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Rainfall Climatology over Middle East Region and its Variability

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Abstract: A better understanding of the rainfall climatology of the Middle East region identifying the mechanisms responsible for the rain producing systems is essential for effective utilization of the water resources over the arid region. A comprehensive analysis on the rainfall climatology of the Middle East region is carried out to bring out the spatial and temporal variation of rainfall and mechanisms responsible for the rain events. The study was carried out utilizing rainfall, OLR, wind and humidity data sets procured from TRMM, NOAA and NCEP-NCAR. Climatology of annual rainfall brings out two areas of alarmingly low rainfall in the Middle East region: one in Egypt, Jordan and adjoining areas and the other in the southern part of Saudi Arabia. Daily 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. Thermodynamic structure of the atmosphere reveals that the region does not have frequent local convection due to insufficient moisture content. The sinking motion associated with the sub tropic high pressure system and subsidence associated with the Walker circulation are responsible for maintaining warm and dry air over the region.

Key words: Rainfall Climatology • Rainfall Variability • Middle East Region • Circulation

INTRODUCTION

Availability of potable water depends mainly on the rainfall. Rainfall amount plays a vital role in all activities of human beings. The Middle East region is located in the middle of wide semiarid and arid areas that extend toward northwest from Sahara in Africa to central Asia. This region covers between latitudes 13°N and 43°N. 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 better understanding of the rainfall climatology of the Middle East region and identifying the mechanism responsible for the rain producing systems are essential for effective utilization of the resources [4]. Carried out an analysis to bring out the origin of winter rainfall in the coastal areas of Saudi Arabia and found four different rain producing systems in the region [5]. Made an investigation on the climate over the United Arab Emirates and identified different bioclimatic zones in the UAE. A comprehensive analysis on the rainfall climatology of the Middle East is still lacking. Hence an attempt is made to carry out rainfall climatology over the Middle East region to bring out the spatial and temporal variation of rainfall and mechanisms responsible for the rain events.

Data and Methodology: The analysis was carried out utilizing the TRMM (Tropical Rainfall Measuring Mission) data to understand 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 [6]. This high resolution data on

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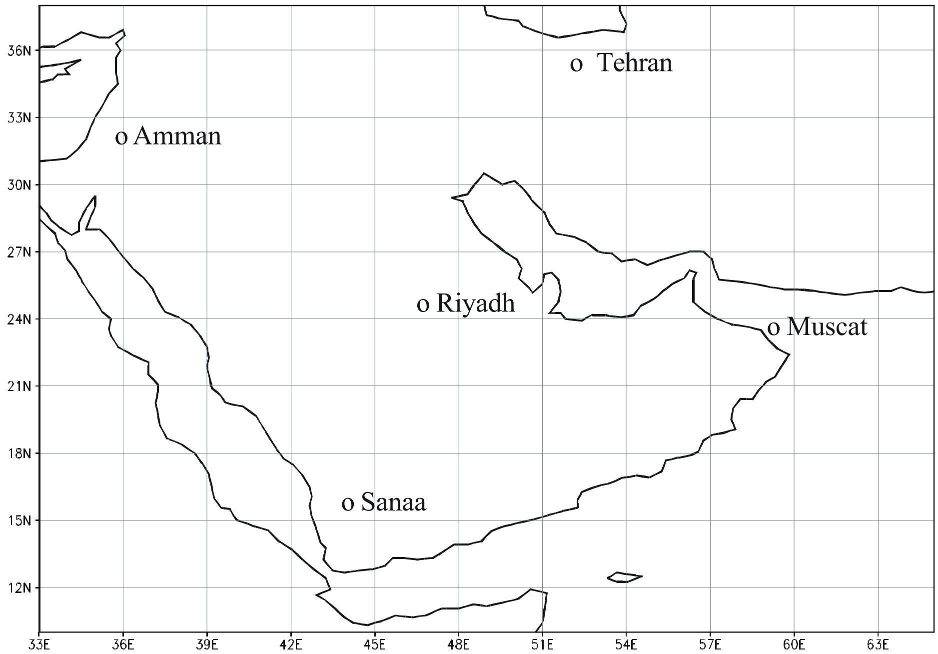

Fig. 1: Map of the Middle East region with location of stations

temporal and spatial domains provide good opportunity to study the rainfall characteristics especially in the arid region of Middle East. The TRMM rain rate dataset contains the output of TRMM Algorithm 3B42, which was made available from TRMM merged high quality /infrared (IR) precipitation and root-mean-square (RMS) precipitation-error estimates. The combined instrument and rain calibration algorithm (3B-42) use an optimal combination of 2B-31, 2A-12, SSMI, AMSR and AMSU precipitation estimates (considered as high quality), to adjust IR estimates from geostationary IR observations. Near-global estimates are made by calibrating the IR brightness temperatures to the high quality estimates. The 3B-42 estimates are scaled to match the monthly rain gauge analyses used in 3B-43. The output is rainfall for 0.25 X 0.25 degree latitude-longitude grid boxes in the earth surface for every 3 hours. 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.

Further, wind at 925 hPa, 850 hPa and 700 hPa and specific humidity (at 8 levels: 1000, 925, 850, 700, 600 and 500 hPa) (resolution: 2.5° X 2.5°) available from NCEP-NCAR reanalysis product [7] and radiosonde data from the Wyoming university site (http://weather.uwyo.edu/) were utilized for the analysis. The climatology of wind over the Middle East region was studied using the NCEP-NCAR data for a period of thirty years (1978-2007) and rainfall climatology was investigated using TRMM data for thirteen years (1997-2009). 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 location of the stations is presented in the Figure 1. To bring out the temporal distribution of rainfall over the Middle East region, daily march of rainfall during the thirteen year period was studied. Hovmoller (time-longitudinal cross section) diagram is used to identify the passage of rain producing systems during the winter and monsoon seasons.

