humidity (shaded) at 500 hPa during the monsoon (a, c, e) active and (b, d, f) break periods. The contour intervals for geopotential height, temperature, and specific humidity are 2 m, 0.2℃, and 0.1 g kg^{-1}, respectively.

the western border of the TP and then turns northward. The situations during the monsoon break period are opposite to those in the active period. For example, cold and dry air persists over the southwest edge of the TP (see Figs. 6d and 6e). These different atmospheric circulation patterns during the monsoon active and break periods should have resulted in altered distribution and transport of atmospheric moisture over the TP.

Firstly, the anomalies of total atmospheric moisture and its transport, which are affected by evolution of the SASM, are given in Fig. 7. During the SASM active period, the cyclone over the Arabian Sea is stronger, which brings warm and moist air mass northeastward to the southwest edge of the TP and leads to formation of the region with the highest moisture. This high moisture region covers the whole Arabian Sea and most of India, with two maximum centers. One is located over the southwest edge of the TP and the other over the northeast of the Arabian Sea, with the center moisture value larger than 5.5 kg m^{-2} (Fig. 7a). The warm-moist air mass could pass across the Himalayas and lead to the higher moisture condition over the southwest TP than over the rest parts of the TP, resulting in a high-low distribution from the southwest to the northeast of the TP. From Fig. 7c, it can clearly be seen that a weak easterly anomaly persists along the south side of the TP, which could transport the moist air from east to west and result in the maximum moisture center over the southwest of the TP. A large westerly anomaly prevails over the whole Arabian Sea and the Bay of Bengal, creating the maximum moisture center over the northeast of the Arabian Sea. Opposite conditions occur during the SASM break period: e.g., a low-high pattern from the southwest to northeast of the TP, and maximum negative centers over the southwest of the TP and northeast of the Arabian Sea, resulting from the weak westerly along the southwest of the TP and strong easterly over the Bay of Bengal (Fig. 7d). The largest moisture difference occurs over the Arabian Sea suggesting that the dominant source of moisture supply to the TP is from the Arabian Sea, consistent with results of Chen et al. (2012).

