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Moisture Transport over the Arabian Sea Associated with Summer Rainfall over Pakistan in 1994 and 2002

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ABSTRACT

In this study, we aimed to elucidate the critical role of moisture transport affecting monsoon activity in two contrasting summers over the Arabian Sea during the years 1994, a relatively wet year, and 2002, a relatively dry year. A comprehensive diagnostic evaluation and comparisons of the moisture fields were conducted; we focused on the precipitation and evaporation as well as the moisture transport and its divergence or convergence in the atmosphere. Monthly mean reanalysis data were obtained from the National Centers for Environmental Prediction (NCEP-I and -II). A detailed evaluation of the moisture budgets over Pakistan during these two years was made by calculating the latent energy flux at the surface ($E-P$) from the divergence of the total moisture transport. Our results confirm the moisture supply over the Arabian Sea to be the major source of rainfall in Pakistan and neighboring regions. In 1994, Pakistan received more rainfall compared to 2002 during the summer monsoon. Moisture flow deepens and strengthens over Arabian Sea during the peak summer monsoon months of July and August. Our analysis shows that vertically integrated moisture transport flux have a significant role in supplying moisture to the convective centers over Pakistan and neighboring regions from the divergent regions of the Arabian Sea and the Bay of Bengal. Moreover, in 1994, a deeper vertically integrated moisture convergence progression occurred over Pakistan compared to that in 2002. Perhaps that deeper convergence resulted in a more intense moisture depression over Pakistan and also caused more rainfall in 1994 during the summer monsoon. Finally, from the water budget analysis, it has been surmised that the water budget was larger in 1994 than in 2002 during the summer monsoon.

Key words: moisture flux, moisture convergence, convection, heavy rainfall

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1. Introduction

Heavy rainfall results from the moisture fluxes that originate from various sources during the summer monsoon over South Asia. Moreover, these moisture resources are critically important to the study of monsoon rainfall. During the summer monsoon season in Southeast Asia, moisture is transported from the Indian Ocean and the Arabian Sea. Warm, moist, low-level winds bring moisture from the Arabian Sea and the Bay of Bengal (BOB) into the hot subcontinent during the South Asian summer monsoon (Pant and Kumar, 1997; Webster et al., 1998; Houze et al., 2007). Furthermore, during the summer monsoon, convection occurs frequently in locations where moisture flows into the subcontinent from the Arabian Sea and the BOB (Medina et al., 2010). This convection results in heavy downpours every year in South Asia. The strong societal impacts of the Indian summer monsoon rainfalls can be seen each year in populated regions of South Asia. As demonstrated by Krishnan et al. (2009), the year-to-year variations of the Indian summer monsoon rainfall affect densely inhabited regions, and slight changes in its strength have massive

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societal impacts (Izumo et al., 2008). Over the Arabian Sea, the atmosphere–ocean interaction elucidates the precipitation over India, including heavy rainfall (Saha and Bavadekar, 1973; Saha, 1974). Shukla and Misra (1977) suggested that a substantial fraction of the moisture, precipitating as monsoon rainfall, comes from the Arabian Sea. Murakami et al. (1984) pointed out that evaporation over the Arabian Sea makes a critical contribution to the moisture supply for monsoon rainfall. Pisharoty (1965) computed the water budget over the Arabian Sea and concluded that the influx of water vapor across the equator was smaller than the evaporation over it. Cadet and Reverdin (1981) studied the moisture budget on a monthly mean basis over the Arabian Sea and the BOB during the summer monsoon, and they found that the 70% of water vapor comes from the Southern Hemisphere while 30% comes from the Arabian Sea. However, the Arabian Sea is a critically important source of moisture fluxes across the western coast of India, causing heavy rainfall there (Saha and Bavadekar, 1977; Rakhecha and Pisharoty, 1996). According to Ninomiya and Kobayashi (1999), the Indian Ocean warm pool is the major moisture source of monsoon rainfall. As demonstrated by Webster (1994), the warm pool is a region where an understanding of ocean–atmosphere interactions is critically important. Trenberth (1991) studied the moisture budget using the global analyses of the European Centre for Medium-range Weather Forecasts (ECMWF) and reported pragmatic results. The moisture budget can be calculated to some extent; it can be computed by measuring vertical moisture tendencies that exhibit divergence. Vertical moisture tendencies and divergence can show a balance of evaporation and precipitation (Trenberth and Guillemot, 1995, 1998). Furthermore, Trenberth and Guillemot (1996, 1998) used the NCEP moisture field precipitation and evaporation to assess the moisture transport and its divergence in the atmosphere.

