DOI:10.28974/idojaras.2022.3.2

IDŐJÁRÁS

Quarterly Journal of the Hungarian Meteorological Service
Vol. 126, No. 3, July – September, 2022, pp. 305–318

Remote sensing study of cloud top absolute temperature with surface rainfall over Lahore (Pakistan) during monsoon

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(Manuscript received in final form April 19, 2021)

Abstract— The study attempts to build a relationship between clouds top absolute temperature and rainfall during monsoon period over Lahore during 2019. For this purpose, meteorological data was taken from Pakistan Meteorological Department (PMD) of few parameters (temperature and rainfall) for Lahore during monsoon period, i.e., from July to September, 2019. The study revealed interesting results for the observed three months. In July and August, the rainfall and temperature trend showed an inverse relation, whereas a decreased trend was observed for both temperature and rainfall during September, 2019. In Pakistan, most of the rainfall is a result of the depressions created over Bay of Bengal and Arabian Sea. High temperatures cause lower pressure that becomes a reason for originating of low pressures/depressions resulting in monsoon rainfall. During September, the average temperature of the study area was lower comparatively that ultimately resulted in low rainfall, and only 54 mm of total rainfall was recorded over Lahore during September, 2019 which was quite less than in July and August. Satellite cloud top temperatures were also taken from EUMETSAT to establish a relation between cloud top absolute temperature and surface rainfall over Lahore.

Key-words: clouds, absolute temperature, rainfall, monsoon, depressions, satellite

1. Introduction

Clouds enhance excitement to the atmosphere and are appealing aesthetically. One would not experience any snow, rain, lightning, thunder, halos, or rainbows without them. A cloud is considered as a visible accumulation of ice crystals or tiny water droplets that are suspended in the air. Cloud are found in a variety of forms at various altitudes (*Barry* and *Chorley*, 2003; *Richardson et al.*, 2017). One of the most observed features is the tropopause level clouds. Satellite based imageries have identified cirrus clouds in the tropics at the tropopause level (e.g., *Heymsfield*, 1986; *Nee et al.*, 1998; *Dessler et al.*, 2006; *Pan* and *Munchak*, 2011). The cloud pattern seems to correlate with the structure of fronts and tropopause in the sub-tropics (e.g., *Noël* and *Haeffelin*, 2007; *Posselt et al*., 2008; *Rani et al.*, 2015). This behavior is expected generally as following processes occur at such dynamical boundaries:

i. rapid variations in humidity and temperature,

ii. vertical development linked with frontal lifting.

Longwave (LW) cloud radiative forcing (CRF), and large shortwave (SW) are found in upper-tropospheric clouds linked with tropical convection. Clouds reflect SW radiation, that cools our earth, and its effect is mainly calculated by cloud optical depth. LW radiations are trapped by clouds, that in turn increases its temperature, warms the climate, and that primarily depends on cloud top temperature. (*Reed* and *Recker*, 1971; *Zeng*, 1999) investigated satellite imageries that observed a peak in stratiform anvil and thin cloud about 175 hPa, that corresponds to nearly 13 km. Upper level divergence measurements were also made, that proposed a peak at about the same level. Various researches have also recommended convective detrainment quite below the tropopause. (*Folkins et al*., 1999, 2000; *Sivakumar* and *Stefanski*, 2009) proposed that convective detrainment occurs below 14 km, based on the concentration of ozone, which is maximum at the stratospheric level (stratospheric ozone). Extreme weather events (floods, heat waves, heavy rainfall, and droughts) have a significant importance in regional and social situations. Changes in extreme precipitation events have significant impacts and pose serious challenges to societies, especially in arid and semi-arid environments (*Kubar et al*., 2007; *Zhisheng et al*., 2015; *Karimi at al.*, 2021).

Generally, most of the clouds are formed based on the following mechanisms:

i. convection and surface warming,

ii. surface topography, and

iii. widespread ascent due to surface air convergence (*Ahrens*, 2007).

1.1. Surface heating and convection

The global circulation pattern in terms of precipitation plays a vital role as far the functionality of the Earth's system is concerned. It transports heat from the tropics to the higher latitudes, and hence it helps to regulate the earth’s temperature. The weather system is severely affected by the Southeast Asia monsoon season. Despite of the fact that lot of research has been conducted on the interactivity of the monsoon seasons, yet the influence of climate change in terms of rising temperatures on monsoon rainfall concentration has not gained much attention in Southeast Asia (*Kripalani* and *Kulkarni*, 1997; Loo et al., 2015; *Panda* and *Sahu*, 2019).

