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ORIGINAL PAPER

Characteristics of precipitation pattern in the Arabian Peninsula and its variability associated with ENSO

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Abstract A detailed analysis of the precipitation pattern of the Arabian Peninsula and its temporal and spatial variability were investigated in connection with ENSO. Also, the variability of precipitable water and circulation characteristics was examined for a better understanding. The study was carried out utilizing TRMM rainfall, NOAA OLR, precipitable water, wind, and humidity data sets. It is evident that Northern Arabian Peninsula receives high amount of rainfall mainly during winter and early summer (November to April) in connection with the passage of mid tropospheric westerly troughs and Mediterranean low-pressure systems. But the precipitation pattern over the Southern Arabian Peninsula reveals that it is mainly during summer (May to October) due to the Arabian Sea branch of monsoon and moisture laden cross equatorial LLJ flow. Further, analysis was carried out to assess the influence of ENSO on the precipitation pattern. Thorough analysis was carried out on the circulation pattern using velocity potential in the lower troposphere to understand the features of variability on Hadley/Walker circulation in relation with organized convection. El Nino and La Nina have profound influence on the rainfall pattern in a different manner in the Northern and Southern Arabian Peninsula. Large-scale circulation pattern as derived from velocity potential indicates that shifting of the rising/sinking limb of Hadley/Walker circulation associated with the ENSO causes variability in precipitation.

Keywords Precipitation pattern · Circulation · El Nino and La Nina · Arid region

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Introduction

Precipitation is the most important weather parameter which is directly involved in all activities of human beings. The Arabian Peninsula is located in the extreme southwestern corner of the Asian continent. According to the climate classification by Thornthwaite, most of the regions in the Arabian Peninsula are either arid or semi arid (Mandaville 1990; Barth 1998). The climate of the Arabian Peninsula is extremely dry as well as arid and receives very small amount of annual rainfall. Also, it lacks lakes and permanent rivers and due to this reason Arabian Peninsula is not conducive for large-scale agricultural production.

A knowledge of spatial precipitation pattern during different months is required for a proper hydrological planning of the Arabian Peninsula. As it is situated in the arid or semi-arid zone, analysis of precipitation climatology and its various teleconnections like ENSO is to be investigated. A few investigations were carried out on climatological features in the Arabian Peninsula (Boer 1997; Barth and Steinkohl 2004). Babu et al. (2011) made a comprehensive analysis of the rainfall climatology of the Middle East and identified two areas of low rainfall, one in Jordan and adjoining areas and the other in the southern part of Saudi Arabia. Varikoden et al. (2010) analyzed the intensity of rainfall in different classes and their contribution to the total seasonal rainfall. They validated TRMM rain rate over land region using station rainfall data and found a significant correlation between them. Their study confirms that TRMM rain rate data can be used over land regions also for studying rainfall characteristics. Variability of rainfall due to local or global reasons affects adversely on all aspects of life in the Arabian Peninsula due to the low amount of rainfall.

Rainfall analysis and several climatology studies have been conducted by many researchers over the Arabian Peninsula (Soltani et al. 2014, 2015; Molanejad et al. 2015; Barth 1999). Yatagai et al. (2008) constructed an algorithm to develop a daily gridded precipitation data set for the Middle East region. Evans (2010) investigated the ability of a regional climate model to simulate the climate of the Middle East and effect of global warming on the precipitation. The spatial contribution of the rainy days in different parts of Iran and its variability were attempted by Nazaripour and Mansouri Daneshvar (2014). Recent trends in climate extreme have been analyzed by Zhang et al. (2005).

Wang (2002) studied the atmospheric circulation cells associated with El Nino southern oscillation using different global data sets. He reported that the equatorial zonal Walker circulation cell is weakened during the warm phase of ENSO. The meridional Hadley circulation cell in the eastern Pacific shows rising of air in the tropics, flowing poleward in the upper troposphere, sinking in the subtropics, and returning back to the tropics in the lower troposphere. Price et al. (1998) analyzed the possible link between El Nino and precipitation in Israel. They reported an enhanced precipitation during the winter season associated with El Nino. Mariotti et al. (2002)) reported a seasonally varying relationship between Euro-Mediterranean rainfall and ENSO. Their analysis revealed that during an El Nino, Western Mediterranean rainfall has a 10 % increase in the autumn. Ashok et al. (2007) found out a different type of El Nino occurrence, called El Nino-Modoki andbrought out their tele-connection. Depending on the season, the effect of El Nino-Modoki is found to be opposite to that of the conventional ENSO. Ashok and Yamagata (2009) explained further characteristics of El Nino-Modoki. They argued that the associated atmospheric effect due to the sea surface warming and cooling in the tropical Pacific seems to be changing. Increased global warming is attributed to the shifts in the El Nino phenomenon. The literature on ENSO brings out the fact that the variation in the equatorial Pacific SST and hence the ENSO affects global circulation. Hence, studies on the variability of rainfall over the Arabian Peninsula due to global factors are important, especially in view of the ENSO cycle. Thus, it is imperative to investigate the influence of ENSO on global circulation and associated rainfall pattern over the Arabian Peninsula.

The impact of North Atlantic Oscillation on the meteorological parameters over the Arabian Peninsula was investigated by Cullen et al (2002) and Tabari et al. (2013). Also, the influence of Madden Julian Oscillation over Arabian Peninsula has been examined by Nazemosadat and Ghaedamini (2010) and Barlow et al. (2005).In this analysis, characteristics of precipitation pattern in the Arabian Peninsula are studied in relation with the variability of precipitable water, humidity, and circulation characteristics. Further, variability of precipitation is investigated in association with El Nino and La Nina. Features of circulation responsible for the rainfall variability associated with the ENSO cycle are studied using velocity potential to identify shifting of rising/sinking limb of circulation associated with the global phenomena.

Data and methodology

The climatology of rainfall and precipitable water for different months were analyzed. The rainfall analysis was made utilizing the Tropical Rainfall Measuring Mission (TRMM) data (http://www.esrl.noaa.gov/psd/data/gridded/). The TRMM rainfall data is utilized to study the spatial and temporal distribution of rainfall over the Arabian Peninsula. The TRMM rain rate data are available at a temporal resolution of 3 h and spatial resolution of $0.25° \times 0.25°$ latitude-longitude grid (Kummerow et al. 1998). Further, details about the algorithm are available at http://trmm.gsfc.nasa.gov/3b42.html. We derived daily rainfall from the 3-hourly rain rates, and monthly composites were prepared for the period 1999 to 2011, and rainfall climatology was investigated utilizing TRMM data for twelve years.