In this study, we conducted an analysis of the moisture transport over the Arabian Sea during the summer monsoon for the years 1994 and 2002. These two years were chosen because of their contrasting monsoon activities, that is, 1994 was a relatively wet years, and 2002 was a relatively dry year. Heavy monsoon rainfall has the devastating impact on the human activities in Pakistan and neighboring regions. We aimed to trace the genesis of the heavy summer monsoon rainfall through data analyses to elucidate the reasons that more rainfall occurred over Pakistan in 1994 compared to 2002.

In the present study, we aimed to answer these questions by evaluating the vertically integrated moisture fluxes and their divergence or convergence between the two contrasting monsoon seasons. We investigated the role of moisture transport over the Arabian Sea on Pakistan during the summer monsoon. Specifically, we focused on the monthly mean water budgets and precipitation over Pakistan. Here, we present the results of our analyses of vertically integrated moisture fluxes and their divergence only for the months of June, July, and August (JJA); the water budget and precipitation results pertain to the period from January to December 1994 and similarly for the year 2002.

The data sources and methodology are presented in section 2. In section 3, vertically integrated moisture fluxes and our analysis of its divergence, as well as a comparison of the moisture budget and precipitation of the respective years 1994 and 2002 are presented. A conclusion is provided in section 4.

2. Data and methods

The data, which consisted of monthly mean of different meteorological parameters from the National Centers for Environmental Prediction (NCEP-I & II) and the National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al., 1996; Kistler et al., 2001), were used in this study. As presented by Flohn et al. (1965) and Rasmusson (1972), over West Africa the total moisture fluxes related to the summer monsoon are dominated by the wind; therefore, we approximated the moisture fluxes using the monthly mean winds. The parameters included in this data (6-h intervals) were horizontal and meridional wind, specific and relative humidity, and surface pressure (resolution 2.5° longitude by 2.5° latitude). Similarly, the resolution of NCEP latent heat net flux (6-h intervals) was

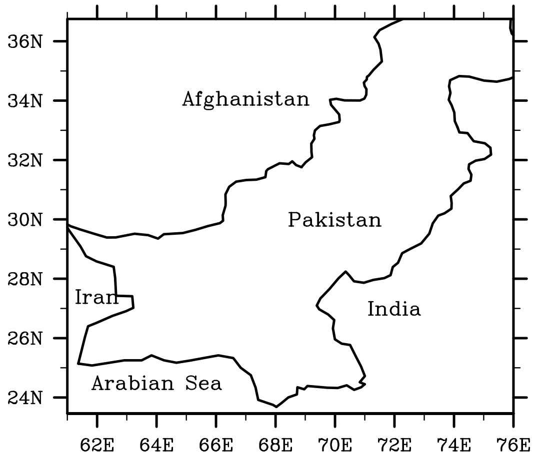

Fig. 1. Map of the study domain.

approximately 1.875° longitude by 1.875° latitude. Another source of precipitation data was the Global Precipitation Climatology Project (GPCP) (Huffman et al., 1997); these data had a resolution of 1° longitude by 1° latitude. In this study, the area of Pakistan is defined as the region 23°46′–36°75′N, 61°–75°5′E (Fig. 1).

The water vapor conservation equation was adopted from Newell et al. (1972a) and Mo and Higgins (1996):

$$\frac{\partial W}{\partial t} = -D(\boldsymbol{Q}) + E - P + R\,, \tag{1}$$

This equation states that the change of the total precipitation water in column W is equal to the difference between the evaporation (E) and the sum of precipitation (P) and the vertically integrated moisture flux divergence $D(\boldsymbol{Q})$ and the runoff R. For long-term means, the tendency term is small, and if we ignore the runoff R and other forms of liquid and frozen water in the atmosphere as suggested by Trenberth and Guillemot (1998), then Eq. (1) becomes