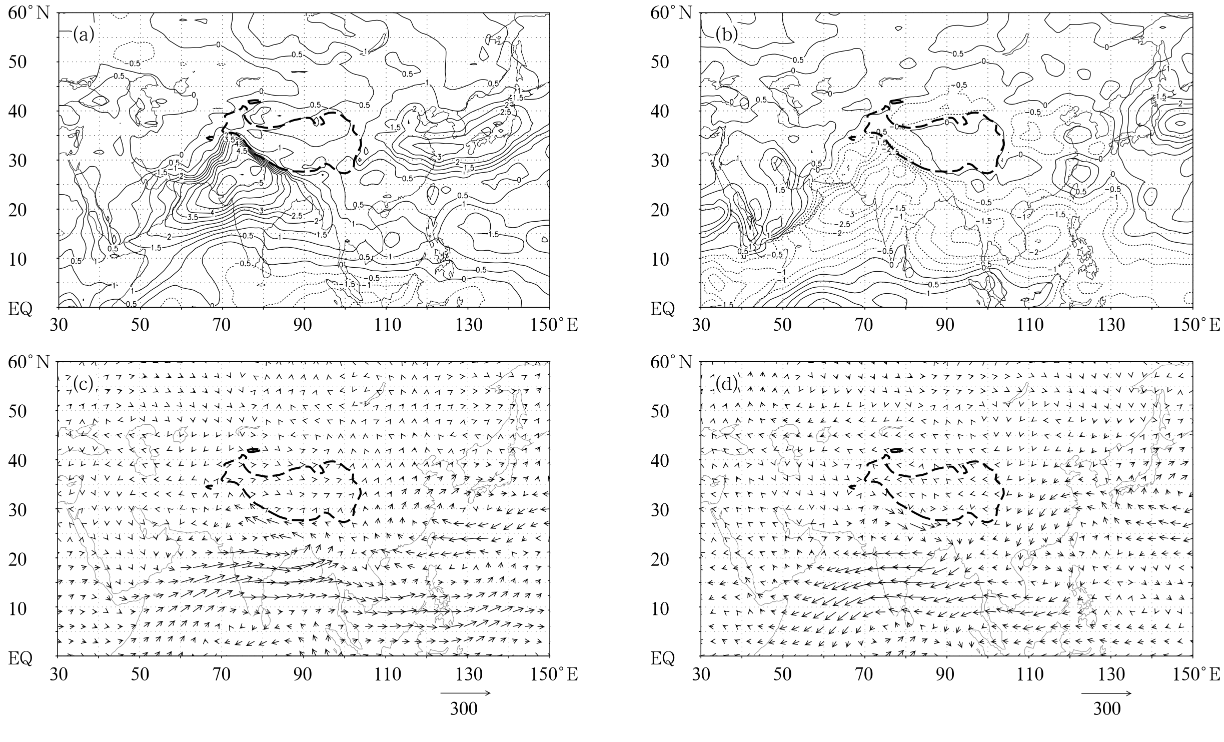

Fig. 7. Anomalies of (a, b) total atmospheric moisture and (c, d) its flux over the South Asian region during the monsoon (a, c) active and (b, d) break periods, integrated for the whole air column. The contour interval for the specific humidity is 0.5 g Kg^{-1}, and the unit vector is 300 kg s^{-1} m^{-1}.

Table 1. Total atmospheric moisture fluxes (10^7 kg s^{-1}) crossing the TP boundaries on all directions and the net flux over the whole TP, averaged for the boreal summer (JJA) of 1979–2010 (denoted by "Climate"), and the anomalies for the SASM active and break periods related to the "Climate"

Flux	West side	East side	South side	North side	West-east	South-north	Net
Climate	6.74	7.56	4.06	0.65	–0.82	3.41	2.59
Active	0.68	0.52	0.89	0.31	0.16	0.58	0.74
Break	–0.24	–0.76	–0.22	0.22	0.52	–0.44	0.08

Note: the TP boundaries are denoted by the 3000-m contours, as represented by the black dashed TP shape in all figures.

Secondly, the total atmospheric moisture fluxes passing across the TP boundaries are calculated, together with the net moisture flux over the whole TP region, as given in Table 1. From the perspective of climatology, strong westerly could have a large input of moisture flux at the western boundary of the TP, but also a larger output at its eastern boundary (see also Fig. 2b), resulting in a low moisture output (–0.82$\times 10^7$ kg s^{-1}) in the west-east direction. In comparison, strong southerly provides the largest net south-north moisture supply of 3.41$\times 10^7$ kg s^{-1} (c.a., 132% of the total moisture flux over the TP), with the major portion brought in from the southern boundary of the TP. Therefore, for the whole total air column, the TP acts as a moisture sink due to strong moisture convergence, which absorbs moisture from its surrounding areas, at a rate of 2.59$\times 10^7$ kg s^{-1}. The moisture sink of the TP and its dominant southerly origin are consistent with the results of previous studies (e.g., Simmonds et al., 1999; Chen et al., 2012). During the SASM active period, weak westerly (see Fig. 7c) brings a weak moisture supply (with a moisture flux of 0.16$\times 10^7$ kg s^{-1}) along the west-east direction, while strong southerly brings in a large moisture supply to the TP region from its southern boundary, at a rate of 0.58$\times 10^7$ kg s^{-1} (c.a., 22% of the total moisture flux over the TP). In total, during the monsoon active period, the moisture transport is 29% strengthened than the climate mean, mainly attributed to the anomalous moisture transport at the southern boundary of the TP. For the SASM break period, the easterly over the whole TP causes negative moisture flux values along the western and eastern boundaries and a net moisture supply to the TP along the west-east direction. However, this moisture supply is almost balanced by the moisture output along the south-north direction.