Precipitable water, specific humidity, and wind data sets were utilized from NCEP-NCAR reanalysis product (Kalnay et al. 1996) that is available at a spatial resolution of $2.5° \times 2.5°$. The horizontal wind at 700 hPa was utilized to obtain velocity potential for understanding the divergence pattern. The climatology of precipitable water and specific humidity on a monthly basis for the Arabian Peninsula were studied using the data for a period of 30 years (1981–2010). Various stations in different parts of the Arabian Peninsula were selected in order to understand the spatial variability of rainfall on a daily basis for the entire year. For this, Tehran (35° 40'N and 51° 26'E) was selected to represent the Northern part, Amman (31° 57'N and 35° 57'E) for Northwestern part, Riyadh (24° 41' N and 46° 42'E) for central part, Muscat (23° 36'N and 58° 37'E) for Eastern part, and Sanaa (15° 21' N and 44° 12' E) for Southwestern part. Figure 1 gives the geographical locations of the stations. Features of daily march of rainfall for 2005 as a typical normal case over the five stations are discussed in detail. Year 2005 is a normal year without El Nino or La Nina.

To understand the role of warming or cooling of ocean surface in the equatorial Pacific on the rainfall and the circulation pattern over the Arabian Peninsula, a thorough examination is made on the circulation pattern during El Nino and

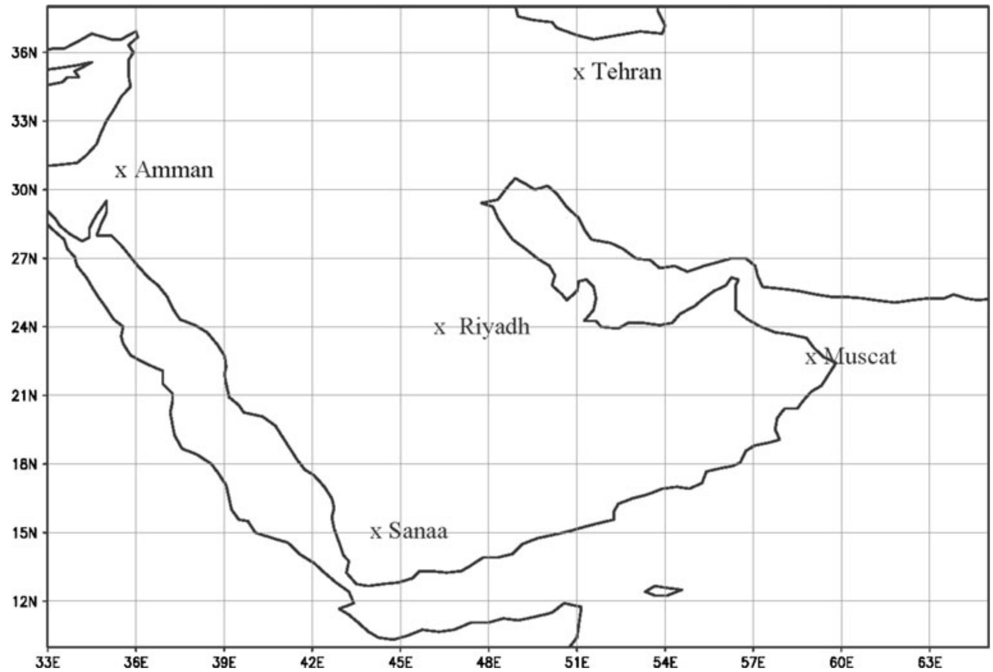

Fig. 1 Map of the Arabian Peninsula with location of stations

La Nina years. On the basis of monthly mean values of SST at Nino 3.4 region, El Nino and La Nina years are identified. Table 1 gives the Ocean Nino Index obtained from CPC NOAA for the period 2000 to 2010. The table gives standard deviation of SST at Nina 3.4 region, average for the 3 months from the long term mean. The italicized ones show the period of warm SST anomaly and El Nino whereas the bold and italicized ones show that of La Nina. The bold values are the ones in which SST anomaly is more than +0.5 or −0.5 which can indicate the cooling and warming. In addition to this, WMO report that contains detailed information about the evolution and intensity of ENSO events (WMO 2002, 2010) was also utilized for the study. Accordingly, 2002 was taken as representative El Nino year and 2010 as La Nina year. Low values of OLR (less than 200 W m^{-2}) indicate the presence of organized convection in the atmosphere; hence, OLR is used as a proxy for organized convection. OLR anomaly for El Nino and La Nina years is employed to assess the rainfall variability. Further, daily march of specific humidity up to 500 hPa for the selected stations during El Nino and La Nina years is made. In addition, velocity potential derived from the horizontal wind is used to assess the spatial pattern of horizontal divergence in the lower troposphere. This is used as a tool to identify the shifting of rising/sinking limb of Hadley/Walker circulation during different phases of the ENSO cycle.

Table 1 Ocean Nino Index (standard deviation of SST for the 3 months at Nina 3.4 region) obtained from CPC NOAA for the period 2000 to 2010

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2000	**−1.6**	**−1.4**	**−1.1**	**−0.9**	**−0.7**	**−0.7**	**−0.6**	**−0.5**	**−0.6**	**−0.7**	**−0.8**	**−0.8**
2001	**−0.7**	**−0.6**	**−0.5**	−0.3	−0.2	−0.1	0	−0.1	−0.1	−0.2	−0.3	−0.3
2002	−0.2	−0.1	0.1	0.2	0.4	*0.7*	*0.8*	*0.9*	*1.0*	*1.2*	*1.3*	*1.1*
2003	**0.9**	**0.6**	0.4	0	−0.2	−0.1	0.1	0.2	0.3	0.4	0.4	0.4
2004	0.3	0.2	0.1	0.1	0.2	0.3	**0.5**	**0.7**	**0.7**	**0.7**	**0.7**	**0.7**
2005	**0.6**	**0.6**	**0.5**	**0.5**	0.4	0.2	0.1	0	0	−0.1	−0.4	−0.7
2006	−0.7	−0.6	−0.4	−0.2	0.0	0.1	0.2	0.3	**0.5**	**0.8**	**0.9**	**1.0**
2007	**0.7**	0.3	0	−0.1	−0.2	−0.2	−0.3	**−0.6**	**−0.8**	**−1.1**	**−1.2**	**−1.3**
2008	**−1.4**	**−1.3**	**−1.1**	**−0.9**	**−0.7**	**−0.5**	−0.3	−0.2	−0.2	−0.3	−0.5	−0.7
2009	−0.8	−0.7	−0.4	−0.1	0.2	0.4	**0.5**	**0.6**	**0.7**	**1.0**	**1.2**	**1.3**
2010	*1.3*	*1.1*	*0.8*	*0.5*	0	−0.4	***−0.8***	***−1.1***	***−1.3***	***−1.4***	***−1.3***	***−1.4***

The italicized ones show the period of warm SST anomaly and El Nino whereas the bold and italicized ones show that of La Nina. The bold values are the ones in which SST anomaly is more than +0.5 or −0.5 which can indicate the cooling and warming

Results and discussions

Twelve-year composite of monthly precipitation derived using TRMM from January to December is shown in Fig. 2. The monthly rainfall pattern depicts that northern region such as Persian Gulf, Iran, Qatar, and parts of Iraq is getting 2–6-mm rainfall during the months November, December, January, February, March, and April. The rainy season for Riyadh is mainly April and May with rain amounts 1–2 mm. Rest of the months, the region between 40–50° E and 15–35° N is completely dry. Over the Southern region, up to 20° N heavy rainfall occurs from May onwards due to the effect of southwest monsoon. The heavy rainfall is observed over Djibouti, Yemen region, East African continent including parts of Ethyopia. Rest of the region is dry with feeble rainfall (less than 0.5 mm). The winter rainfall during October to February and early summer during March to May over the Northern Arabian Peninsula is due to the remnants of Mediterranean Sea low-pressure systems which move from West to East as westerly trough visible at mid troposphere about 500 hPa. The precipitation during May–September is contributed from the Arabian Sea branch of southwest monsoon and cross equatorial flow with moisture from Arabian Sea. On the basis of rainfall climatology, over the Arabian Peninsula, Northern region gets rain during the winter and spring (October–April) whereas the Southern region gets more rain during the summer monsoon season (May–September).

