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Climatology of Rainfall, Precipitable Water and Circulation over Middle East Region And Their Variability

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Abstract: A comprehensive analysis on the rainfall climatology of the Middle East region and its temporal and spatial variability are studied in relation with variability of precipitable water and circulation characteristics. The study was carried out utilizing rainfall, OLR, wind and humidity data sets procured from TRMM, NOAA and NCEP-NCAR. The rainfall analysis indicates that northern region gets rainfall mainly during winter and spring associated with the passage of Mediterranean low pressure systems whereas rain over the southern region is caused mainly by the monsoon organized convection, cross equatorial flow and remnants of low pressure systems associated with the monsoon during the summer season. Further, analysis was carried out to assess the influence of ENSO on the rainfall pattern. Monthly SST at Nino 3.4 region, OLR and wind were utilized for the analysis. El Nino and La Nina years are identified on the basis of SST at Nino 3.4 region. Thorough analysis was carried out on circulation pattern using velocity potential in the lower troposphere to understand 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 different manner in the northern and southern Middle East. 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 rainfall.

Key words: Rainfall Climatology · Rainfall Variability · Middle east region · Circulation

INTRODUCTION

Rainfall amount plays a vital role in all activities of human beings and it influences living standard of a region. The Middle East region is located in arid area that extends toward northwest from Sahara in Africa to central Asia. Most of the Middle East region behaves like a desert due to severe aridity except Black Sea and Southern Caspian Sea coasts [1, 2]. South of Ghor basin, South and Southeast Syria, South Iraq, Arabian plateau, central and eastern parts of Iran are arid regions. Within this region, Eastern Syria, Rub Al-Khali, Dashte-Kavir and Dasht-e-Lut deserts are hyper arid [3]. Due to this arid nature of the Middle East region, water resources are not adequate to cater various needs of lives.

A knowledge of rainfall climatology is helpful for proper planning of the region. As the Middle East is situated in the arid or semi arid zone, analysis on rainfall climatology is important for the region. A few investigations were carried out on climatological features in the Middle East. Boer [4] made an investigation on the climate over the United Arab Emirates and identified different bioclimatic zones in the UAE. Barth and Steinkohl [5] carried out an analysis to bring out the origin of winter rainfall in the coastal areas of Saudi Arabia and reported four different rain producing systems in the region. Babu *et al*. [6] made a comprehensive analysis on 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. Hamza *et al*. [7] analysed the intensity of rainfall in

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different classes and their contribution to the total seasonal rainfall. They validated TRMM rainfall over land region using station rainfall data and could obtain significant correlation between them. Their study confirms that TRMM rainfall data can be used over land regions also for the comparison purposes to identify the rainfall characteristics. Variability of rainfall due to local or global reasons affects adversely on all aspects of life in the Middle East due to the low amount of rainfall. Hence studies on the variability of rainfall over the Middle East due to global factors are important, especially in view of the ENSO cycle.

Wang [8] studied the atmospheric circulation cells associated with El-Nino southern oscillation using different global data sets. He found out 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 sub tropics and returning back to the tropics in the lower troposphere. Price *et al*. [9] analysed the possible link between El-Nino and precipitation in Israel. They established that there exists an enhanced precipitation during the winter seasons associated with El Nino years. Mariotti *et al*. [10] reported seasonally varying relationship between Euro-Mediterranean rainfall and ENSO. Their analysis reveals that during an El-Nino, western Mediterranean rainfall has a 10 % increase in the autumn. Ashok *et al*. [11] found out a different type of El Nino occurrence, called El Nino Modoki and analysed their tele conections. Depending on the season, the effects of El Nino Modoki is found to be opposite to those of the conventional ENSO. Ashok and Yamagata [12] reported the characteristics of El Nino Modoki. They argued that the patterns of sea surface warming and cooling in the tropical Pacific seem to be changing as in the associated atmospheric effects. Increased global warming is attributed to the shifts in the El Nino phenomena. The literature on ENSO brings out the fact that variation in the equatorial Pacific SST and hence the ENSO affects global circulation. Thus it is imperative to investigate the influence of ENSO on global circulation over the Middle East region and associated rainfall pattern.

In this analysis, rainfall climatology is studied in relation with variability of precipitable water, humidity and circulation characteristics. Further, variability of rainfall 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.

Data and Methodology: The climatology of rainfall and precipitable water for different months were analysed. The horizontal wind at 700 hPa was utilized to obtain velocity potential for understanding the divergence pattern. The rainfall analysis was made utilizing the TRMM (Tropical Rainfall Measuring Mission) data and precipitable water, specific humidity and wind were utilized from NCEP-NCAR.