Local convection features were examined using thermodynamic parameters: Lifting Condensation Level (*LCL*), Level of Free Convection (*LFC*), Limit of Convection (*LOC*), Convective Available Potential Energy (*CAPE*), Convection Inhibition Energy (*CINE*) etc., evaluated from the radiosonde data.

Convective available potential energy is the total energy used up by the surface air parcel when it rises from *LFC* to the *LOC*. The computation of *CAPE* was performed using the equation given below.

$$CAPE = \int_{LFC}^{LOC} \frac{R(Tp - Te)}{p} \, dp$$

Where Tp is the parcel temperature, Te is the environmental temperature and R is specific gas constant for air. In the present study, *CAPE* value is computed by integrating the above equation numerically, considering thin layers of the atmosphere of 1 hPa thickness from *LFC* to *LOC*. The Tp value is taken from a profile of saturated adiabat and Te value is taken from interpolating the environmental profile.

The evaluation of *CINE* was carried out in a similar manner. It is the energy required for raising an air parcel of unit mass from surface to *LFC* (crossing the stable layer near the surface) since the parcel is colder than the environmental air. Thus *CINE* was evaluated using the equation

$$CINE = \int_{Surface}^{LFC} \frac{R(Te - Tp)}{p} \, dp$$

The other thermodynamic parameters were evaluated as per the methodology described in Babu (1996).

RESULTS AND DISCUSSIONS

Climatology: The rainfall climatology over the Middle East region is studied using monthly composites of daily rainfall. On the basis of close resemblance of rainfall features in different months, they are grouped together. Accordingly January, April, July and October are chosen as representative months for rainfall describing pattern over the region. Figure 2a-d represents rainfall climatology for January, April, July and October respectively. Northern Oman and adjoining Middle East region get more than 0.2 mm rainfall per day during January (Figure 2a). Maximum rain belt is over the western part of Iran and this region gets more than 3 mm rain. Yeman, southern Oman and southern Saudi Arabia get scanty rain. Another region in the western coast of Red Sea (Egypt, Sudan and Eritrea) also receives scanty rain during January. During April (Figure 2b), maximum rainfall is found over the northwest Iran (more than 4 mm) and the rainfall amount decreases to the southeast. Parts of Sudan, Egypt, southern Iran and southern Oman get scanty rain. The rainfall pattern during July (Figure 2c) is different from earlier months. In July, Pakistan and Somalia region (in the east and south) get more than 0.5 mm rain. Ethiopia and southwestern area of coastal Yemen receive more than 4 mm rain due to the influence of monsoon. The rest of the area in the Middle East gets scanty rain. During September, the entire Middle East is almost dry (figure is not included). During October (Figure 2d), coastal region of Caspian Sea (more than 3 mm), northwestern part of Iran (more than 3 mm) southeastern region of Ethiopia and adjoining northern area of Iraq, Syria and Turkey (more than 2 mm) get rainfall. However, southern Saudi Arabia, southern Iran, the region east of southern Iran and northern Egypt receive scanty rain. In general, over the Middle East, northern region gets rain during the winter season and spring. Southern and southeastern regions in the Middle East get more rain during the southwest monsoon season. Dry weather prevails most parts of the Middle East during September and October. Since annual rainfall pattern is required for many applications, climatology of annual rainfall is described in the next section.

Figure 2e 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).

We examined the cause for the alarmingly low rainfall. These areas lie over the subtropical high pressure belt. The subtropical high pressure belt has a seasonal movement in the south-north direction according to the position of the Sun. During the summer season, the subtropical high pressure system in the longitudinal belt 35°E-65°E lies over these areas. To confirm, we analysed the annual mean climatology of velocity potential at 700 hPa over the region (Figure 3). These areas have strong divergence and coincide with the region of minimum annual rainfall (Figure 2e). The divergence can be attributed to the sinking motion associated with the subtropical high pressure system. In addition, the descending branch of the Walker circulation centered over these areas during the Indian summer monsoon season can be thought of another mechanism responsible for intensifying the sinking motion. Thus the Middle East in general and southern part and northern Red Sea and adjoining region in particular are not conducive for the formation of the rain bearing clouds. Seasonal migration of the sub tropic high pressure system results in aerial changes of the sinking motion. The sinking motion makes