5.2 Moisture distribution and transport related to the strong and weak monsoons

It is shown in Section 4 that the SASM index has a strong anual variation, and we have identified five strong and five weak monsoon years. To investigate the moisture condition and moisture transport associated with the strong/weak monsoon years, anomalies of the atmospheric variables relative to the climate mean of 1979–2010 at 500 hPa during the strong and weak monsoon years are presented in Fig. 8. During the strong monsoon years, the TP summer low becomes much weaker, resulting in negative geopotential height anomalies over the southern TP and the South Asian region (Fig. 8a). Large positive temperature anomalies cover most of the central and northwestern TP and the northeastern Asian region (Fig. 8c). Negative temperature anomalies occupy most of India and the tropical belt. The temperature anomaly distribution shows an enhanced meridional temperature contrast during the strong monsoon years. For the specific humidity, however, the moisture contrast in the east-west is much larger than that in the north-south direction (Fig. 8e). The positive specific humidity anomaly occurs over the west TP and most of India, with the maximum centered around 35°N, 80°E. Affected by the weak TP summer low, the strong westerly over the TP is weakened and results in an easterly anomaly (Fig. 8g), which could cause the water vapor transport reversely from the east to west TP. Strong cyclones form in both the Bay of Bengal and the South China Sea, which can transport the warm and moist air westward and northward. In comparison to the strong monsoon years, opposite conditions happen in the weak monsoon years. For example, positive geopotential height anomalies cover most the southern TP and the South Asian region (Fig. 8b), and almost the entire TP region is dominated by cold (negative temperature anomaly in Fig. 8d) and dry (negative specific humidity anomaly in Fig. 8f) air masses.