$$E - P = D(\boldsymbol{Q})\,, \tag{2}$$

where

$$D(\boldsymbol{Q}) = \nabla \cdot \boldsymbol{Q}\,. \tag{3}$$

The vertically integrated moisture flux ($\boldsymbol{Q}$) can be expressed as

$$\boldsymbol{Q} = \frac{1}{g}\int_0^{p_{\rm s}} q\boldsymbol{V}\,dp\,, \tag{4}$$

where q is the specific humidity, p is the pressure, $p_{\rm s}$ is the surface pressure, $\boldsymbol{V}$ is the wind vector, and g is the acceleration due to gravity. The vertical integration of Eq. (4) was performed from the surface to 300 hPa. The missing data above 300 hPa had a nearly negligible influence on the result due to the concentration of water vapor in the lower troposphere. As suggested by Fasullo and Webster (2003) regarding the vertically

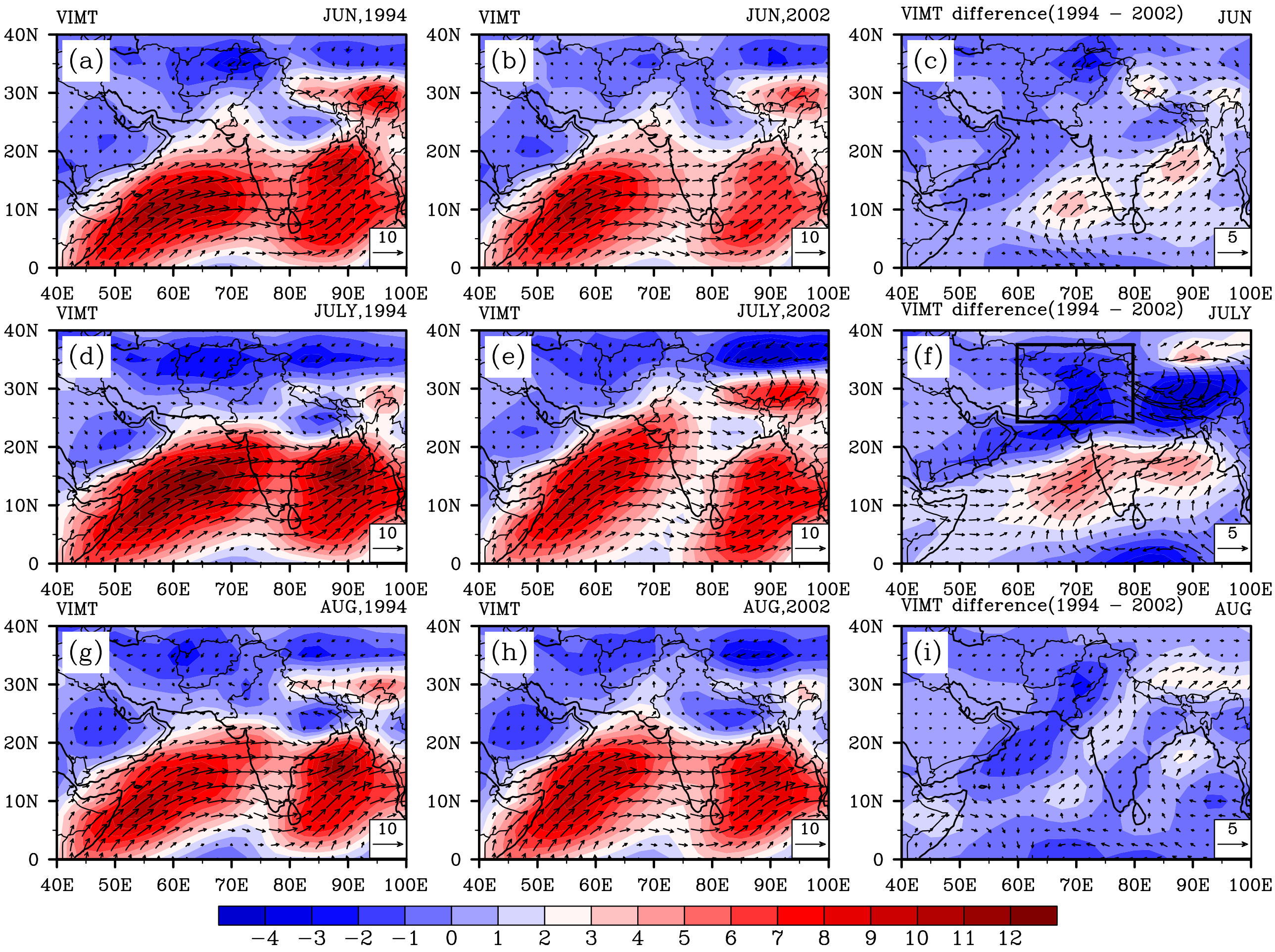

Fig. 2. (a–i) Comparison of monthly mean vertically integrated moisture total transport (VIMT, shaded, unit: kg m^{-1} s^{-1}) and VIMT difference (shaded) between 1994 and 2002, superimposed with vertically integrated wind component vectors.