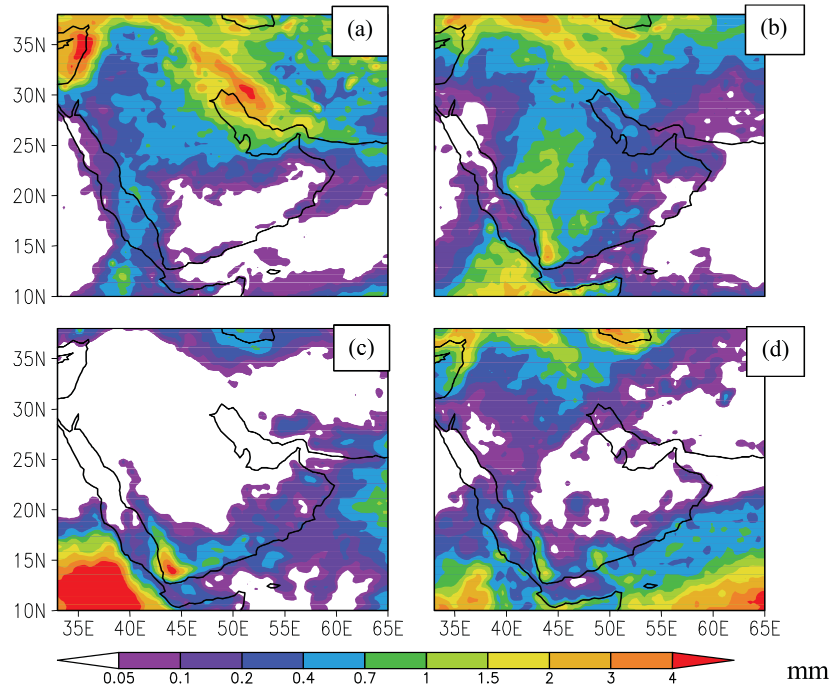

Fig. 2: Composite of daily rainfall (mm) over the Middle East for (a) January, (b) April, (c) July and (d) October

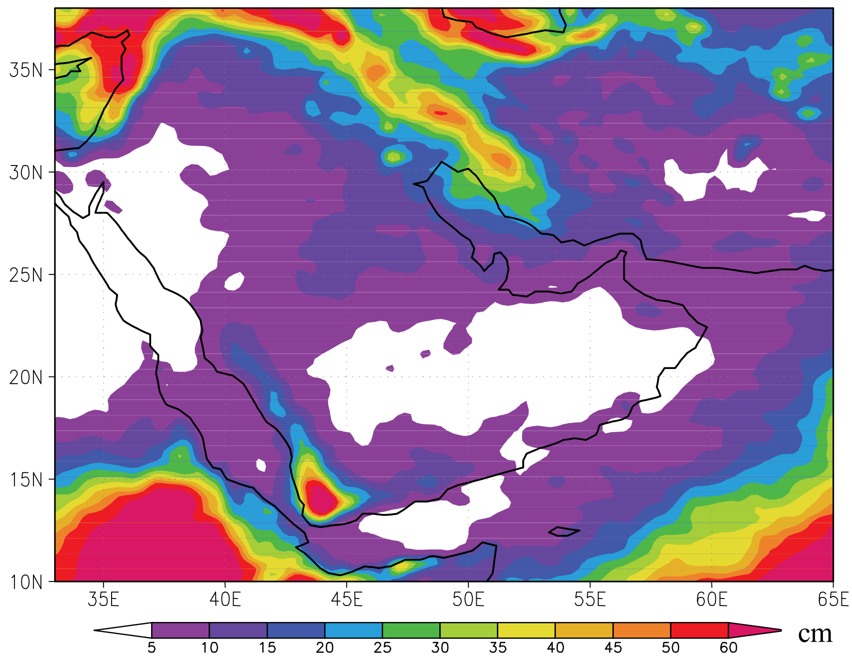

Fig. 2e: Composite of annual rainfall (cm) for the Middle East region.

the air dry and warm leading to clear sky situation. The scarcity of moisture in the atmosphere over the region is due to the sinking motion.

We analysed the moisture content of the atmosphere over different stations in the Middle East region. Vertical time sections of specific humidity ($g\ kg^{-1}$) over these five stations were used to describe seasonal variation of the moisture content (Figure 4a-e). At Tehran, the specific humidity values are between 4 and 12 $g\ kg^{-1}$ in the layer below 900 hPa and a high value of 12 $g\ kg^{-1}$ is

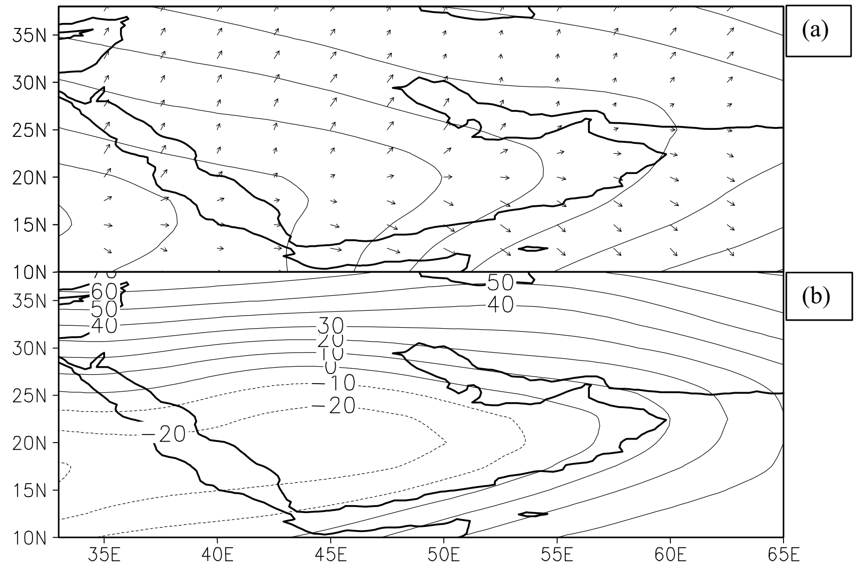

Fig. 3: Climatology of annual (a) velocity potential for 1978-2007 (-1X10•^{5} m^2 s•^{1}) and divergence pattern over the Middle East region at 700 hPa and (b) Stream function (-1X10•^{5} m^2 s•^{1}).