Affected by the above different atmospheric dy-

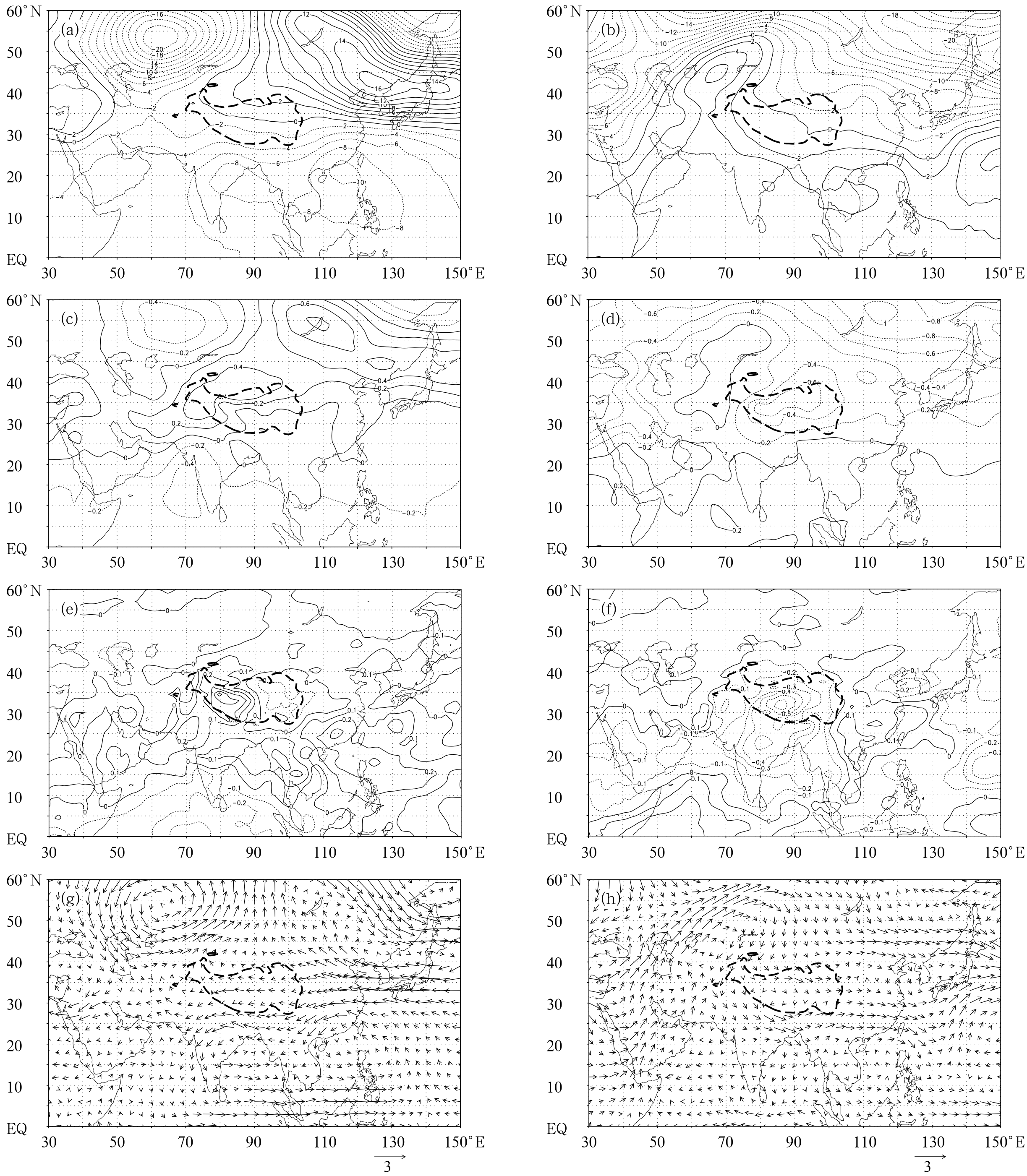

Fig. 8. Anomalies of (a, b) geopotential height (m), (c, d) temperature (℃), (e, f) specific humidity (g kg^{-1}) and (g, h) wind speed (m s^{-1}) at 500 hPa, from the climate mean of 1979–2010, over the South Asian region in summer, during the strong (a, c, e, g) and weak (b, d, f, h) monsoon years. The contour intervals for geopotential height, temperature, and specific humidity are 2 m, 0.2℃, and 0.1 g kg^{-1}, respectively.

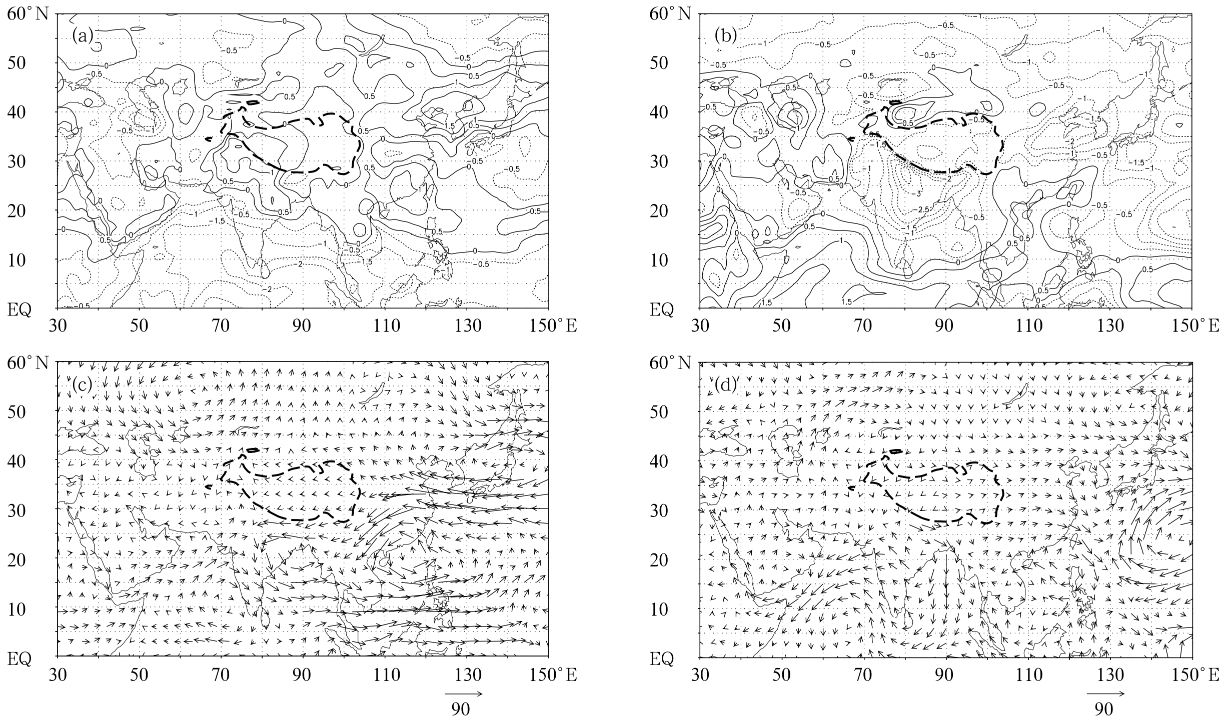

Fig. 9. Anomalies of (a, b) water vapor and (c, d) its fluxes, integrated from 500 to 10 hPa, relative to the climate mean of 1979–2010, over the South Asian region, during the boreal summer of (a, c) strong and (b, d) weak monsoon years.