The TRMM rainfall data is used to study the spatial and temporal distribution of rainfall over the Middle East region. The TRMM rain rate data is available at a temporal resolution of 3 hour and spatial resolution of 0.25° X 0.25° latitude-longitude grid [13]. Further details about the algorithm is available at http:// trmm.gsfc.nasa.gov/ 3b42.html. We derived daily rainfall from the 3 hourly rain rate and monthly composites were prepared for the period 1999 to 2011 (12 years).

Precipitable water, specific humidity and wind data sets were utilized from NCEP-NCAR reanalysis product [14] that are available at a spatial resolution of 2.5° X 2.5°. The climatology of precipitable water and specific humidity on a monthly basis for the Middle East region was studied using the data for a period of thirty years (1981-2010) and rainfall climatology was investigated utilizing TRMM data for twelve years (1999-2011). The spatial variation of rainfall was studied for the stations in different parts of the Middle East region. Accordingly, Tehran (35° 40'N & 51° 26'E) was selected to represent northern part, Amman (31° 57'N & 35° 57'E) for north-western part, Riyadh (24° 41' N & 46° 42'E) for central part, Muscat (23° 36'N & 58° 37'E) for eastern part and Sanaa (15° 21' N & 44° 12' E) for south-western part. The geographical locations of the stations are presented in the Figure 1. To bring out the temporal distribution of rainfall over the Middle East region, daily march of rainfall during the twelve year period was studied. Analysis of daily march of rainfall for 2010 as a typical case over the five stations is discussed in detail.

To understand the role of warming or cooling of ocean surface in the equatorial Pacific on the rainfall and circulation pattern over the Middle East region, a thorough examination is made on the circulation pattern during El Nino and La Nina years.

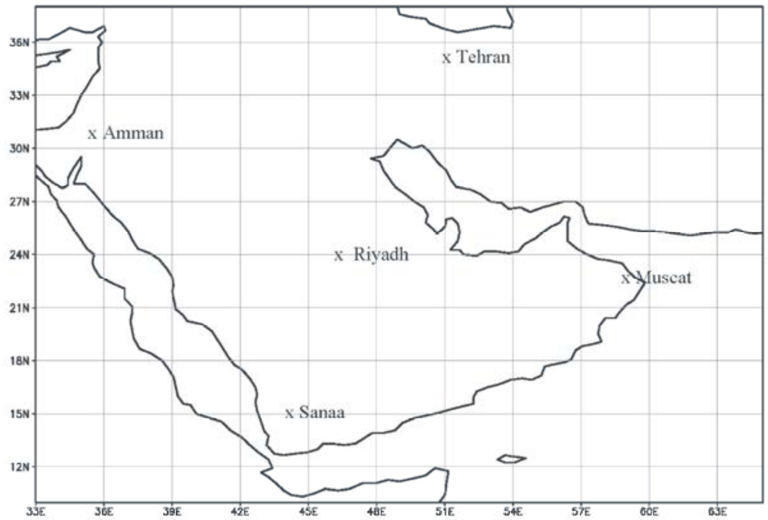

Fig. 1: Map of the Middle East region with location of stations

On the basis of monthly mean values of SST at Nino3.4 region, El Nino and La Nina years are identified. In addition to this, WMO reports that contain detailed information about the evolution and intensity of ENSO events [15, 16] 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 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 ENSO cycle.

RESULTS AND DISCUSSIONS

The rainfall climatology over the Middle East region is studied using monthly composites of daily rainfall (Figure 2) for January to December. Persian Gulf and adjoining areas get more than 4 mm of daily rainfall during December and January. The region of Caspian Sea and a narrow region extending to Persian Gulf get more than 2 mm of rainfall during February, March, April and November also. In addition, Israel and adjoining southeastern Mediterranean Sea also get more then 4 mm of rainfall during January, February and December. The rest of the areas in the Middle East get scanty or no rain during winter season. During June and July, coastal Somalia, southwestern Oman and adjoining areas get more than 6 mm of daily rainfall. The rainfall pattern in August is similar but amount is less. In addition, southwestern Oman (near Sanaa) gets more than 2 mm of rainfall during March to June. The amount of rainfall received over the rest of the areas during summer season is scanty. The monthly rainfall pattern indicates that the rainfall amount is very small over the Middle East region during other months. In general, over the Middle East, northern region gets rain during the winter and spring. Southern region in the Middle East get more rain during the summer monsoon season. Since annual rainfall pattern is required for many applications, climatology of annual rainfall is described in the next section.