integrated moisture transport above 300 hPa, the specific humidity is negligible above this level and is not part of the reanalysis (Kalnay et al., 1996). Moreover, they posit that above 300 hPa the specific humidity has a negligible impact on the calculation of total vertically integrated moisture transport.

However, Eqs. (3) and (4) can be evaluated from the analyses, and we conducted a systematic evaluation of the monthly fields by calculating the vertically integrated moisture fluxes and their divergence. In addition, both the terms on the left-hand side of Eq. (2) calculated from the 6-h integrated NCEP reanalysis data and the GPCP data were used to determine the water budget of both the selected years. The rate of evaporation was calculated using the latent heat net flux at the surface as described by Trenberth and Guillemot (1998). In addition, for the region considered in the present study, we computed the total vertically integrated moisture flux convergence, horizontal fluxes, and meridional net fluxes, respectively, in time series averaged over the total area of Pakistan.

3. Results and discussion

3.1 *Vertically integrated moisture transport*

The vertically integrated total moisture fluxes plotted from surface pressure level to the 300-hPa level are shown in Figs. 2a–i for the contrasting years 1994 and 2002 during the summer monsoon season. The main moisture transports occurred from southwest to north, with strong wind components toward India and Pakistan from the Arabian Sea, and the main moisture transport occurred from southeast to north from the Bay of Bengal during the rainy period of both years. These vertically integrated moisture transports vectors supplied moisture toward the convective centers over Pakistan and neighboring regions from the divergent regions of the Arabian Sea and the BOB and contri-