Figure 3 represents the climatology of annual rainfall for the Arabian Peninsula. The central region between 18° N to 25° N which includes parts of Oman, Saudi Arabia, Yemen, Egypt, northern Sudan, Jordan, Israel, and a small area in Iran receive very feeble amounts of rainfall (<50 mm per year). It is evident that the heavy rainfall bands with more than 500 mm are distributed either north of 30° N or south of 15°N in the area near the border of Iran and Iraq and adjoining area of Turkey in the north (more than 400 mm). Ethiopia and Eastern Sudan also receive relatively high amount of annual rainfall (more than 500 mm).

Figure 4 gives the monthly composites of precipitable water from January to December. It shows that the precipitable water value over the Arabian Peninsula is less than 20 kgm^{-2} except in the southern region during monsoon season (June to

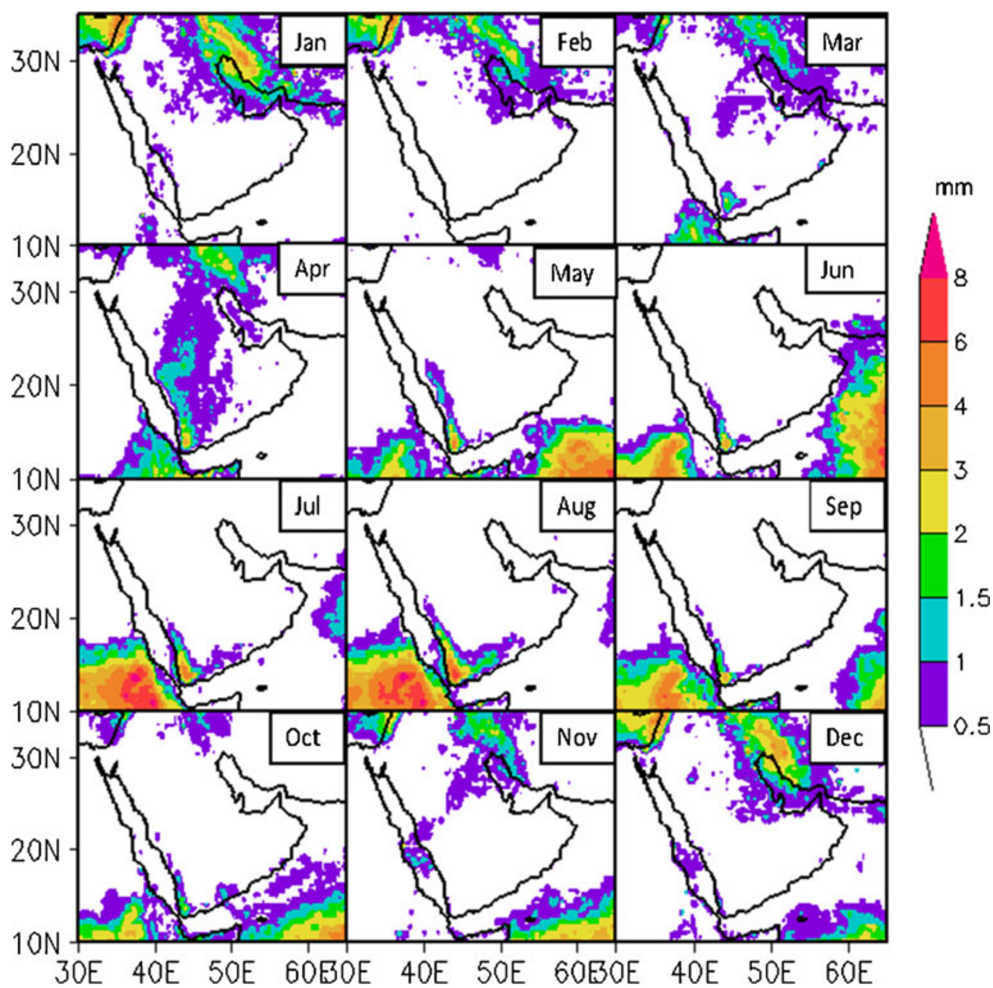

Fig. 2 Composite of daily rainfall (mm) over the Arabian Peninsula for January to December

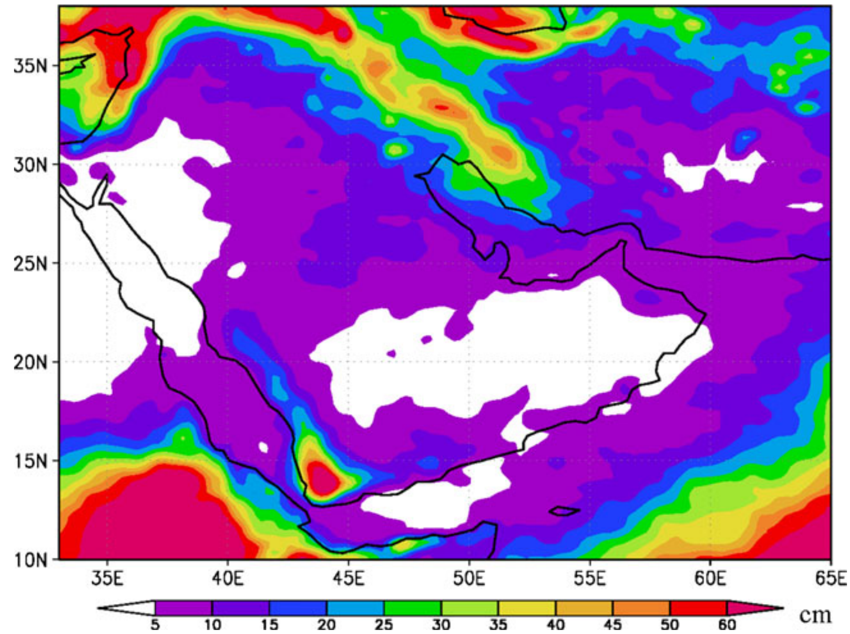

Fig. 3 Composite of annual rainfall (cm) for the Arabian Peninsula

September). Most of the Northern Arabian Peninsula is with value less than 10 kgm^{-2}. The amount of precipitable water is feeble towards West and North from Oman. Insufficient moisture content due to the sinking of the air parcels originating