Figure 3 represents the climatology of annual rainfall for the Middle East. It is striking to note that most parts of Oman, Saudi Arabia, Yeman, Egypt, northern Sudan, Jordan, Israel and a small area in Iran receive very small amount of rainfall (< 5 cm per year). In general, the annual rainfall over the Middle East region is less than 10 cm except in the area near the boarder of Iran and Iraq and adjoining area of Turkey in the north (more than 40 cm). Ethiopia and eastern Sudan in the south-western Middle East also receive good amount of rainfall (more than 50 cm).

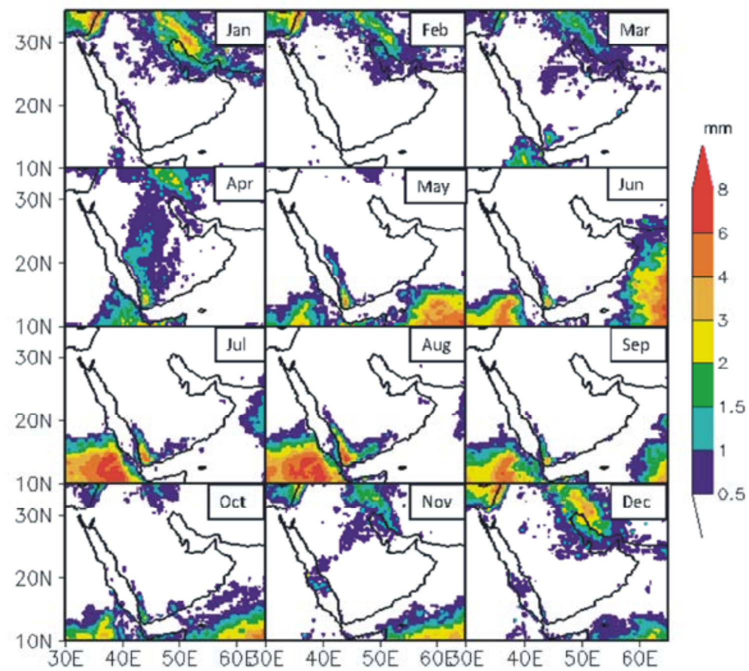

Fig. 2: Composite of daily rainfall (mm) over the Middle East for January to December

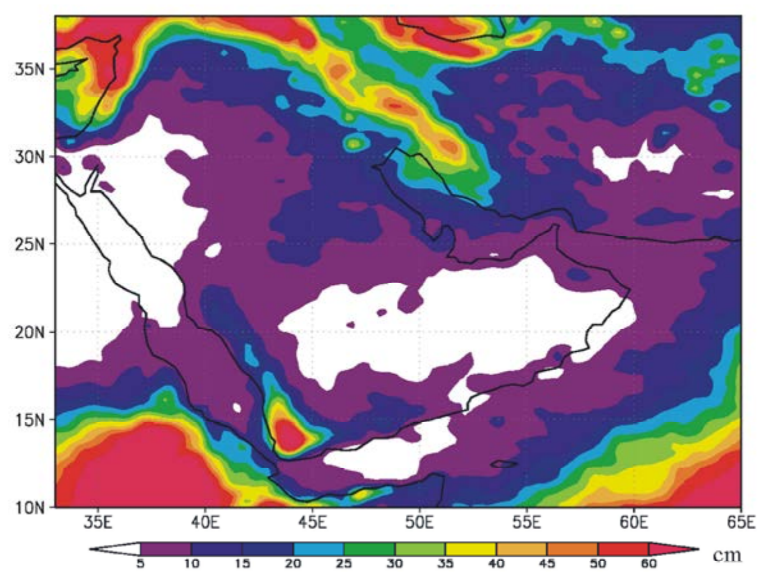

Fig. 3: Composite of annual rainfall (cm) for the Middle East

To understand features on spatial and temporal variability of rainfall, daily march of rainfall over different stations in the Middle East is studied (Figure is not included). The stations selected for the analysis are Tehran, Amman, Riyadh, Muscat and Sanaa, representing different locations of the Middle East region. The daily march of rainfall at Tehran indicates that this region receives rainfall during November to May. The amount of rainfall is 10 to 25 mm/day. Amman station gets rainfall mainly during spring and winter. During spring this station receives rain spells of more than 10 mm. However, the quantity of rainfall received during winter is less than 8 mm. It is striking to note that no rainfall is received over Tehran and Amman during the summer season as monsoon system does not have any effect over the northern Middle East. Riyadh station gets a few rain