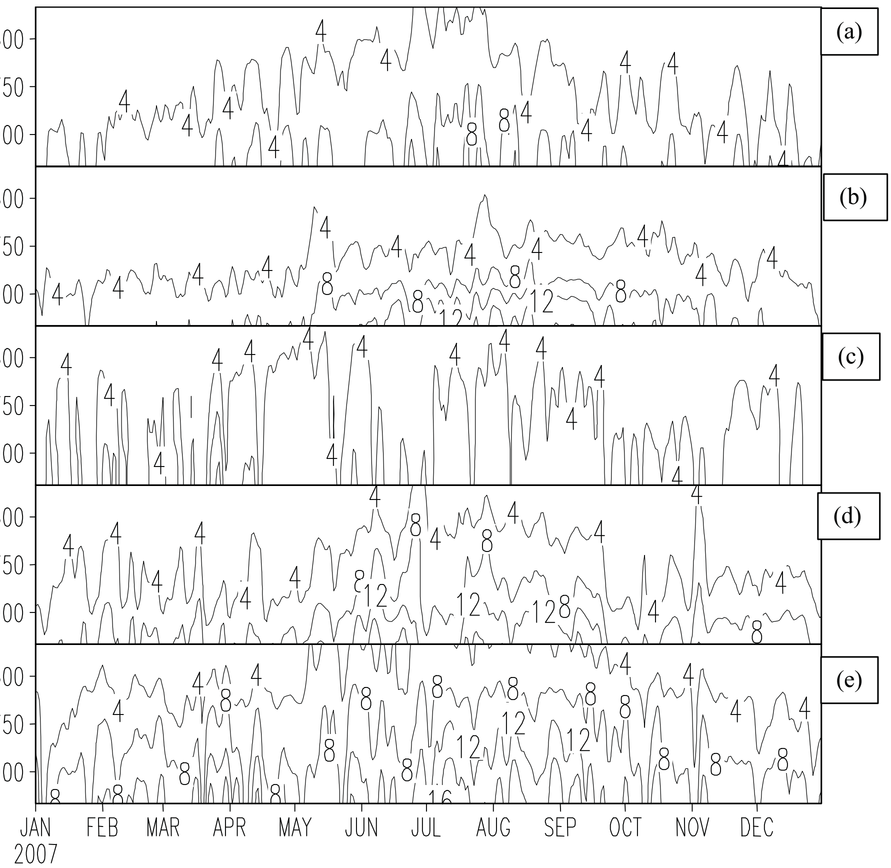

Fig. 4: Vertical-time section of humidity for 1st January to 31st December for (a) Tehran, (b) Amman, (c) Riyadh, (d) Muscat and (e) Sanaa

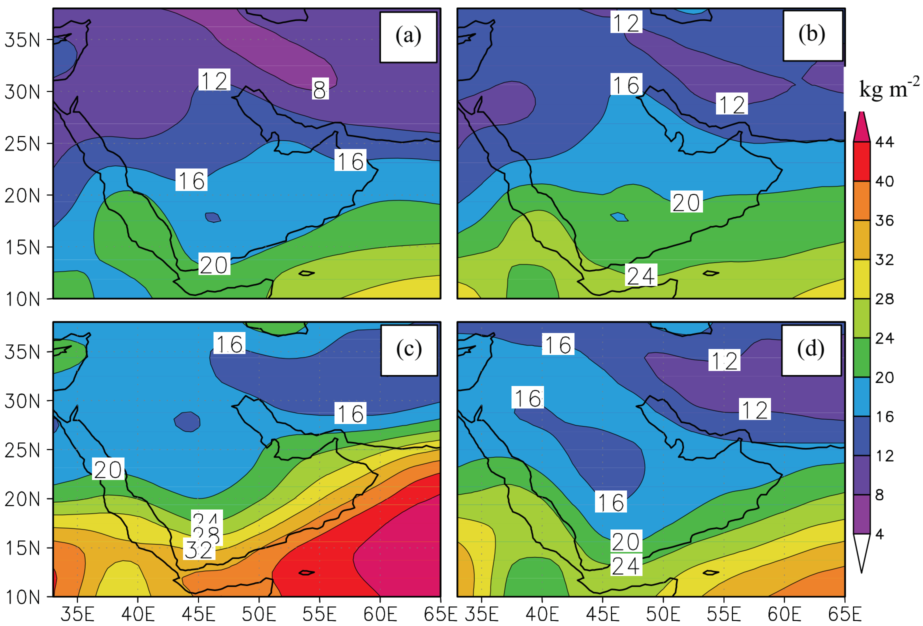

Fig. 5: Climatology of seasonal precipitable water (kg m^{-2}) for (a) January, (b) April, (c) July and (d) October.

observed for a few days during the summer season (Figure 4a). In July, the entire layer from surface to 500 hPa contains more than 4 g kg^{-1} with more than 12 g kg^{-1} on certain days in the surface. Even though the specific humidity value at the surface of Amman (Figure 4b) exceeds 16 g kg^{-1} for a few days in August, the high specific humidity values are confined in the lower atmosphere. At Riyadh (Figure 4c), the specific humidity value is small (less than 4 g kg^{-1}) in the lower atmosphere up to 600 hPa, might be due to absence of nearby moisture source as well as the sinking motion. On the other hand, Muscat (Figure 4d) and Sanaa (Figure 4e) are rich in moisture near the surface (more than 15 g kg^{-1}) due to moisture pumping from Arabian Sea associated with the summer monsoon. All rain events at these stations coincide with the high specific humidity values in the atmosphere. Similar features were seen for most of the stations in different years in the Middle East. In general, the moisture content of the atmosphere is small and confined in a shallow layer over the Middle East region. There are cases of relatively high values of specific humidity over the Middle East during the passage of weather systems (in the southern region: originated from the Arabian Sea and in the northern region from the Mediterranean Sea). But such situation of relatively high moisture content in the atmosphere persists during the life period of the low pressure system only.