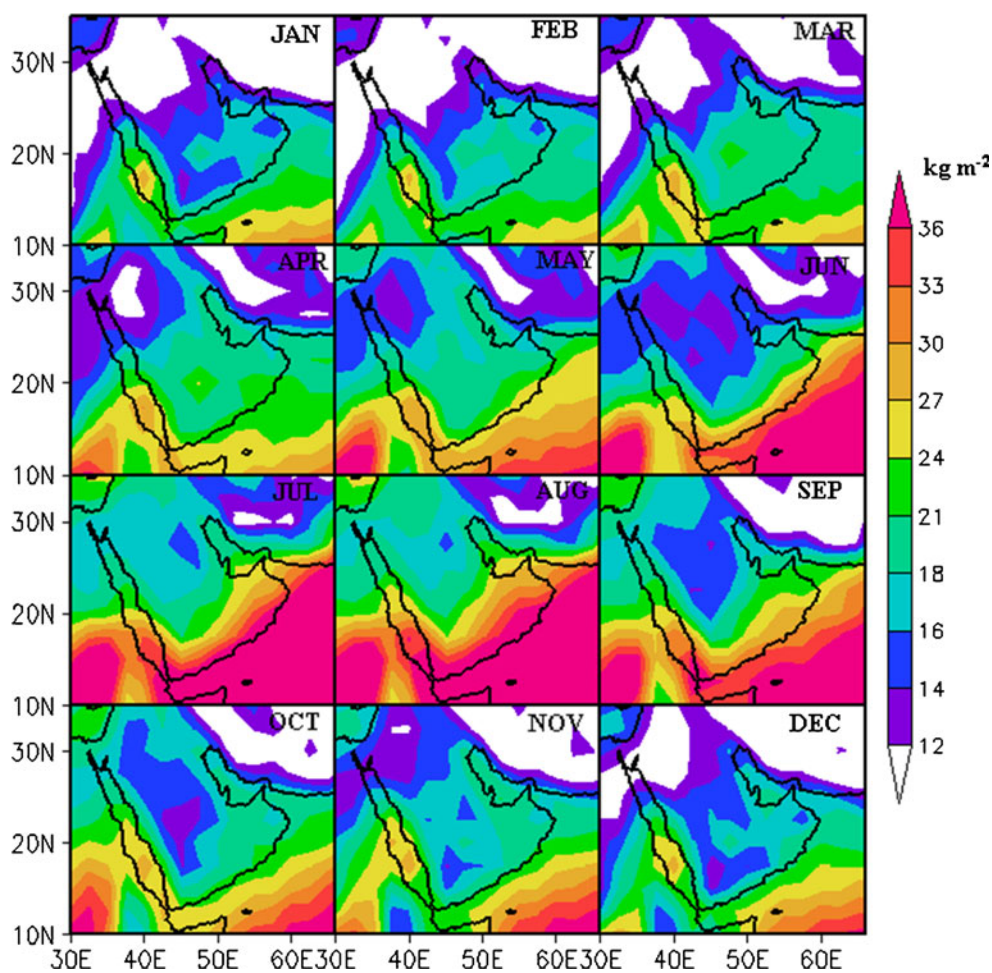

Fig. 4 Climatology of precipitable water (kg m^{-2}) for January to December

from Hadley cell can be the reason for the very small value. Presence of water bodies such as Mediterranean Sea, Black Sea, Caspian Sea, Arabian Sea, Persian Gulf, and Red Sea does not help in increasing the precipitable water and moisture content over the region.

Figure 5 depicts the climatology of annual precipitable water over the Arabian Peninsula. It is evident that most of the precipitable water amount is confined to the southern region. The precipitable water decreases from 33 to 10 kgm^{-2} towards north. The precipitable water content is more towards the region of Arabian Sea. The precipitable water content is more than 30 kg m^{-2} over the Somalia region caused by the moisture laden wind from the Arabian Sea. In this context, it is to be noted that even though the annual mean climatology of rainfall shows high values over the Northern Arabian Peninsula, the same for precipitable water shows less than 20 kgm^{-2}. But there should be some mechanisms in the atmosphere to produce rainfall, and precipitable water content is a necessary but not sufficient parameter to produce rainfall.

Variability on organized convection in different months over the Arabian Peninsula during normal, El Nino, and La Nina years are studied on the basis of long-term average of OLR (Fig. 6), OLR anomaly during an El Nino year (Fig. 7) and OLR anomaly during a La Nina year (Fig. 8). The OLR climatology pattern indicates two regions of feeble organized convection in the Arabian Peninsula. One is in the Northern region during December, January, February, and March (with an average OLR value less than 220 Wm^{-2}) and the other is a small area in the Southwestern region during June, July, August, and September. OLR anomaly during many El Nino and La Nina years is examined, and representative cases are presented in Fig. 7 for El Nino (2002) and Fig. 8 for La Nina (2010). During the El Nino year (Fig. 7), negative anomaly of OLR is found during January and February with a value of 20 Wm^{-2} in certain regions in the Southern Arabian Peninsula. Even though this negative anomaly value does not bring the OLR below 200 Wm^{-2} in an average pattern, it is capable of lowering the OLR value for individual days. These low OLR values indicate presence of organized convection. However, positive anomaly occurred in most of the areas during May, June, and July.

The features of OLR anomaly (Fig. 8) during the La Nina year (2010) are strikingly different from that of the El Nino year. OLR anomaly was positive and extended large area in the northern Arabian Peninsula between October and March. It is interesting to note that negative OLR anomaly also prevailed over a small area in the Southern or Southeastern sector during May, June, July and August. A comparison is made with features of OLR anomalies during 2002 (El Nino year) and during 2010 (La Nina year). The positive and negative anomalies reverse in association with the ENSO cycle. Instead of negative anomaly over the Northern region during the winter season of El Nino year, positive anomaly occurred during La Nina year. During the summer season, by the influence of El Nino, positive OLR anomaly occurred, and the sign of the anomaly changed due to the La Nina, especially in the Southern Arabian Peninsula.

Figure 9 depicts the daily rainfall observed for the different stations in the Arabian Peninsula from January to December in the year 2005. Year 2005 is considered as a typical normal year without El Nino or La Nina such that it can represent the general features of rainfall over the stations. The stations selected for the analysis are Tehran, Amman (Northern part)

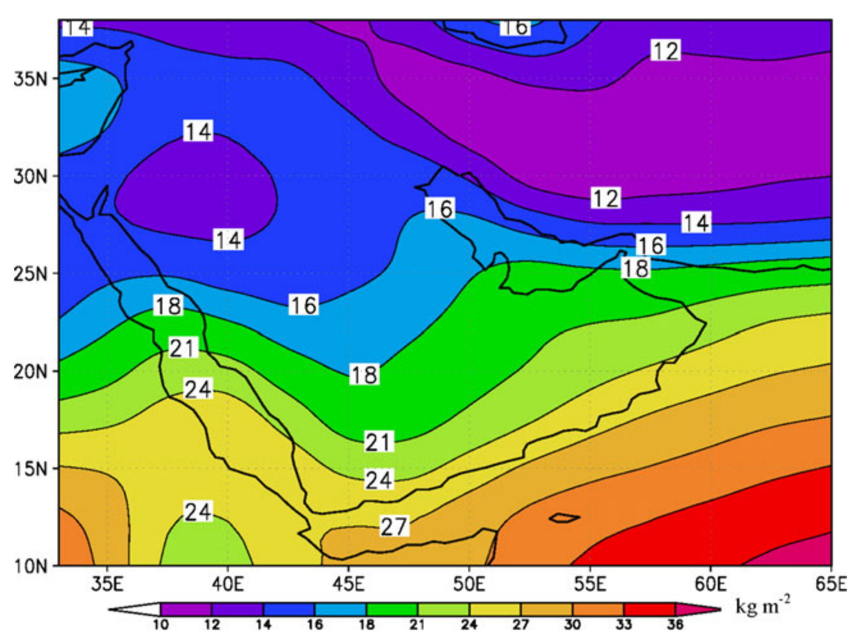

Fig. 5 Climatology of annual precipitable water (kg m^{-2}) for the Arabian Peninsula