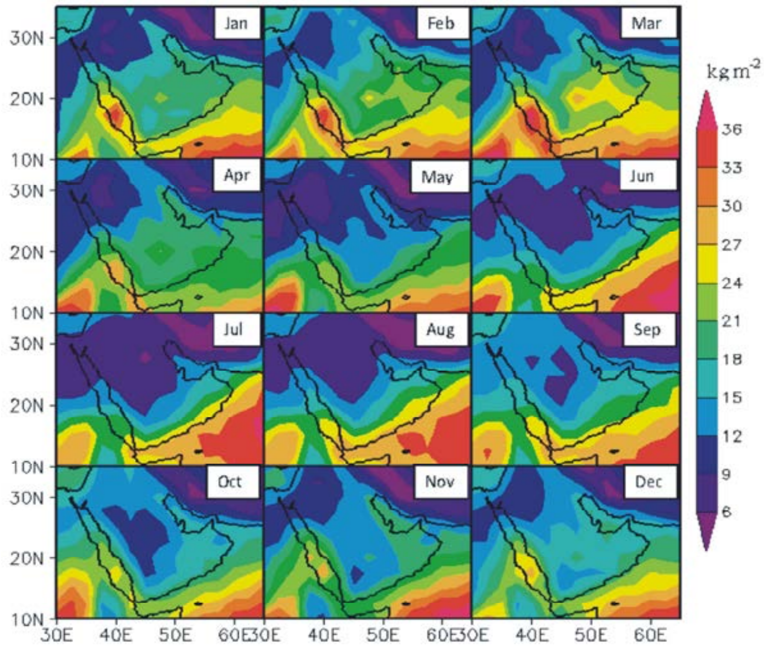

Fig. 4: Climatology of precipitable water (kg m^{-2}) for January to December

spells during spring (March and April) and winter (November, December, January and February). The amount of rainfall and number of rain events are small over Riyadh. Muscat gets rainfall during winter, spring and summer, even though the amount of rainfall and number of rainy days are small. The bottom panel describes the daily march of rainfall over Sanaa. This station gets rainfall during March to August and no 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 period of certain locations in the Middle East such as Oman, U.A.E, most parts of Saudi Arabia and eastern Yemen.

Further, we analysed the climatology of precipitable water over the Middle East region for different months (Figure 4). The precipitable water over Oman is less than 20 kg m^{-2} except during the monsoon season. The precipitable water decreases towards west and north from Oman. Scarcity of moisture due to the sinking motion associated with the sub tropic high pressure system can be the reason for the small value. Even nearby water bodies (Mediterranean Sea, Black Sea, Caspian Sea, Arabian Sea, Persian Gulf and Red Sea) do not help to shoot up the precipitable water in the Middle East region. Mean annual precipitable water climatology (Figure 5) indicates that the value over Oman is around 20 kg m^{-2} with higher value (more than 26 kg m^{-2}) in the Arabian Sea coast. The precipitable water values are high (more than 30 kg m^{-2}) over Somalia region caused by the pumping of humid air from the Arabian Sea during the summer season and the values decrease toward north.

It is appropriate to carry out a comparison between the climatology of annual precipitable water (Figure 5) and the climatology of annual rainfall (Figure 3). The precipitable water over Oman and adjoining area is more than 20 kg m^{-2} but receives less than 10 cm rainfall in a year. On the other hand, north western Iran receives more than 40 cm rainfall though the precipitable water value over the region is 12 kg m^{-2}. Hence the availability of precipitable water in the atmosphere alone need not produce rainfall. The atmosphere should have favourable conditions for the formation of cloud and rain.

Variability on organized convection in different months over the Middle East region during normal, El Nino and La Nina years are studied on the basis of long term average of OLR (Figure 6), OLR anomaly during an El Nino year (Figure 7) and OLR anomaly during a La Nina year (Figure 8). The OLR climatology pattern indicates two regions of feeble organized convection in the Middle East. One is in the northern region during December, January, February and March (with average OLR value less than 220 W m^{-2}) and the other is a small area in