Some areas on the earth absorb the sunlight more than others. As a result, the air in contact with such areas becomes warmer than the surrounding air: a hot air bubble thermal results, it rises, and as it mixes with cooler drier air around, it starts losing its individuality. Now its upward motion slows down and before that it absolutely dilutes, another thermal comes and rises the air bit more (*Fig. 1a*). As the air cools, it becomes heavy and downward motion starts. Slowly and gradually the cool air descends and replaces the rising warm air. Now inside the cloud there is the rising air, and around it is the sinking air (*Barry* and *Chorley*, 2003).

1.2. Topography

Topography is the study of the shape and structures of the earth’s surface, e.g., mountains, hills, basins, etc. Horizontally developed clouds can not pass through a big obstacle, e.g., mountain and air has to cross over it. Such forced lifting along an obstacle is known as orographic uplift. Usually large air masses rise, when they move across stretched mountainous belt (*Fig. 1b*). Due to this lifting, cooling takes place and here clouds will form in humid air. Clouds formed in this way are called orographic clouds. When the air sinks on the leeward (away from wind) of the mountain, it gets warm. While the air is moving downhill, it is drier as most of the moisture present occur as precipitation, and clouds was removed on the windward side. The region on the leeward side experiencing less precipitation is named rain shadow (*Kirshbaum et al*., 2018; *Stockham et al.,* 2018).

1.3. Widespread ascent and clouds

As the mountains force air to rise, the convergence (flowing together) of air in the lower troposphere will result in the lifting of air and formation of clouds. The main cause of this lifting of air is cyclonic storm system. Another cause of this air lifting are weather fronts (*Fig. 1c,d*).

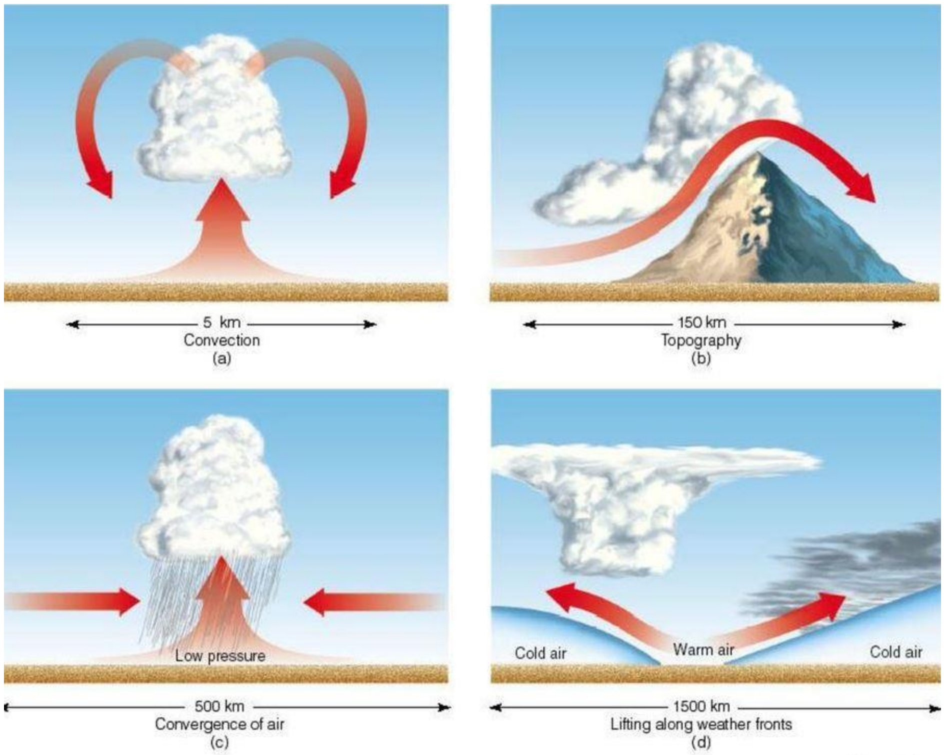

Fig. 1. (a-d): The primary ways clouds form: (a) surface heating and convection; (b) forced lifting along topographic barriers; (c) convergence of surface air; (d) forced lifting along weather fronts. (Source: *Ahrens* and *Henson*, 2021)

1.4. Occurrence of monsoon

The periods of pre-monsoon and post-monsoon are significant in a way that the changing wind pattern gives birth to cyclonic circulation over the Arabian Sea and Bay of Bengal. Almost 80 tropical storms (tropical cyclones with wind speeds greater than or equal to 17 m/s) generate in the world's water bodies annually (*Chang et al.*, 2004). Among them, around 6.5% generate in the North Indian Ocean (Arabian Sea and Bay of Bengal) (*Knapp et al.*, 2010; *Bewoor* and *Kulkarni*, 2009).