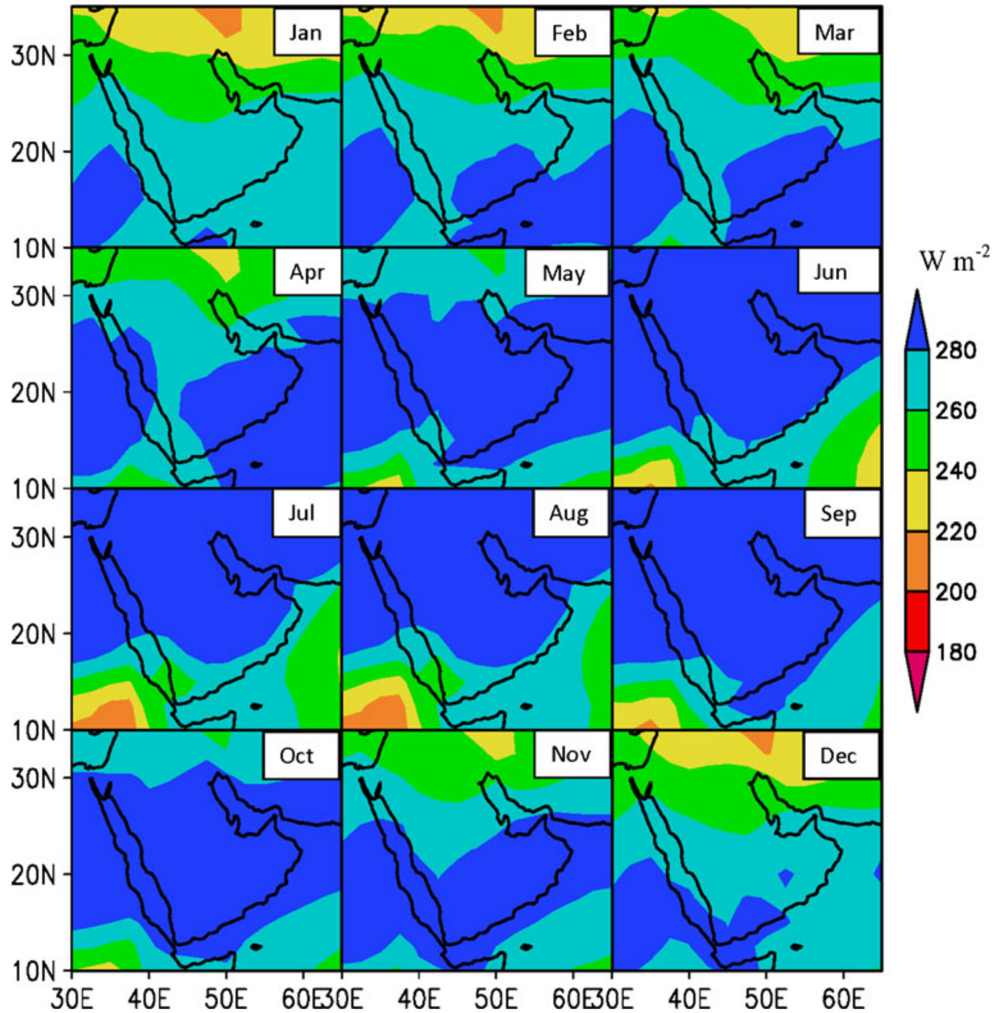

Fig. 6 Climatology of OLR (W m^{-2}) for January to December

Riyadh, Muscat (Middle part), and Sanaa (Southern region), representing different parts of the Arabian Peninsula.

From the figure, Tehran receives rainfall mainly in January to April with 10–20 mm and from August to December less than 10 mm. The station Amman has rainfall periods only in January to April and late October to December with less than 10 mm. The same values for Riyadh are also observed. It is interesting to note that no rainfall is received over Tehran and Amman during the summer season as the monsoon system does not have any effect over the Northern Arabian Peninsula. Riyadh station gets a few rain spells during spring (March and April) and winter (November, December, January, and February). The amount of rainfall and the number of rain events are small over Riyadh.

Muscat is a dry place with less amount of rainfall (<5 mm). It gets rainfall during winter, spring, and summer, even though the amount of rainfall and the number of rainy days are small. Sanaa gets considerable amount of precipitation with 10–20 mm during March to August and less rain in the other months. From the analysis, we found that Northern stations receive rain mainly in winter and spring. On the other hand, the rain over the southern region occurs during the summer season. It is difficult to identify rainy periods of certain locations in the Arabian Peninsula East such as Oman, U.A.E, most parts of Saudi Arabia, and Eastern Yemen.

We examined the time-height intensity diagram (Hovmoller diagram with height in the y axis on a daily basis) of specific humidity for the five stations in five panels during El Nino year (Fig. 10) and La Nina year (Fig. 11). During El Nino year, the specific humidity value is found to decrease in the Southern Arabian Peninsula (bottom panel, Sanaa). But the specific humidity signature over the Northern station (top panel) during the winter season of El Nino is not remarkable. The effect of El Nino is not strong to influence Mediterranean systems that pass over the Northern Arabian Peninsula during winter season to increase the specific humidity values. The effect of La Nina is felt in the southern region of the Arabian Peninsula (bottom panel, Sanaa) during the summer season. The specific humidity values are found to increase near the surface, and the high values extended to a large atmospheric column during the summer season of La