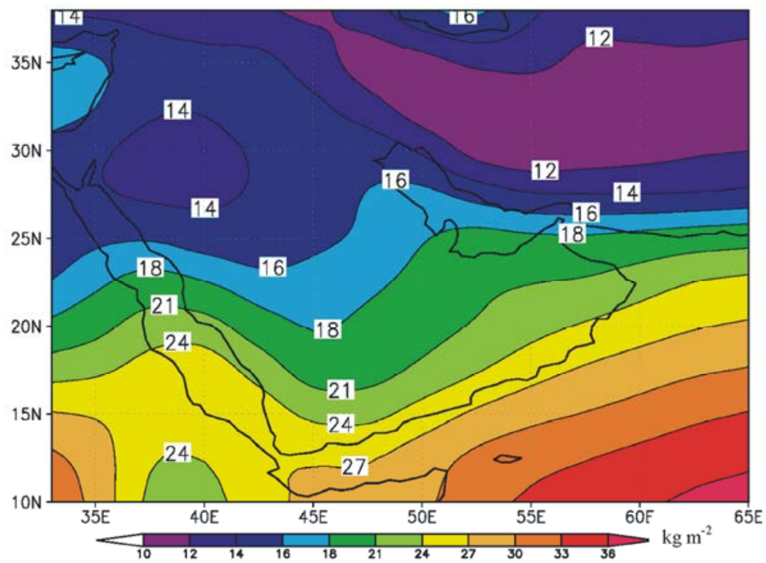

Fig. 5: Climatology of annual precipitable water (kg m^{-2}) for the Middle East

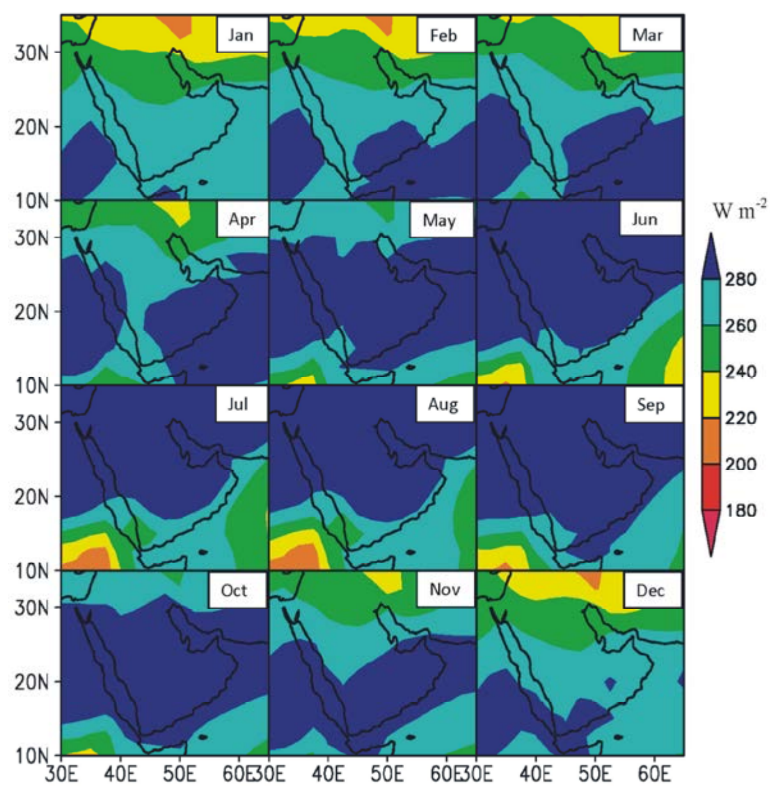

Fig. 6: Climatology of OLR (W m^{-2}) for January to December

the south-western region during June, July, August and September. OLR anomaly during many El Nino and La Nina years are examined and representative cases are presented in Figure 7 for El Nino (2002) and Figure 8 for La Nina (2010). During the El Nino year (Figure 7), negative anomaly of OLR is found during January and February with a value of 20 W m^{-2} in certain regions in the southern Middle East. Even though this negative anomaly