namical and thermodynamic circulations, large differences of the total moisture and its flux are expected during the strong and weak monsoon years (see Fig. 9). During the strong monsoon years, the total water vapor anomalies appear positive over the whole TP region, but negative in the South Asian region and the tropical belt (Fig. 9a). The decreased westerly (or anomalous easterly) causes the water vapor to transport from the east to west (Fig. 9c), which results in a maximum over the western instead of the eastern part of the TP. This eastward moisture transport leads to a water vapor supply along the west-east direction, with the net flux value of 0.62×10^7 kg s^{-1} (see Table 2), which exceeds the negative moisture supply in the south-north direction and ensures an overall net moisture supply to the TP region from outside. In comparison with those during the monsoon active period (see Fig. 7 and Table 1), the TP moisture sink is also strengthened during the strong monsoon years, but mainly due to the transport by the decreased westerly (anomalous easterly) rather than by the enhanced southerly. During the weak monsoon years, large negative water vapor anomalies cover almost the whole TP and the South Asian region, with the maximum negative value less than –3.0 g kg^{-1} over the Bay of Bengal (Fig. 9b). Opposite to those in the strong monsoon years, an anticyclone forms over the Bay of Bengal. The anticyclone brings cold and dry air from the southwest of the TP, resulting in maximum negative water vapor anomalies over the Bay of Bengal (Fig. 9d). The strong divergence along the west-east direction (with a net negative flux value of -0.78×10^7 kg s^{-1}) is dominant during the weak monsoon years, suggesting weakening of the moisture supply from outside to the TP region.

To sum up, the TP moisture sink and related moisture transport are affected significantly by the evolution of the SASM, mainly through the adjustments in the moisture spatial distribution and transport.

Table 2. Total atmospheric moisture fluxes (10^7 kg s^{-1}) crossing the TP boundaries and the net flux over the whole TP, averaged for the boreal summer (JJA) of 1979–2010 (denoted by "Climate"), and the strong monsoon and weak monsoon years

Flux	West side	East side	South side	North side	West-east	South-north	Net
Climate	6.74	7.56	4.06	0.65	–0.82	3.41	2.59
Strong	–0.41	–1.03	–0.44	0.05	0.62	–0.49	0.13
Weak	–0.11	0.67	–0.13	–0.21	–0.78	0.08	–0.70

6. Conclusions

Based on the ECMWF ERA-Interim reanalysis data from 1979 to 2010, the spatial distribution and transport of total atmospheric moisture over the TP are analyzed, together with the associated impacts of the South Asian summer monsoon. From the climatological perspective, the TP acts as a total air moisture sink in summer, with a net moisture flux of 2.59×10^7 kg s^{-1}, mainly supplied from the southern boundary along the latitude belts over the Bay of Bengal and the Arabian Sea. The monsoon active/break periods and strong/weak monsoon years are defined by using different monsoon indices for comparisons. The influences of the SASM on the TP moisture sink and the related moisture transport are quantitatively examined, which shows great differences in the magnitudes and spatial distributions of moisture between monsoon active and break periods and between strong and weak monsoon years. For example, large positive moisture anomalies occur over the southwest of the TP and the Arabian Sea during the monsoon active period, resulting in a horizontal moisture inhomogeneity over the TP. The anomalous easterly transports the warm-moist air from the Bay of Bengal northward to the south edge of the TP and then extends westward, resulting in high moisture over the southwest of the TP. For the monsoon break period, the westerly anomalies bring cold-dry air from the continental regions to the southwest of the TP, causing large negative moisture anomalies there. For the whole TP region, the total moisture supply is more strengthened than the climate mean (c.a., an increase of 22% of the total moisture flux over the TP) during the monsoon active period, which is mainly contributed by the transport from the south boundary of the TP. However, during the monsoon break period, the strengthened moisture supply to the TP by the westerly anomalies as well as the weakened supply by the weakened southerly anomalies result in a slightly weakened total moisture supply to the TP. Similar conditions happen during the strong/weak monsoon years, i.e., the TP moisture sink is much strengthened/weakened in the strong/weak monsoon years. However, due to the different moisture distribution and transport, the contributions are mainly from the moisture transport in the west-east direction, which greatly differs from those during the monsoon active/break periods. Therefore, it can be concluded that the TP moisture and its transport can be greatly affected by the SASM evolution, through the adjustments in the moisture spatial distribution and transport.

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REFERENCES

Annamalai, H., and J. M. Slingo, 2001: Active/break cycles: Diagnosis of the intraseasonal variability of the Asian summer monsoon. *Climate Dyn.*, **18**, 85–102.