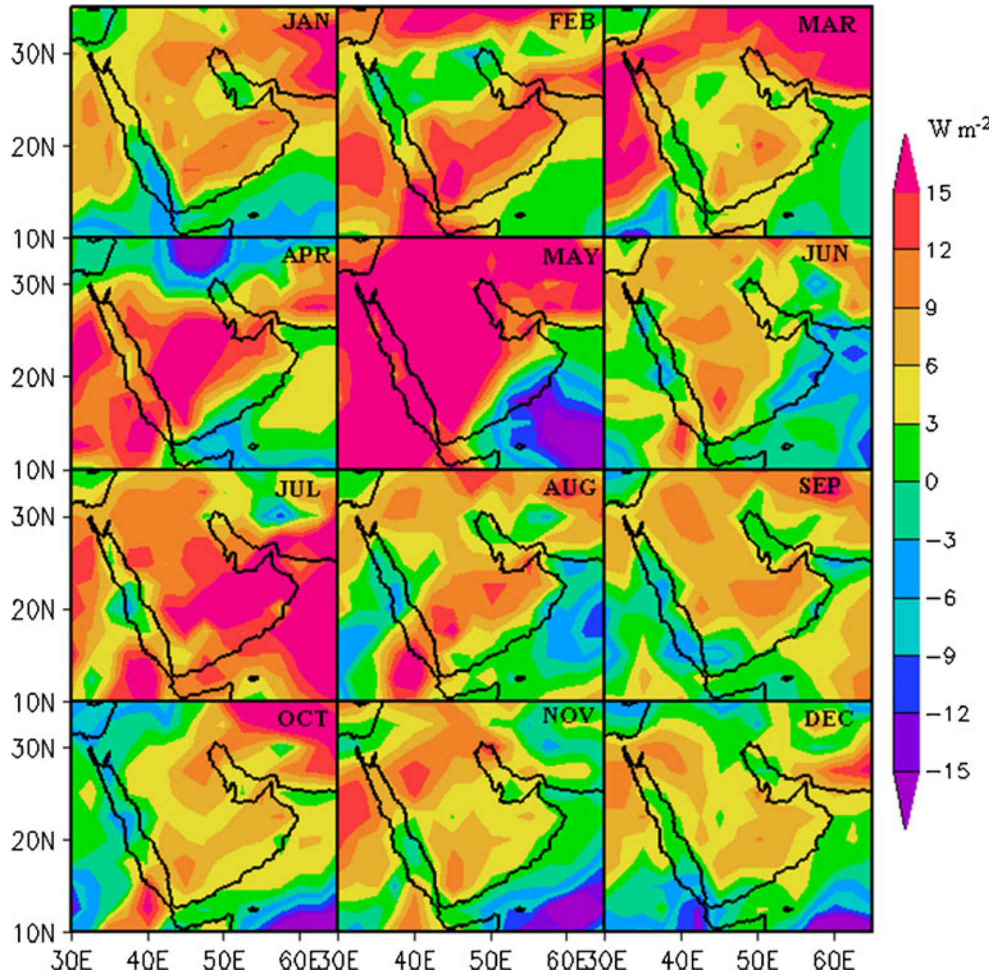

Fig. 7 OLR anomaly (W m^{-2}) during El Nino year for January to December

Nina year over the Southern Arabian Peninsula (Sanaa station). This is in agreement with OLR anomaly.

In order to study the effect of ENSO cycle on a global circulation pattern over the Arabian Peninsula, we examined velocity potential and stream function at 700 hPa during June–July of El Nino and La Nina years. Figure 12 represents the velocity potential and stream function during June–July 2002 for El Nino year. The horizontal divergence as indicated by the velocity potential value is slightly more during El Nino year. This is due to increase in sinking motion associated with the large-scale circulation. It is difficult to have rainfall associated with the monsoon organized convection as the air in the Arabian Peninsula is warm and dry due to the sinking motion. During the winter season of El Nino, the velocity potential value is slightly less over a few areas in the Northern Arabian Peninsula. Thus, there is a possibility to have more cloudiness associated with the passage of a Mediterranean system during the winter season of El Nino. The OLR pattern during the winter and summer of El Nino year agrees with the features inferred from circulation pattern.

Figure 13 represents the velocity potential and stream function during June–July 2010 for La Nina year. The location of maximum velocity potential during the La Nina year is shifted from its normal location. In addition, the velocity potential values over the Southern Arabian Peninsula during June–July of La Nina year is less compared to normal year. So, the possibility for formation of rainfall due to passage of the remnants of organized convection associated with the monsoon system is more during summer (June to September) of La Nina year. Generally, rain events in the Southern Arabian Peninsula are caused mainly by the monsoon system. During summer (June to September) of La Nina year, the conditions are favorable for cloudiness, as the intensity of sinking limb is weak over the region. On the other hand, central and northern Arabian Peninsula has relatively high values of velocity potential, especially during winter. Thus, winter (November to February) of La Nina year is not favorable for cloudiness in the central and northern Arabian Peninsula. This can bring down the rainfall associated with the passage of a Mediterranean system as the air over the Arabian Peninsula is dry and warm.