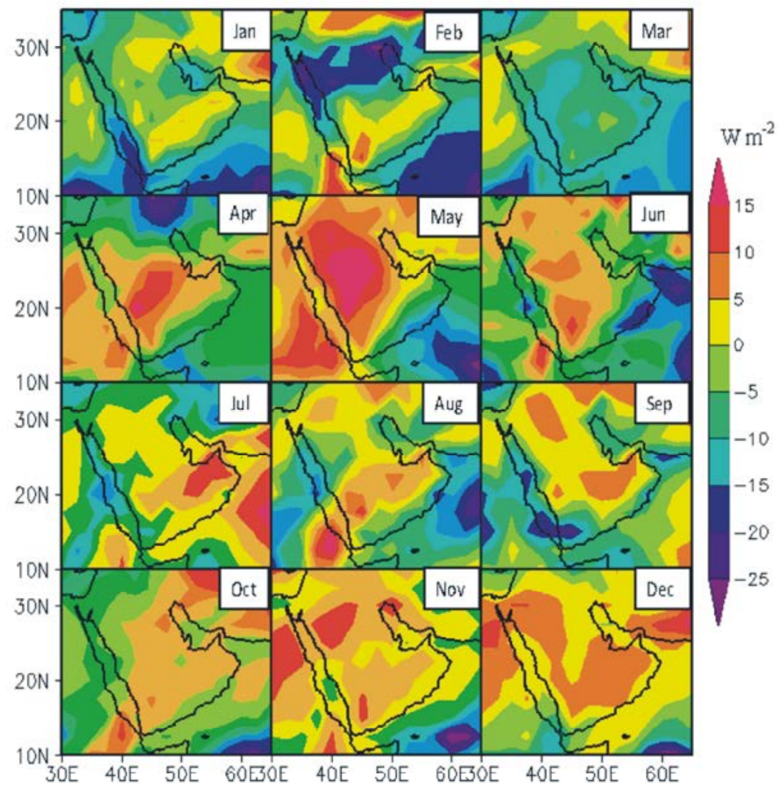

Fig. 7: OLR anomaly (W m^{-2}) during El Nino year for January to December

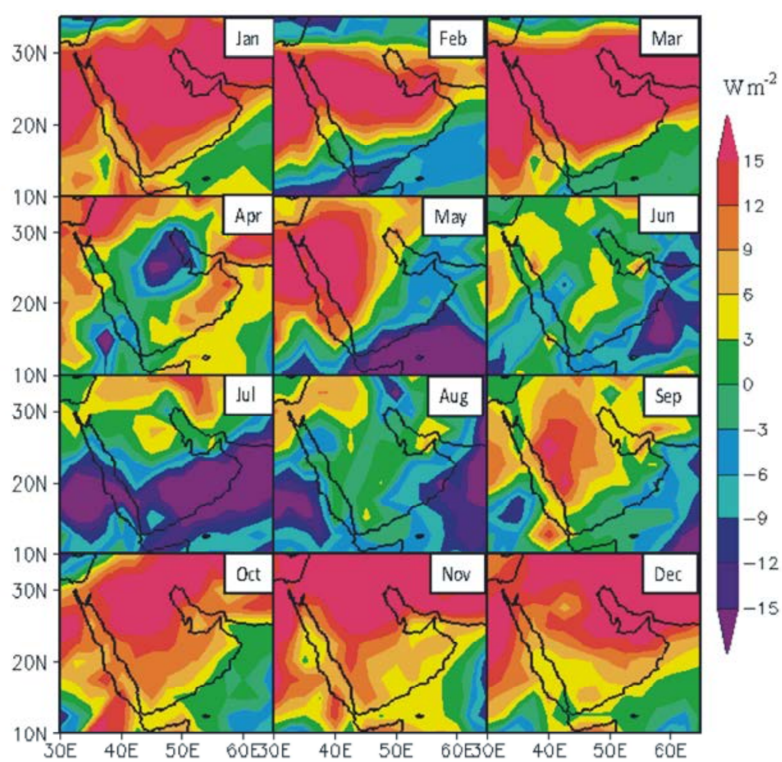

Fig. 8: OLR anomaly (W m^{-2}) during La Nina year for January to December

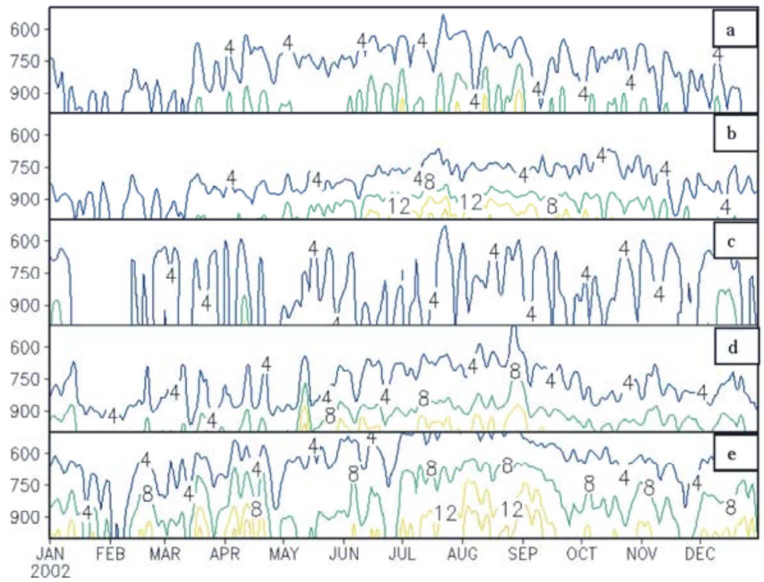

Fig. 9: Vertical-time section of specific humidity (g kg^{-1}) for El Nino year during 1st January to 31st December for (a) Tehran, (b) Amman, (c) Riyadh, (d) Muscat and (e) Sanaa

value does not bring the OLR below 200 W m^{-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 as low OLR value represents presence of organized convection. However, positive anomaly occurred in most of the areas during May, June and July.