Bao, Q., J. Yang, Y. M. Liu, et al., 2010: Roles of anomalous Tibetan Plateau warming on the severe 2008 winter storm in central-southern China. *Mon. Wea. Rev.*, **138**(6), 2375–2384.

Chen, B., Z. Y. Wang, and Y. Sun, 2008: Interdecadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidence. *Int. J. Climatol.*, **28**(9), 1139–1161, doi: 10.1002/joc.1615.

—, X. D. Xu, S. Yang, et al., 2012: On the origin and destination of atmospheric moisture and air mass over the Tibetan Plateau. *Theor. Appl. Climatol.*, **110**, 423–435, doi: 10.1007/s00704-012-06141-y.

Ding, Y. H., and D. R. Sikka, 2006: Synoptic systems and weather. *The Asian Monsoon.* B. Wang, Ed., Springer-Verlag, Berlin, Heidelberg, 131–201.

Dong, H. P., S. X. Zhao, and Q. C. Zeng, 2007: A study of influencing systems and moisture budget in a heavy rainfall in low latitude plateau in China during early summer. *Adv. Atmos. Sci.*, **24**(3), 485–502, doi: 10.1007/s00376-007-0485-z.

Duan, A. M., and G. X. Wu, 2005: Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. *Climate Dyn.*, **24**(7–8), 793–807, doi: 10.1007/s00382-004-0488-8.

Fekete, B. M., C. J. Vörösmarty, and W. Grabs, 1999: Global composite runoff fields based on observed river discharge and simulated water balances. Technical Report No. 22, Global Runoff Data Center, Koblenz, 115.

—, —, —, 2000: UNH/GRDC composite runoff fields V1.0. Durham, NH: Complex Systems Research Center, University of New Hampshire, Koblenz, Germany: Global Runoff Data Center (GRDC). See http://www.grdc.sr.unh.edu/.

—, and P. V. Joseph, 2003: On breaks of the Indian monsoon. *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **112**, 529–558.

—, M. Rajeevan, and P. A. Francis, 2007: Monsoon variability: Links to major oscillations over the equatorial Pacific and Indian oceans. *Curr. Sci.*, **93**, 182–194.

—, P. N. Vinayachandran, and P. A. Francis, 2003: Droughts of the Indian summer monsoon: Role of clouds over the Indian Ocean. *Curr. Sci.*, **85**, 1713–1719.

—, —, —, et al., 2004: Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. *Geophys. Res. Lett.*, **31**, doi: 10.1029/2004GL019733.

Gadgil, S., Y. P. Abrol, and P. R. S. Rao, 1999: On growth and fluctuation of Indian foodgrain production. *Curr. Sci.*, **76**, 548–556.

—, and P. R. S. Rao, 2000: Farming strategies for a variable climate—A challenge. *Curr. Sci.*, **78**(10), 1203–1215.

Gao Dengyi, Zou Han, and Wang Wei, 1985: Influences of Brahmaputra river water passage on the precipitation. *Mountain Research*, **3**(4), 239–249. (in Chinese)

Goswami, B. N., and R. S. Ajaya Mohan, 2001: Intraseasonal oscillations and interannual variability of the Indian summer monsoon. *J. Climate*, **14**, 1180–1198.

—, R. S. Ajayamohan, P. K. Xavier, et al., 2003: Clustering of synoptic activity by Indian summer monsoon intraseasonal oscillations. *Geophys. Res. Lett.*, **30**(8), doi: 10.1029/2002GL016734.

Hsu, H. H., C. T. Terng, and C. T. Chen, 1999: Evolution of large-scale circulation and heating during the first transition of Asian summer monsoon. *J. Climate*, **12**, 793–810.

Krishnamurthy, V., and J. Shukla, 2000: Intraseasonal and interannual variability of rainfall over India. *J. Climate*, **13**, 4366–4377.

—, and Zhou W., 2012: Quasi-4-yr coupling between El Niño–Southern Oscillation and water vapor transport over East Asia–WNP. *J. Climate*, **25**, 5879–5891, doi: 10.1175/JCLI-D-11-00433.1.

—, Z. P. Wen, W. Zhou, et al., 2012: Atmospheric water vapor transport associated with two decadal rainfall shifts over East China. *J. Meteor. Soc. Japan*, **90**, 587–602, doi: 10.2151/jmsj.2012-501.