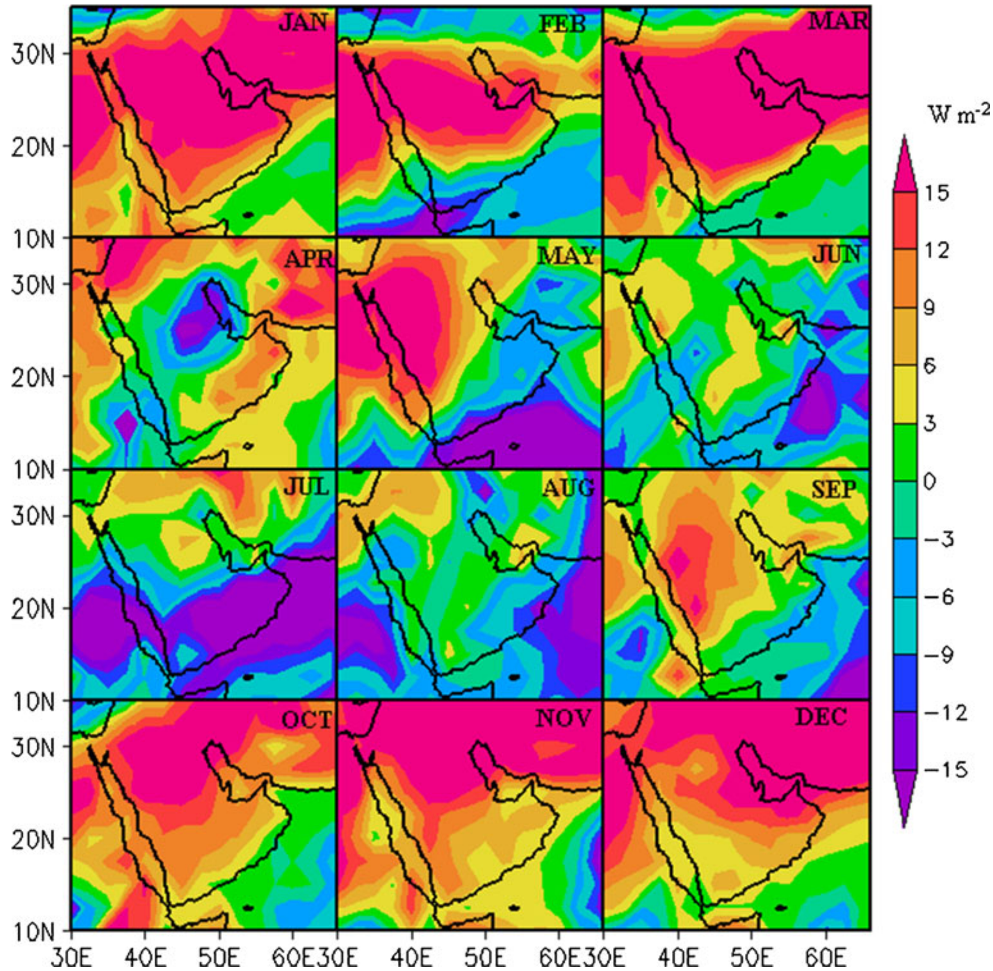

Fig. 8 OLR anomaly (W m^{-2}) during LaNina year for January to December

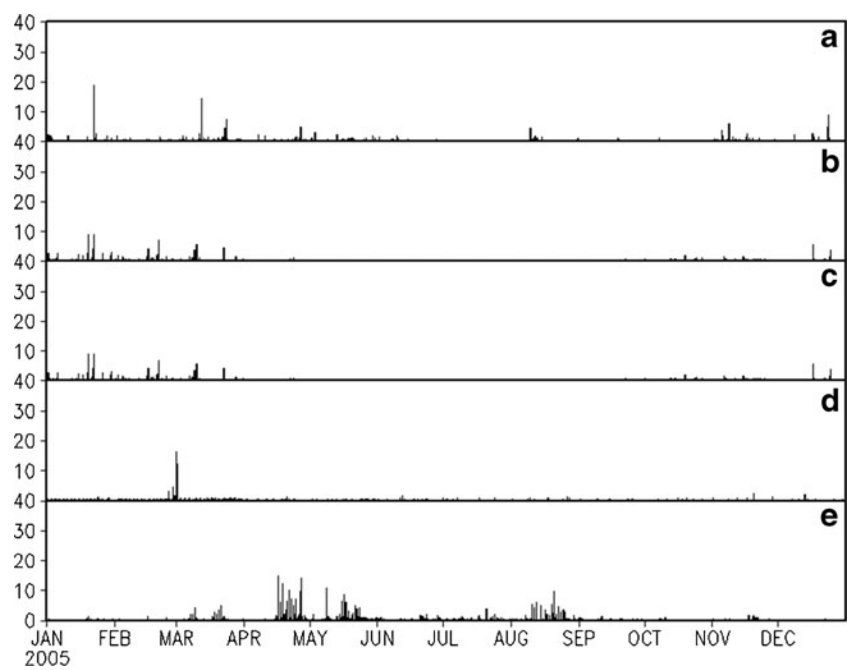

Fig. 9 Daily march of rainfall (mm) on an annual basis over different stations in the Arabian Peninsula for 2005 during 1st January to 31st December over **a** Tehran, **b** Amman, **c** Riyadh, **d** Muscat and **e** Sanaa

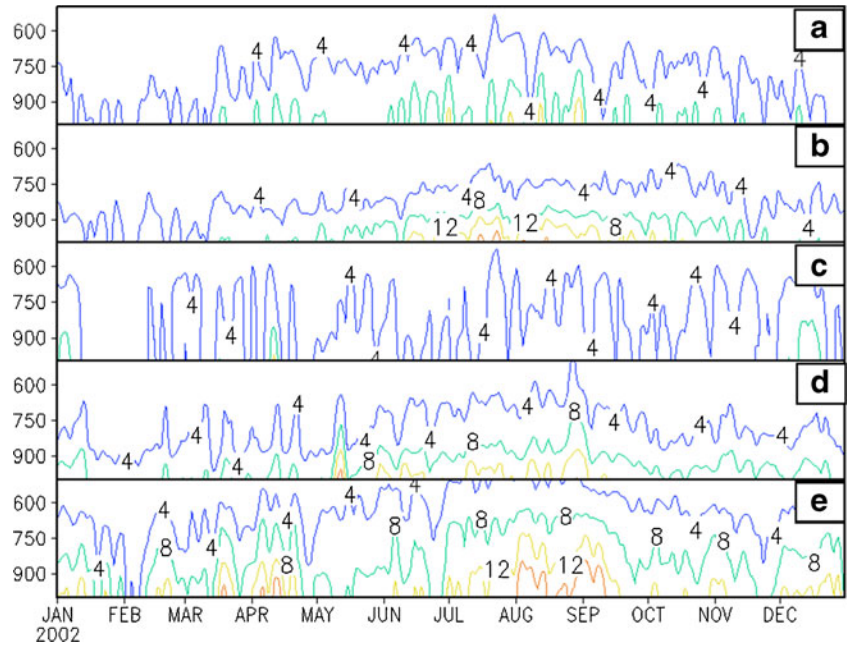

Fig. 10 Height-time intensity diagram of specific humidity (g kg^{-1}) for El Nino year during 1st January to 31st December over **a** Tehran, **b** Amman, **c** Riyadh, **d** Muscat and **e** Sanaa

The rainfall pattern varies during El Nino and La Nina years. As discussed in the previous section, the southern region gets rainfall mainly during summer season (June to September) associated with monsoon system, and Northern region gets rainfall during winter and spring (November to April) associated with passage of Mediterranean system. According to the location of sinking limb of circulation during ENSO cycle, the rainfall pattern in the Arabian Peninsula varies. The effect is different in the northern and southern areas and during summer and winter seasons.

Conclusions

The study investigated the climatology of daily precipitation in different parts of the Arabian Peninsula and also influence of El Nino/La Nina on the precipitation. It is found that the south, central, and western Arabian Peninsula get small amount of rainfall in most of the months. Two areas of low annual rainfall in the Arabian Peninsula are Northeastern Egypt and Southern part of Saudi Arabia. Air parcels rise from the equatorial belt and sink in the subtropical high near the Arabian Peninsula. By this sinking motion, warm dry air is

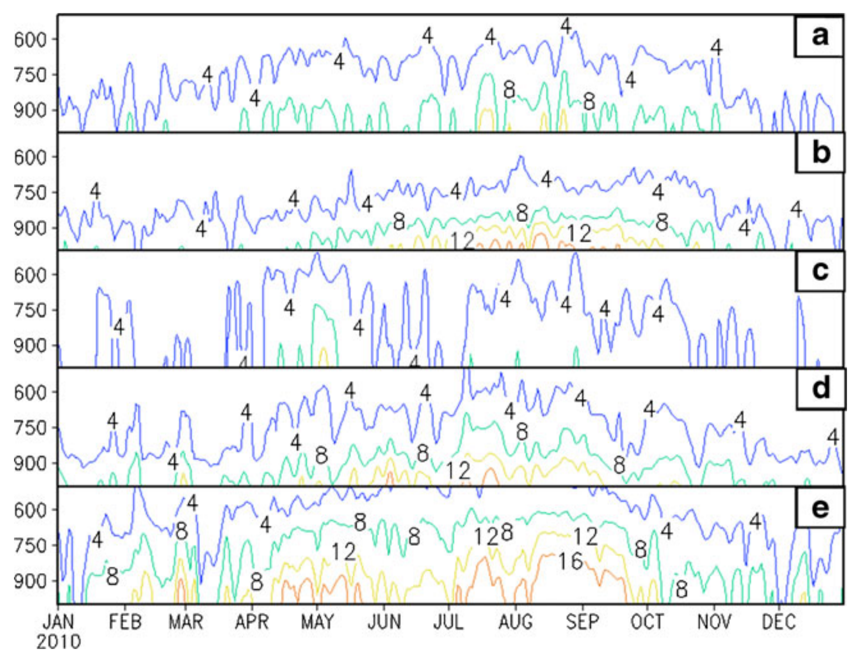

Fig. 11 Height-time intensity diagram of specific humidity (g kg^{-1}) for La Nina year during 1st January to 31st December over **a** Tehran, **b** Amman, **c** Riyadh, **d** Muscat and **e** Sanaa