The features of OLR anomaly (Figure 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 Middle East during October, November, December, January, February and March. It is interesting to note that negative OLR anomaly also prevailed over a small area in the southern or south-eastern 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 winter season of El Nino year, positive anomaly occurred during La Nina year. During 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 Middle East.

We examined vertical time section (on a daily basis) of specific humidity for the five stations in five panels during El Nino year (Figure 9) and La Nina year (Figure 10). During El Nino year, the specific humidity value is found to decrease in the southern Middle East (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 need not be so strong to influence Mediterranean systems that pass over the northern Middle East during winter season to increase the specific humidity values. The effect of La Nina is felt in the southern region of Middle East (bottom panel, Sanaa) during 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 Nina year over the southern Middle East (Sanaa station). This is in agreement with OLR anomaly.

In order to study the effect of ENSO cycle on global circulation pattern over the Middle East region, we examined velocity potential and stream function at 700 hPa during June-July of El Nino and La Nina years. Figure 11 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 Middle East region is

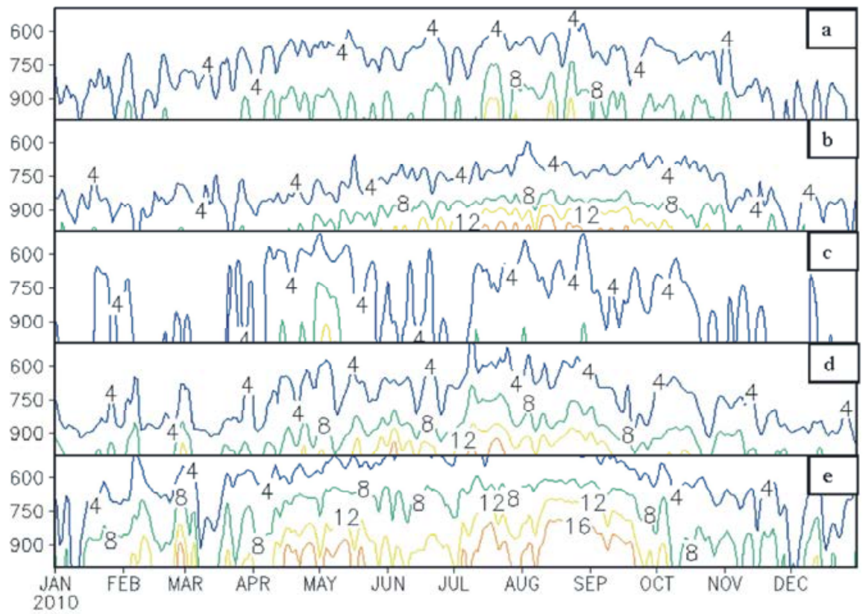

Fig. 10: Vertical-time section of specific humidity (g kg^{-1}) for La Nina year during 1st January to 31st December for (a) Tehran, (b) Amman, (c) Riyadh, (d) Muscat and (e) Sanaa

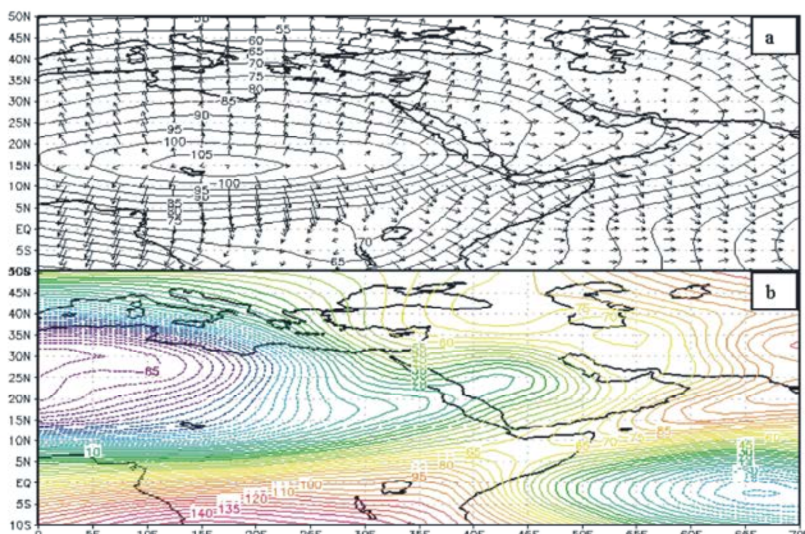

Fig. 11: Composite of (a) Velocity potential (-1X10^{-5} m^2 s^{-1}) for June-July 2002 (El Nino) and divergence pattern over the Middle East region at 700 hPa (top panel) and (b) Stream function (-1X10^{-5} m^2 s^{-1}) in the bottom panel