Li, X. Z., Z. P. Wen, and W. Zhou, 2011: Long-term change in summer water vapor transport over South China in recent decades. *J. Meteor. Soc. Japan*, **89A**, 271–282.

Li, C. F., and M. Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast. *J. Climate*, **9**, 358–375.

Liu, Y. M., Q. Bao, A. M. Duan, et al., 2007: Recent progress in the impact of the Tibetan Plateau on climate in China. *Adv. Atmos. Sci.*, **24**(6), 1060–1076, doi: 10.1007/s00376-007-1060-3.

Meehl, G. A., 1987: The annual cycle and interannual variability in the tropical Pacific and Indian Ocean region. *Mon. Wea. Rev.*, **115**, 27–50.

Rajeevan, M., S. Gadgil, and J. Bhate, 2010: Active and break spells of the Indian summer monsoon. *J. Earth System Sci.*, **119**(3), 229–247.

Sajani, S., S. N. Beegum, and K. K. Moorthy, 2007: The role of low-frequency intraseasonal oscillations in the anomalous Indian summer monsoon rainfall of 2002. *J. Earth Syst. Sci.*, **116**(2), 149–157.

Sato, T., and F. Kimura, 2007: How does the Tibetan plateau affect the transition of Indian monsoon rainfall? *Mon. Wea. Rev.*, **135**, 2006–2015, doi: 10.1175/MWR3386.1.

Simmonds, I., D. H. Bi, and P. Hope, 1999: Atmospheric water vapor flux and its association with rainfall over China in summer. *J. Climate*, **12**, 1353–1367.

Tao Shiyan, Chen Longxun, Xu Xiangde, et al., 1999: *Progresses of Theoretical Study in the Second Tibetan Plateau Atmosphere Scientific Experiment:*

Part I. China Meteorological Press, Beijing, 348 pp. (in Chinese)

—–, Q. Bao, B. Hoskins, et al., 2008: Tibetan Plateau warming and precipitation changes in East Asia. *Geophys. Res. Lett.*, **35**(14), L14702, doi: 10.1029/2008gl034330.

Wang, B., R. G. Wu, and K. M. Lau, 2001: Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific-East Asian monsoons. *J. Climate*, **14**, 4073–4090.

—–, V. O. Magaña, T. N. Palmer, et al., 1998: Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.*, **103**, 14451–14510.

Webster, P. J., and S. Yang, 1992: Monsoon and ENSO: Selectively interactive systems. *Quart. J. Roy. Meteor. Soc.*, **118**, 877–926.

Wu, G. X., Y. M. Liu, H. Bian, et al., 2012: Thermal controls on the Asian summer monsoon. *Sci. Rep.*, **2**, 404, doi: 10.1038/srep00404.36.

—–, X. Y. Shi, Y. Q. Wang, et al., 2008: Data analysis and numerical simulation of moisture source and transport associated with summer precipitation in the Yangtze River valley over China. *Meteor. Atmos. Phys.*, **100**(1–4), 217–231, doi: 10.1007/s00703-008-0305-8.

Xu Xiangde, Tao Shiyan, Wang Jizhi, et al., 2002: The relationship between water vapor transport features of Tibetan Plateau-monsoon “large triangle” affecting region and drought-flood abnormality of China. *Acta Meteor. Sinica*, **60**, 257–266. (in Chinese)

Yao, T. D., H. Zhou, and X. X. Yang, 2009: Indian monsoon influences altitude effect of δ^{18}O in precipitation/river water on the Tibetan Plateau. *Chinese Sci. Bull.*, **54**, 2724–2731, doi: 10.1007/s11434-009-0497-4.

Ye Duzheng, and Gao Youxi, 1979: *Meteorology of the Qinghai-Xizang Plateau*. Chinese Science Press, Beijing, 278 pp. (in Chinese)

Zhou Libo, Zou Han, Ma Shupo, et al., 2008: Study on inmpact of the South Asian summer monsoon on the down-valley wind on the north slope of Mt. Everest. *Geophy. Res. Lett.*, **35**, L14811, doi: 10. 1029/2008GL034151.

—–, —–, —–, et al., 2012: Observed impact of the South Asian summer monsoon on the local meteorology in the Himalayas. *Acta Meteor. Sinica*, **26**(2), 205–215, doi: 10.1007/s13351-012-0206-0.