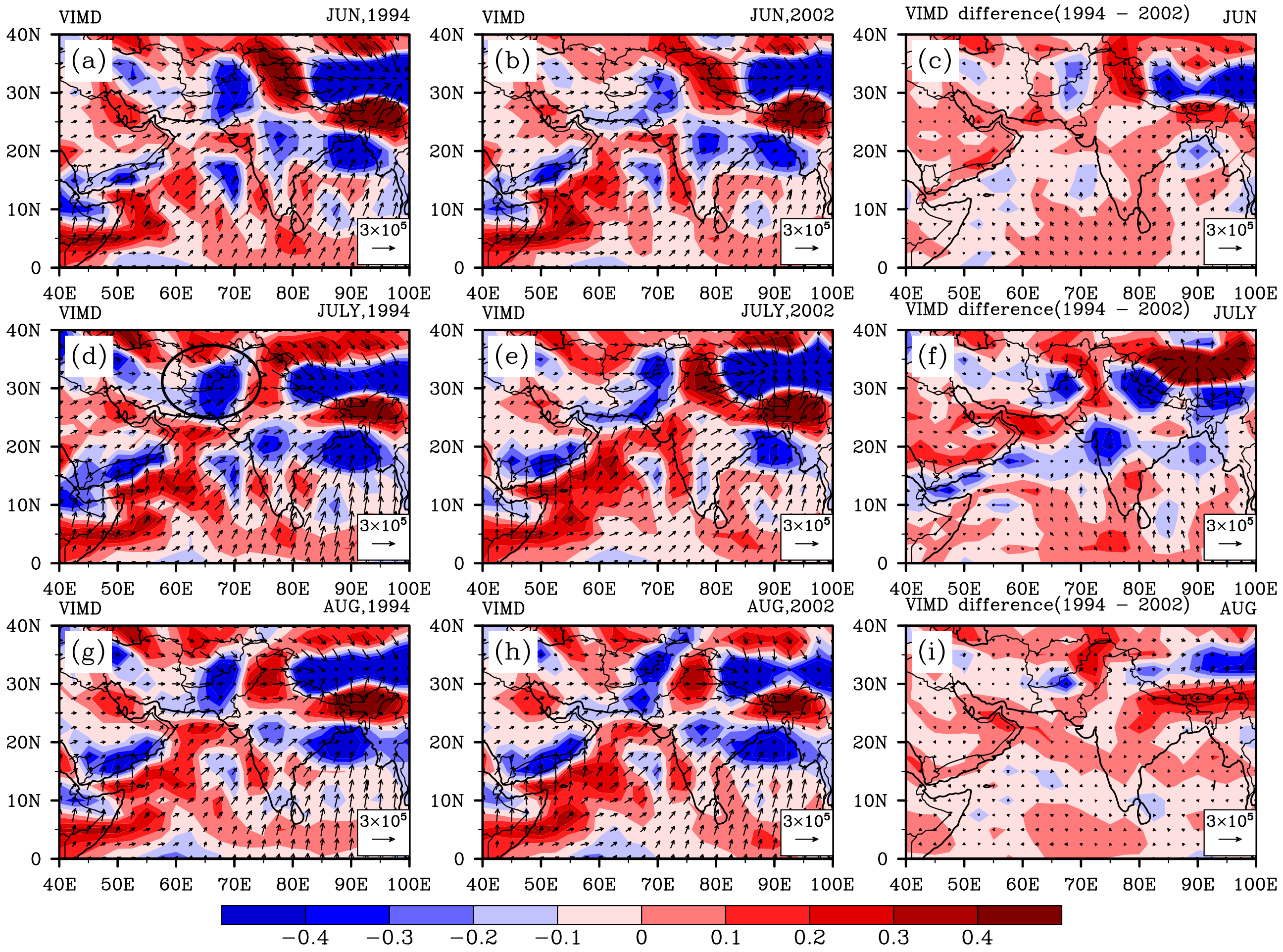

Fig. 3. (a–i) Comparison of monthly mean vertically integrated moisture flux divergence or convergence (VIMD, shaded) and VIMD difference (shaded) between 1994 and 2002, superimposed with divergent wind component vectors (units: 10^{-5} kg m^{-2} s^{-1}).

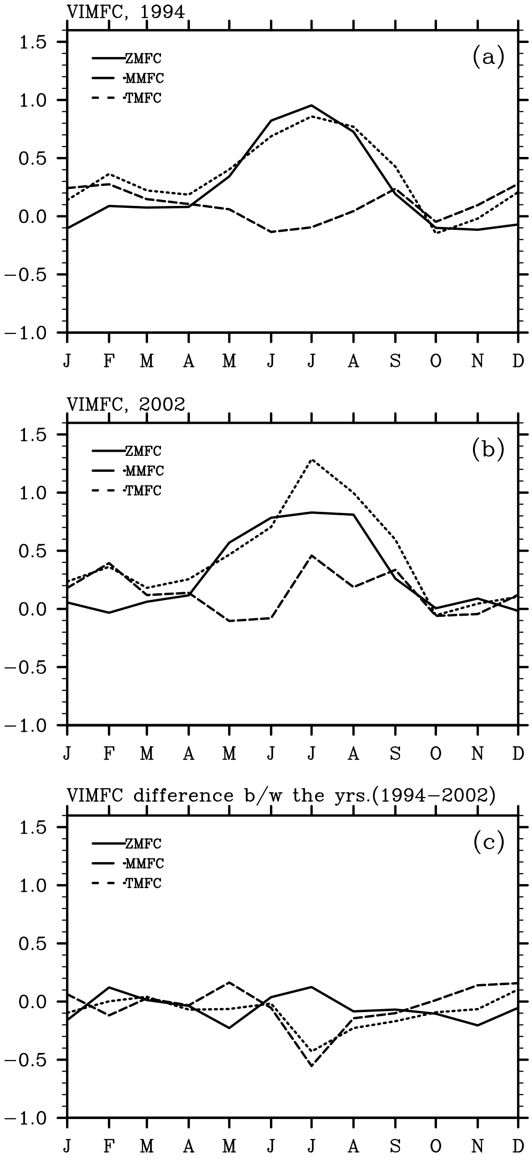

Fig. 4. (a–c) Monthly mean total vertically integrated zonal moisture flux convergence (ZMFC) (units: 10^{-5} kg m^{-2} s^{-1}), meridional moisture flux convergence (MMFC), and the total moisture flux convergence (TMFC), including their differences between 1994 and 2002, over the total averaged area of Pakistan (23°46′N–36°75′N, 61°–75°5′E).