Further, we analysed the climatology of precipitable water over the Middle East region for the representative months: January, April, July and October (Figure 5a-d). 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 (Figure 3). 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 5e) 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 5e) and the climatology of annual rainfall (Figure 2e). 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}.

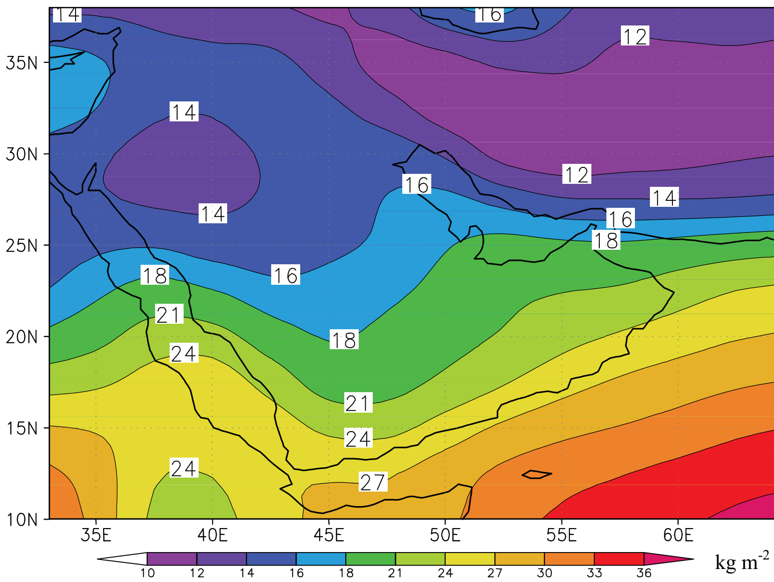

Fig. 5e: Climatology of annual precipitable water (kg m•²) for the Middle East and Indian region

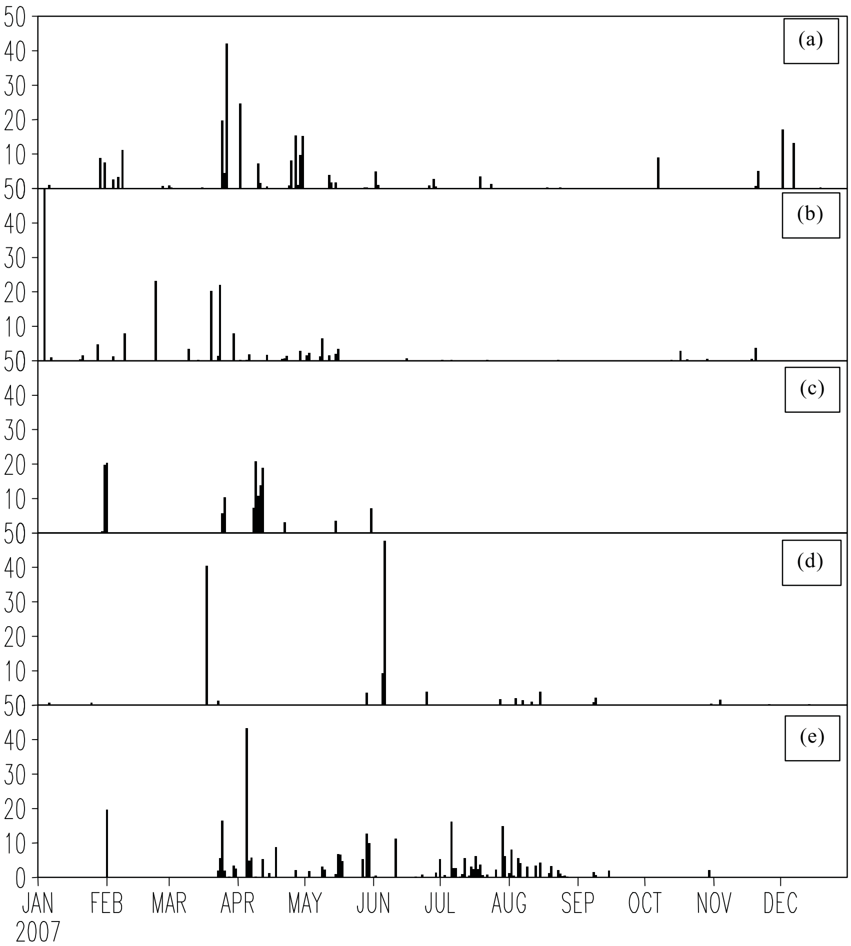

Fig. 6: Daily march of rainfall over the stations (a) Tehran, (b) Amman, (c) Riyadh, (d) Muscat and (e) Sanaa

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.

Spatial and Temporal Variation of Rainfall: To understand features on spatial and temporal variability of rainfall, daily march of rainfall during a year over different stations in the Middle East is studied. The stations selected for the analysis are Tehran, Amman, Riyadh, Muscat and Sanaa (the location of the stations is presented in Figure 1), representing different locations of the Middle East region. From the annual pattern, rainy season for different location in the Middle East region is identified and possible mechanisms for the rain events are discussed.