warm and dry due to the sinking motion. During winter season of El Nino, the velocity potential value is slightly less over a few areas in the northern Middle East region (Figure is not included). Thus there is a possibility to have more cloudiness associated with the passage of Mediterranean system during the winter season of El Nino. The OLR pattern during winter and summer of El Nino year agrees with the features inferred from circulation pattern.

Figure 12 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 Middle East region during June-July of La Nina year is less compared to normal year. So, the possibility for formation of rainfall due to passage of remnants of organized convection associated with the monsoon system is more

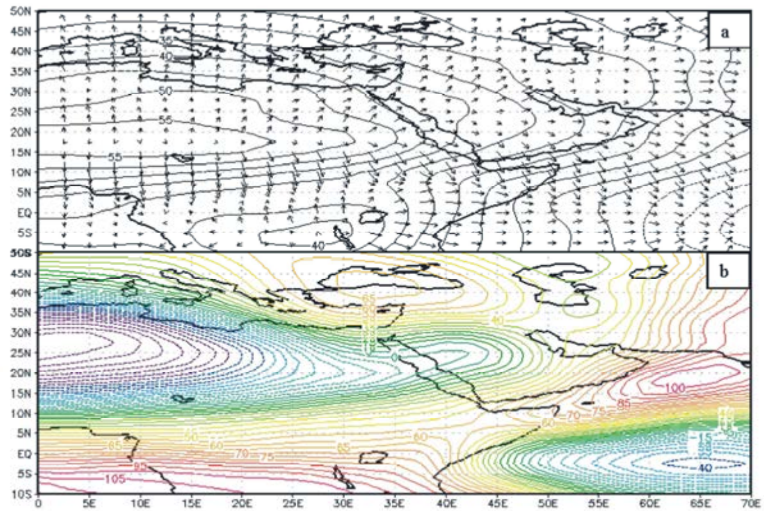

Fig. 12: Composite of (a) Velocity potential (-1X10^{-5} m^2 s^{-1}) for June-July 2010 (La Nina) and divergence pattern over the Middle East region at 700 hPa (top panel) and (b) Stream function (-1X10^{-5} m^2 s^{-1}) in the bottom panel

during summer of La Nina year. Generally, rain events in the southern Middle East region are caused mainly by the monsoon system. During summer of La Nina year, the conditions are favourable for cloudiness, as the intensity of sinking limb is weak over the region. On the other hand, central and northern Middle East region have relatively high values of velocity potential especially during winter (Figure is not included). Thus winter of La Nina year is not favourable for cloudiness in the central and northern Middle East region. This can bring down the rainfall associated with the passage of Mediterranean system as the air over the Middle East region is dry and warm.

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 associated with monsoon system and northern region gets rainfall during winter and spring associated with passage of Mediterranean system. According to the location of sinking limb of circulation during ENSO cycle, the rainfall pattern in the Middle East region varies. The effect is different in the northern and southern areas and during summer and winter seasons.

CONCLUSIONS

Climatology of daily rainfall in different months indicates that the south central and western Middle East get small amount of rainfall in most of the months. Two areas of low annual rainfall in the Middle East are north-eastern Egypt and southern part of Saudi Arabia. The sinking motion associated with the sub tropic high pressure system and sinking limb of Walker circulation can be considered as the reasons for the warm and dry air. Due to these reasons, moisture content is small over the Middle East and is confined in the lower troposphere. Daily rainfall analysis indicates that the northern Middle East region gets rainfall mainly during winter and spring associated with the passage of Mediterranean low pressure systems whereas rain over the southern region is caused mainly by the monsoon organized convection, cross equatorial flow and remnants of low pressure systems during the summer monsoon season. Moreover, the rainfall pattern in the central and southern parts of the Middle East does not have any consistency. El Nino and La Nina have profound influence on the rainfall pattern in different manner in the northern and southern Middle East. 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 Middle East.

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