buted to moisture convergence over the study area (Fig. 2). The qualitative analysis of moisture transport agreed well with the study of Trenberth and Guillemot (1998), in which they found a strong northward moisture flow from the Southern Hemisphere subtropics via the Somalian jet into India and Southeast Asia during the Asian summer monsoon season. Furthermore, Fasullo and Webster (2003) described in detail the vertically integrated moisture transport directly associated with the primary monsoon driving force. Additionally, they indicated that the centers of deep convection near western India, the BOB, and Southeast Asia (where moisture convergence is stronger) are supplied with moisture transported from the divergent regions of the Southern Hemisphere and the Arabian Sea. From our analysis, it is obvious that the moisture divergence in 1994 is stronger, especially in July (Fig. 2d) over the Arabian Sea and the BOB compared to the months of June and August. On the other hand, in 2002 no such intense activity was apparent in the months of summer monsoon. These results show that moisture transport was larger in 1994 compared to 2002. Notably, by calculating the difference between the years 1994 and 2002, a stronger northwestward moisture flow moving along the Himalayas was well depicted over the BOB, especially in the month of July (Fig. 2f, indicated by a black rectangle). This may have enhanced the convergence over the northern part of Pakistan and neighboring regions. Additionally, from southwest to north, stronger flow over the Arabian Sea furnished moisture to Pakistan and contributed more to the deep convection over that region in 1994 compared to 2002. In addition to contributing to moisture convergence over Pakistan and neighboring regions, the eastward vertically integrated moisture transport vectors (larger in 1994 than 2002) were responsible for bringing moisture toward the major convective centers of the monsoon from the divergent regions of the Arabian Sea and the BOB (Fig. 2).

3.2 *Vertically integrated moisture divergence/convergence*

The vertically integrated moisture divergence fluxes were calculated and plotted from surface pressure level to 300 hPa for the summer months (JJA) of the selected years. As evident in Fig. 3, the vertically moisture flux divergence was stronger over the Arabian Sea during JJA for both years. Notably, in July and August divergence flux was stronger compared to that in June over the Arabian Sea of both years. These results indicate that more moisture transport toward Pakistan and neighboring regions was due to moisture pumped from the Arabian Sea by strong southwesterly winds. During the summer monsoon (JJA), deep convergence was also located over the central and southwestern parts of Pakistan, the Tibetan Plateau, and the southeastern part of India, Bangladesh, and the BOB of both years. But the convergence is stronger in July and August 1994 over Pakistan (Fig. 3d, black circle), and resulted in more rainfall during these periods in 1994 compared to the summer months (JJA) of 2002. Moreover, the convergence over the central and southwestern parts of Pakistan was significantly different between the studied years. Furthermore, the moisture flux divergence difference (1994–2002) was determined between the years. From the field analysis, we calculated that the convergence was located well over the central and southwest parts of Pakistan in all months of summer monsoon, but it was stronger over Pakistan especially in the month of July (Fig. 3f, black circle).

However, the more meaningful analysis emerged from the moisture flux convergence for our study region because moisture convergence is directly linked to vertical motion and therefore rainfall (Zheng and Eltahir, 1998). The time series plots (Fig. 4), the horizontal moisture flux convergence, meridional and the total moisture flux convergence including the difference between the years, were calculated for the total averaged area of Pakistan. As shown in Fig. 4a, the horizontal and total vertically integrated moisture flux convergence was positive in the summer monsoon period (JJA), but meridional flux convergence were negative during the same period. Moreover, the total vertically integrated moisture flux convergence as well as meridional convergence was negative in the months of (JJA), but the horizontal moisture flux convergence was positive during the same period (Fig. 4c). These results show that the horizontal wind in 1994 was much larger compared to 2002, which brought more moisture into the convection centers over Pakistan. The magnitude of zonal fluxes was, in general, larger than that of meridional fluxes as suggested by Zheng and Eltahir (1998). However, the strong moisture convergence over the study area led to more rainfall in 1994. Similarly, in 2002 (Fig. 4b), the zonal, meridional (approximately positive in JJA), and total vertical moisture flux convergence had positive values during the summer monsoon that related to weaker monsoon rainfall compared to 1994.