The daily march of rainfall at Tehran (located in the northern part of the Middle East) is represented in Figure 6a. We examined the daily pattern of rainfall for 13 years and found that Tehran receives rainfall from November to May. The amount of rainfall is 10 to 25 mm/day. Amman station (located in the north-western part) gets rainfall mainly during spring and winter (Figure 6b). 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 monsoon season. Figure 6c presents the rainfall pattern over Riyadh (located in the central part of the Middle East). This station gets a few rain spells during March, April, November, December, January and February. The amount of rainfall and number of rain events are small over Riyadh. Muscat (located in the eastern part) gets rainfall during winter, spring and summer (Figure 6d), even though the amount of rainfall and number of rainy days are small. Figure 6e describes the daily march of rainfall over Sanaa (located in the south-western part of the Middle East). 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. As explained earlier, this region gets scanty rain due to the effect of sinking motion and hence the rainy period varies with year. As an example for this category, major rain events at Muscat in 2007 were during April, July and August and no rain occurred in winter. In 2000, no rain occurred during summer but received a few spells during April, October and November. Such contrasting rain features are exhibited during different years by the stations in this region.

The rainfall features at Saiq (57°39'E & 23°04'N), a hilly station (height above msl is 1923 m) and adjacent to Muscat are analysed for studying the effect of orography on rainfall pattern (figure is not included). The behavior of rainfall pattern over this station is similar to that of Muscat. The rainfall of this station during the summer monsoon season is more than that of Muscat due to topography of the station. Thus during June, July and August, the humid air in the windward side of the mountain range produces more rain by orography in this station due to the monsoon system. However, rainfall pattern during winter does not show any remarkable increase since the system is different and the wind direction is not perpendicular to the mountain range. Further, it is noticed that whenever rain producing mechanism exists, rain occurs over both stations although the quantity is slightly different due to the orography.

A Hovmoller diagram (Figure 7) is employed to understand the cause for rain producing system over the northern region. The TRMM rain rate (averaged over the latitude belt, 33.25°N-33.5°N) is used in the Hovmoller diagram, to identify the mechanism for the rainfall over Baghdad as a representative case. From the Hovmoller diagram, we infer that the rain event over Baghdad is due to the passage of the low pressure system originated from the Mediterranean region. We confirmed the influence of the Mediterranean system by carrying out similar analysis for other rain events over Tehran, Amman, Riyadh and Muscat. During winter season, sea is warmer than land and formation of low pressure system takes place regularly over the Mediterranean region since this is a region of transient cyclogenesis [8, 9, 10]. These low pressure systems are frontal in nature and move to the east. The systems intensify when the conditions are favourable and dissipate during adverse situations. The passage of Mediterranean low pressure system gives rise to rain in the northern stations during winter and spring. As explained earlier, Baghdad, Tehran and Amman get major portion of rainfall from the Mediterranean system.

For a better understanding of the role played by the Mediterranean low pressure systems on rainfall over the Middle East, a thorough study was carried out. It is found that small vortices or low pressure systems with small horizontal extension are formed frequently during winter

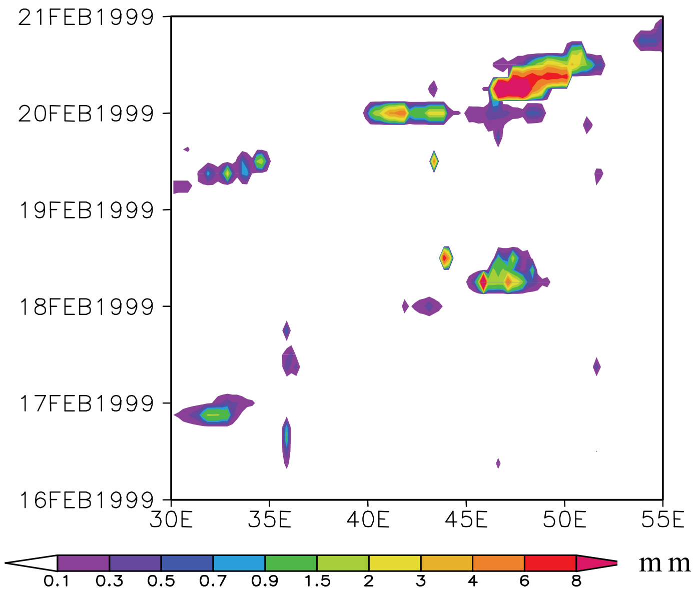

Fig. 7: Hovmoller diagram for TRMM Rain Rate GPI (mm) (a) averaged over 33.25°N-33.5°N for Mediterranean system