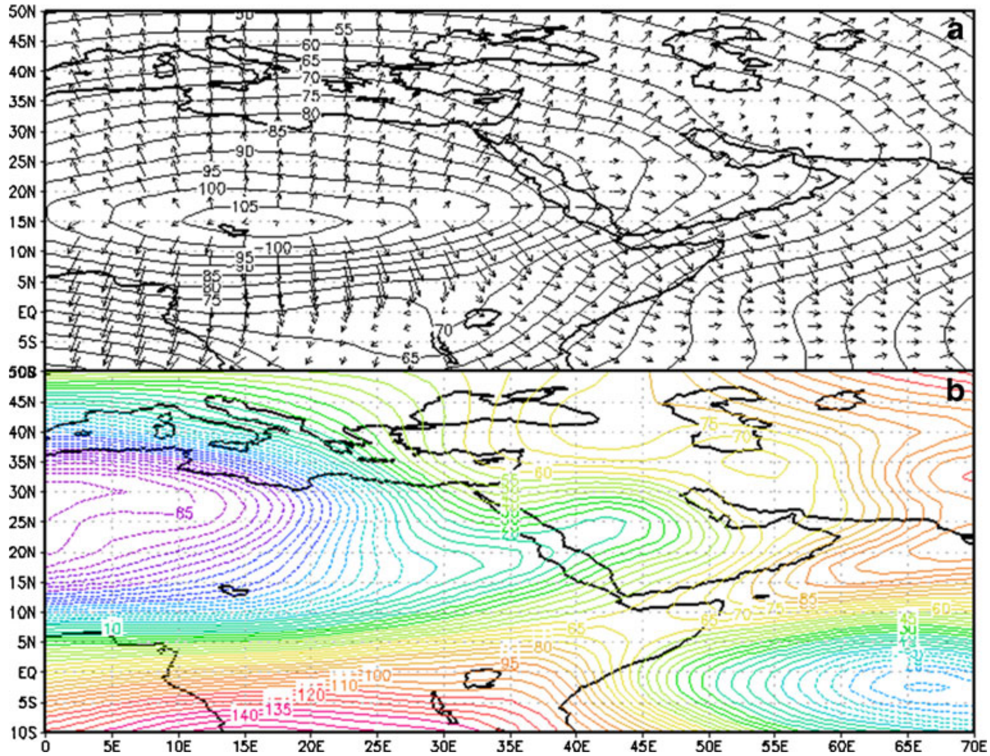

Fig. 12 Composite of **a** Velocity potential (-1×10^{-5} m^2s^{-1}) for June–July 2002 (El Nino) and divergence pattern over the Middle East region at 700 hPa (*top panel*) and **b** stream function (-1×10^{-5} m^2 s^{-1}) in the *bottom panel*

prevailing over this region with less moisture content confined mainly to lower troposphere. Temporal variation of precipitation depicts that the most stations over the northern Arabian Peninsula get rainfall mainly during winter (October to February) and early summer (March to May) in connection with the passage of the westerly troughs originating from Mediterranean Sea. But rain over the southern region is caused mainly by the Arabian Sea branch of monsoon organized convection, moisture laden cross equatorial flow, and remnants of low-pressure systems during the summer

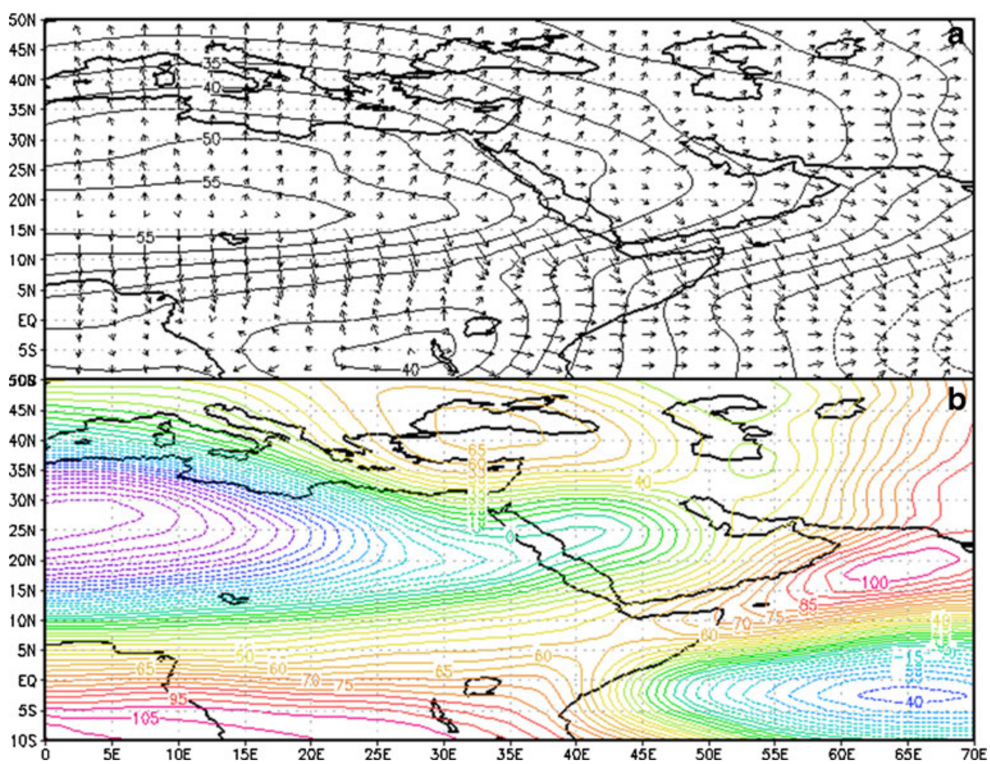

Fig. 13 Composite of **a** Velocity potential (-1×10^{-5} m^2 s^{-1}) for June–July 2010 (La Nina) and divergence pattern over the Middle East region at 700 hPa (*top panel*) and **b** stream function (-1×10^{-5} m^2 s^{-1}) in the *bottom panel*

monsoon season. El Nino and La Nina have profound influence on the rainfall pattern in a different manner in the Northern and the Southern Arabian Peninsula. It is found that the possibility for formation of rainfall due to passage of the remnants of organized convection associated with the monsoon system is more during summer of La Nina year. During summer of La Nina year, the conditions are favorable for cloudiness, as the intensity of sinking limb is weak over the region. On the other hand, central and northern Arabian Peninsula has relatively high values of velocity potential, especially during winter. Thus, winter of La Nina year is not favorable for cloudiness in the Central and Northern Arabian Peninsula. Large-scale circulation pattern as derived from velocity potential indicates that shifting of the rising/sinking limb of Hadley/Walker circulation associated with the El Nino and La Nina causes variability in rainfall. The effect varies with season and location in the Arabian Peninsula.

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