3.3 *Water budget*

To examine the difference between evaporation and precipitation ($E-P$) fields over Pakistan and the Arabian Sea for the contrasting monsoon years, we computed the water budget values on a monthly scale for the contrasting monsoons over the total averaged area of Pakistan (Figs. 5 and 6). Figures 5d and g shows

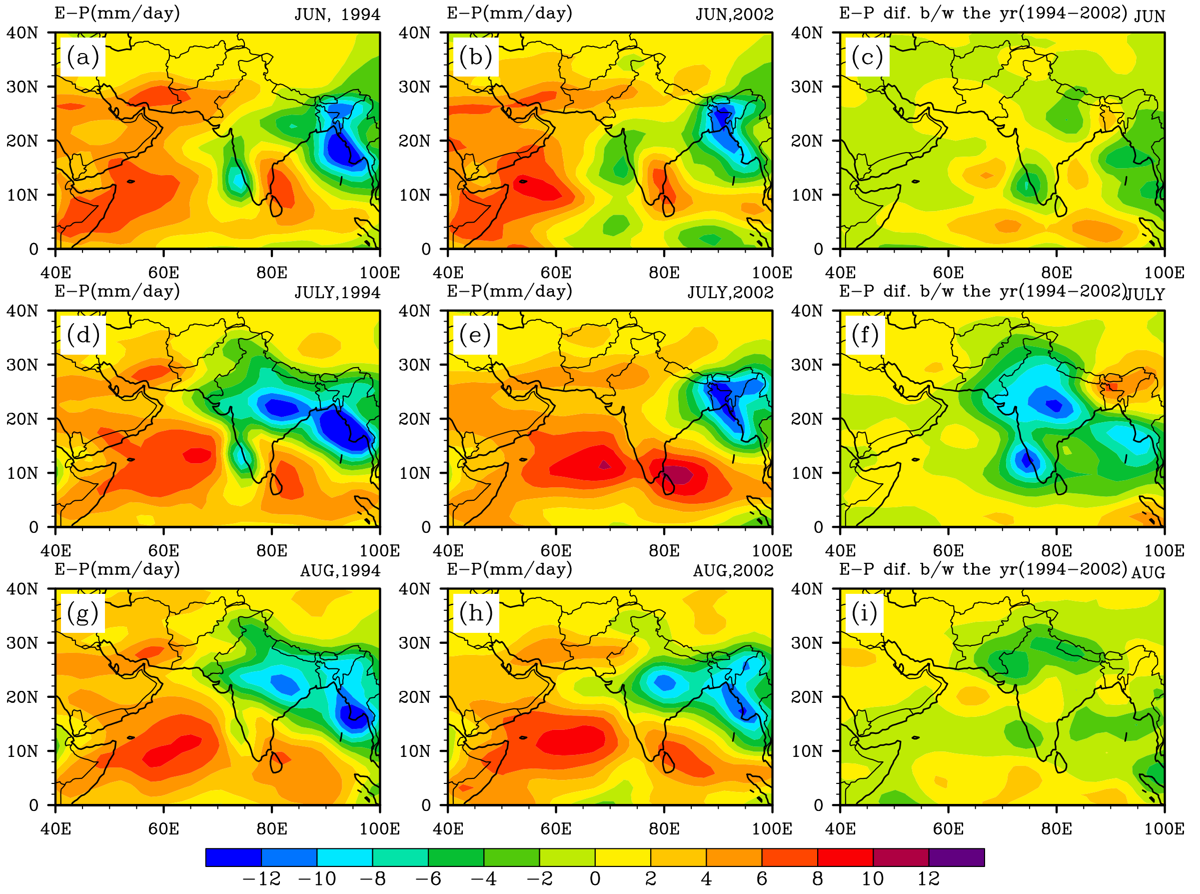

Fig. 5. (a–i) Comparison of monthly mean evaporation minus precipitation (E–P, mm d^{-1}), including E–P difference between 1994 and 2002 during the summer monsoon period (JJA).