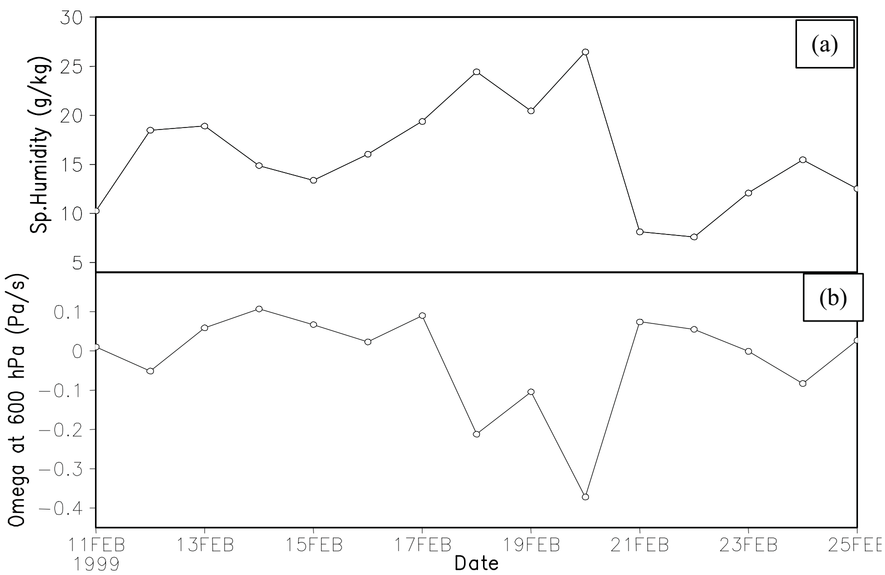

Fig. 8(a): Daily march of Sum of Specific Humidity (g/kg) in the column from 1000 hPa to 300 hPa over Baghdad and (b) Daily march of vertical velocity (omega in Pa/s) at 600 hPa over Baghdad

and spring over the Mediterranean region. Most of the low pressure systems propagate eastward, crossing the Middle East region. We made analysis on specific humidity, wind pattern, vorticity, divergence and vertical velocity pertaining to different low pressure systems formed over the Mediterranean region. The formation of the system is marked by an increase in cyclonic vorticity and low level convergence. As the low pressure system moves to the east, the dynamic structure also shifts to the east. In association with the passage of the Mediterranean low pressure system, the moisture content over the Middle East region increases considerably. We present features of a Mediterranean low pressure system that formed during 17th February, 1999 when it passes over Baghdad. Figure 8a represents sum of specific humidity for the column from 1000 to 300 hPa during 11th to 25th February for Baghdad. The increase in specific humidity on 18th (24 g kg^{-1}) and 20th (27 g kg^{-1})

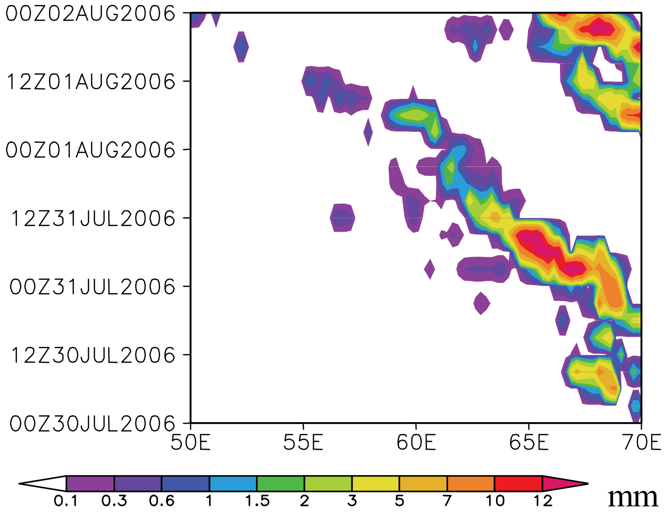

Fig. 9: Hovmoller diagram for TRMM Rain Rate (mm) averaged over 15.25°N-15.5°N for monsoon system.

were due to the passage of low pressure systems. The low level convergence ($1X10^{-5}$ s^{-1}) and cyclonic vorticity ($2X10^{-5}$ s^{-1}) values at 850 hPa level were also relatively high during these days (figures are not included). The dynamic structure of the atmosphere was favourable for vertical lifting due to the combined effect of low level convergence, frictional convergence and cyclonic vorticity. We analysed the vertical velocity at 600 hPa over Baghdad for the above period (Figure 8b). On 18^{th} and 20^{th} February, strong upward directed vertical velocity prevailed over the station. The upward directed vertical velocity values at 600 hPa on 18^{th} and 20^{th} were 2.6 cm/s and 4.9 cm/s (after converting omega in Pa/s into cm/s) respectively. The vertical lifting in the moisture rich environment (Figure 8a) was the cause for the rain on 18^{th} and 20^{th}. Thus the passage of the low pressure systems gives rise to rain over the Middle East region. The low pressure system gets dissipated during its propagation over the Middle East due to non availability of moisture.

The south-western Middle East region gets rainfall during March-May and July-August. The major rainy season of the region is March to May and is caused by the moisture rich wind from the Arabian Sea in the presence of the ITCZ while passing through this region to the north. Hence the amount of rainfall and number of rainy days are more during March to May in comparison with July to August. The remnants of organized convection formed as part of the Indian summer monsoon is responsible for the rainfall during July to August. The rainfall pattern over this region is similar to that of East Africa due to its proximity to the East Africa. In the East Africa, most of the annual rainfall is concentrated in two clearly distinct rainy seasons, in March–May and October–November, which correspond to the period when the ITCZ crosses the equator in its seasonal migration [11-16].

In an examination of rain producing system in the south-western part of the Middle East during July-August, we found that the organized convection as part of the monsoon system plays vital role in the rain events. As in the earlier case, a Hovmoller diagram (Figure 9) is used to understand the propagation of the monsoon organized convection from the east. The TRMM rain rate (averaged over the latitude belt, 15.25°N-15.5°N for representing Sanaa station) is used in the time-longitudinal cross section, to understand the rain producing system. From Figure 5e, the rainy days over Sanaa station is identified. We found that the rain events over this region during July-August are due to the passage of the organized convection as part of the monsoon system. Since the ITCZ passes over this region in its southward movement, it gives rise to organized convection in association with monsoon during July-August [17]. The role of monsoon organized convection in producing rainfall during the season is confirmed by carrying out similar analysis for other rain events at Sanaa.

Thermodynamic Structure of the Atmosphere: We examined the thermodynamic structure of the atmosphere over different stations in the Middle East to identify the role played by the local convection in producing rainfall over the region. The conditions favourable for local convection are high moisture in the lower atmosphere and instability. The instability is provided by the local heating. In the Middle East region, local heating and hence the surface temperature is high during the afternoon hours especially during summer, sufficient for the instability mechanism. Even though surface temperature is high, local convection is not triggered due to small amount of water vapour. The low moisture content is reflected in low LCL value (less than 400 hPa) and low CAPE (less than 300 J kg^{-1}) or no CAPE in most of the days. The surface humidity value increases whenever remnant of a low pressure system passes over the region such as Mediterranean system or monsoon organized convection. Even though the low pressure system gets dissipated during its passage over the Middle East region due to the aridity, the moisture content of the atmosphere increases. Subsequently, the LCL lowers (even below 800 hPa). This is favourable for triggering convection since instability prevails in most of the afternoons. High CAPE value alone need not produce convective rain. There are situation in which the surface air parcel cannot achieve the CAPE value since no lifting mechanism is available for crossing the stable layer (against the CINE value). The passage of a low pressure system helps to increase the moisture content of the lower atmosphere. More over, high CAPE value, low CINE value and favourable condition for vertical lifting provided by the low pressure system make the surface air parcel to cross the stable layer near the surface and to rise for a large height helping the formation of the local convective clouds. We present the thermodynamic structure of the atmosphere over Muscat associated with a local convection derived from the radiosonde ascent at 1200 UTC of 9th March, 2002.

The surface humidity on 9th March, 2002 was 54 % and CAPE value corresponding to 12 UTC observations was 802 J kg^{-1}. The amount of rainfall reported on the next day morning was 33 mm. Even though this rain event was caused mainly by the local convection, passage of a Mediterranean system on the previous day helped to increase the water vapour content of the atmosphere. This relatively high humidity lowered LCL to 875 hPa and brought the LFC to 672 hPa. The LOC (level up to which the temperature of the parcel is more than the environmental air) was beyond 400 hPa. This made the CAPE to 802 J kg^{-1}. The CINE value was 336 J kg^{-1}. Since the surface air parcel was able to cross this lowest stable layer up to 672 hPa (by the combined effect of buoyancy and the vertical lifting extended by the remnant of the Mediterranean cyclonic system prevailed over the region), formation of cloud and a rainfall of 33 mm occurred as reported in the next day morning.

In contrast, at Muscat, the CAPE value corresponding to 00 UTC radiosonde observation on 17th April, 2003 was 1097 J kg^{-1} but the rainfall on the next day was scanty. By the passage of Mediterranean system, the surface humidity increased and produced rain over Muscat on 16th April. Even though the system helped to increase humidity, persistence of overcast condition reduced insolation and subsequently local heating. The rain and less local heating made the lower layer of the atmosphere to become stable. It might be considered that triggering of local convection was inhibited by the non availability of the instability and hence no rainfall occurred due to local convection even with the high CAPE value.

We have examined many cases of rain events in different stations over the Middle East region and found that no incident in which local convection alone could produce rain over the region due to very small value of moisture content. Hence CAPE values are small (less than 300 J kg^{-1}) in most of the cases or no CAPE value at all. However, passage of remnants of low pressure systems from the Mediterranean or Arabian Sea helps to increase the moisture content of the atmosphere. Since local heating and subsequent instability prevails, increase in moisture content is favorable for the formation of local convection. We found that relatively high CAPE values (1000 J kg^{-1}) and associated local convective precipitation occur due to the increase in moisture content by the passage of the low pressure systems in different parts of the Middle East region.

Muscat gets rain during winter and spring when Mediterranean system passes over the region. Muscat also gets a few monsoon spells in most of the years as it is located in the coast of the northern Arabian Sea. However, total annual rainfall over this station is small. This station does not have any regular rainfall pattern. In certain years, more rain is during spring due to the Mediterranean system. But in other years, more rain is during summer due to the influence of monsoon. Tehran and Amman get rainfall during November to May due to the passage of the Mediterranean system only. These stations do not get any rainfall during monsoon season since they are located in the northern or northwestern parts of the Middle East. Riyadh (located in the central part of the Middle East) also does not get much monsoon rain. The rainfall over this region is caused mainly by the Mediterranean system. The south-western Middle East region (eg Sanaa station) gets rainfall during March to May and July to August. Since this station is located in the south-western part of the Middle East, it does not get any rain due to Mediterranean system. Riyadh and Muscat are located near the area of sinking motion and hence the rainfall amount is small. Due to this reason, these stations exhibit typical arid climatic conditions and do not have any regular rainy season. According to the favorable circulation pattern and rain producing mechanisms, the rainy period is different.

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. South-western part of the Middle East receives a rainfall of more than 2 mm/day during May to September and northern Middle East gets more than 3 mm/day during November to March. We found that the north-western, south-western and south-eastern parts of the Middle East get more annual rainfall compared to other parts. Two areas of minimum 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 atmosphere. 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 season. The area in between receives rainfall during winter and spring due to the Mediterranean system and during summer due to monsoon, even though the amount is small. More over, the rainfall pattern in the central and southern parts of the Middle East does not have any consistency. Thermodynamic structure of the atmosphere over the Middle East is not favorable for local convective precipitation in most of the cases due to insufficiency of moisture content as reflected in the CAPE as well as LCL values. However, passage of low pressure systems shoot up water vapor content and hence give rise to local convection.

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