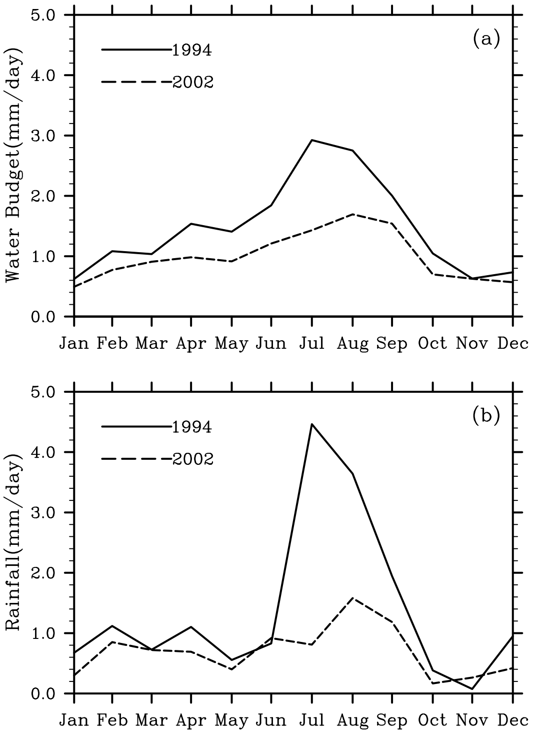

Fig. 6. (a, b) Comparison of monthly mean water budget (mm d^{-1}) and monthly mean GPCP precipitation (mm d^{-1}) between the contrasting years, over the total averaged area of Pakistan (23°46–36°75′N, 61°–75°5′E).

the negative values of $E-P$ over Pakistan and neighboring regions, but $E-P$ was positive in the summer months (JJA) of the comparative year 2002. From the analyses of above these figures it can be deduced that the precipitation was much more than the evaporation over the study area in 1994 during the monsoon season. On the other hand, positive values of $E-P$ over the Arabian Sea show that evaporation was larger than precipitation in both studied years. Moreover, the divergence of the moisture fluxes accounts for the bulk of the $E-P$ quantity over the Arabian Sea. The maximum precipitation occurred especially in the months of July ($\sim$ 4.4 mm d^{-1}) and August (3.6 mm d^{-1}), whereas the water budget in July (2.8 mm d^{-1}) and August (2.4 mm d^{-1}) is also greater in 1994 (Figs. 6a and b). Conversely, in 2002, the precipitation and water budget were very small during the summer monsoon.

3.4 *Precipitation*

The rainfall time series plot (Fig. 6b) was drawn over the total averaged area of Pakistan using the GPCP rain gauge-satellite combined dataset for both the years. The precipitation on a monthly basis for the years 1994 and 2002 were computed and compared. Heavy rainfall occurred, particularly in the months of July, August, and also September 1994 compared to the year 2002. In addition, heavy rainfall represents much more latent heat that was released into the study area, and this latent heat was instrumental in creating a feedback effect that caused divergent flows, resulting in more moisture transport. This complex effect increased the amount of moisture over Pakistan and neighboring regions in 1994 relative to 2002. Therefore, it is remarkable that the monsoon activity was at its maximum during the months of July and August 1994 in Pakistan. This study was conducted independently for both years, and the analyses do not pertain to the combined study.

4. Conclusion

The most important results of this study are those for vertically integrated moisture transport, which was larger in 1994 than in 2002 over the Arabian Sea and the BOB during the summer monsoon. Specifically, this transport was at its maximum during the months of July and August 1994 compared to the same months in 2002. However, it is clear that more moisture was supplied from the Arabian Sea by strong southwesterly winds toward Pakistan and neighboring regions in 1994 relative to 2002. Moreover, from the analysis of the peak periods of summer monsoon in 1994, the moisture flow over the Arabian Sea strengthened and deepened. The moisture convergence existed during the summer monsoon over Pakistan, but it was stronger in 1994 than in 2002. Additionally, these moisture convergence developments were enhanced by the strong southwesterly winds over the northern Arabian Sea. Abundant moisture was located over Pakistan, which has a critical role in enhancing convection as well as cloud formation, thunderstorms, and rainfall in 1994. On the other hand, no such activities occurred in 2002. Further, in July 1994 the moisture convergence was stronger than in June and August 1994. Therefore, more rainfall occurred in July 1994 compared to the July 2002 summer monsoon. Similarly, the water budget was obviously larger during the month of July 1994 relative to July 2002.

This case study confirms that the moisture flux from the Arabian Sea plays a dominant role in monsoon rainfall over Pakistan and neighboring regions. Finally, our study also highlights the importance of Arabian Sea moisture transport during the summer monsoon.

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