1.5. Monsoon rainfall and circulation

The major characteristic of monsoons is that they cause rainfall that might lead to coastal and urban flooding. As per study conducted by NASA, between 50–75% of the annual rainfall in Pakistan and India is due to monsoon (*Huang* and *Margulis*, 2011). Land and sea breezes occur as a result of the difference in heat capacity of land and sea surface (i.e., their temperature rises for a given heat input) (*Betts*, 2000). In summer, the solar radiation is strong, and during winter, the pressure is low, because land surface is cool and ocean is warmer as well (*Betts*, 2000). The winds gust gradually move from southwest (SW) during summer and from northeast (NE) during winter (*Fig. 2a,b*). Hence, the climatologists have defined monsoon as a large scale wind system that either prevails or powerfully affects the climate of a large regions, and also in which the direction of the wind flow reverses from winter to summer (*Margulis* and *Entekhabi*, 2001).

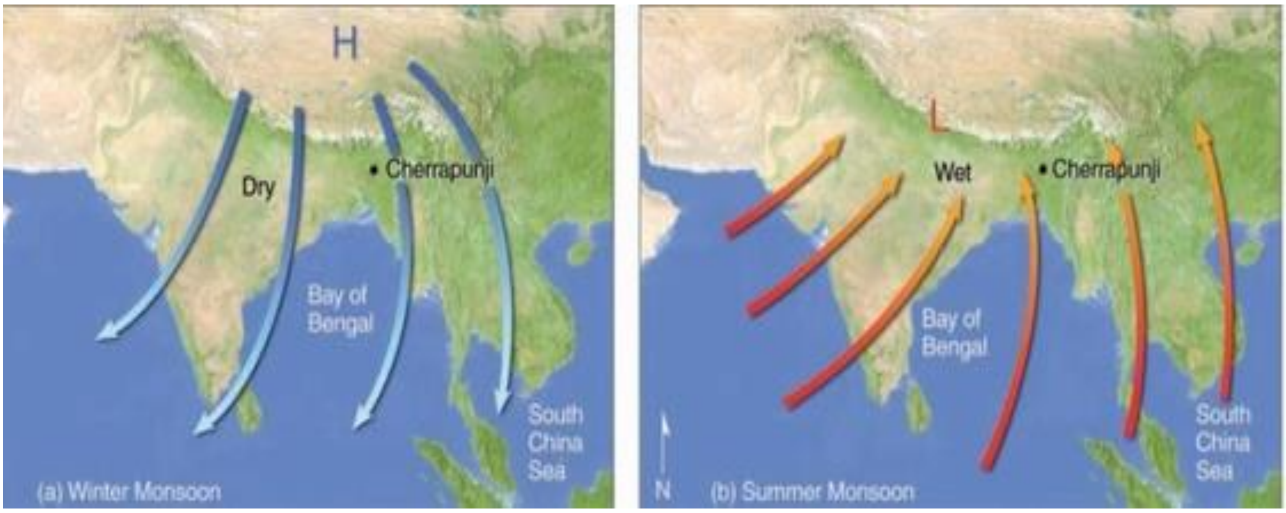

Fig. 2. Monsoon circulations. (source: *Ahrens* and *Henson*, 2021)

Plenty of valuable water is been provided to Asia by monsoon rainfall. The economy of most of the monsoon climatic region that includes South, East, and Southeast (SE) Asia depends mainly on agriculture, that is further dependent on monsoon rainfall. Hence, the fate of the region is dependent upon the direction and flow of the monsoon winds (*Barros* and *Hwu*, 2002). Any deviation of the monsoonal pattern can affect the agriculture operations over such regions threatening their economies.

2. Study area and methodology

Lahore is Pakistan's second largest metropolitan city and the provincial capital of Punjab Province. It stretches over a total land area of 404 square kilometers and is almost 24 kilometers away from the Indian border (*Daly et al*., 2004). Lahore is bounded by the Sheikhupura district on its north and west, on the south by Kasur district, while on the east by Wagha (*Fig. 3ab*). The geographical coordinates (latitude, longitude) of Lahore are 31°34' N, 74°18' E. The climate of Lahore is semi-arid, where in June (hottest month) the average temperature routinely exceeds 40 °C. The monsoon season extends from mid-July till mid-September experiencing heavy rainfalls and thunderstorms with the possibility of cloudbursts resulting in coastal and urban flooding. January is the coolest month with dense fog (*Medeiros et al*., 2005). Lahore receives an average monsoon rainfall precipitation of 628.8 millimeters. In 2009, it received below normal monsoon rainfalls as a result of El-Nino over Pakistan (*Juang, et al*., 2007). In 2011, Lahore received the highest ever annual rainfall when 1,576.8 millimeter of rainfall was recorded. Normal rainfall was observed in Lahore in 2007 and 2010 (*Hunt et al.*, 2018; *Siddiqui* and *Siddiqui*, 2019). (*Fig. 4*) shows average maximum and minimum values of average monthly temperatures of Lahore, Pakistan.

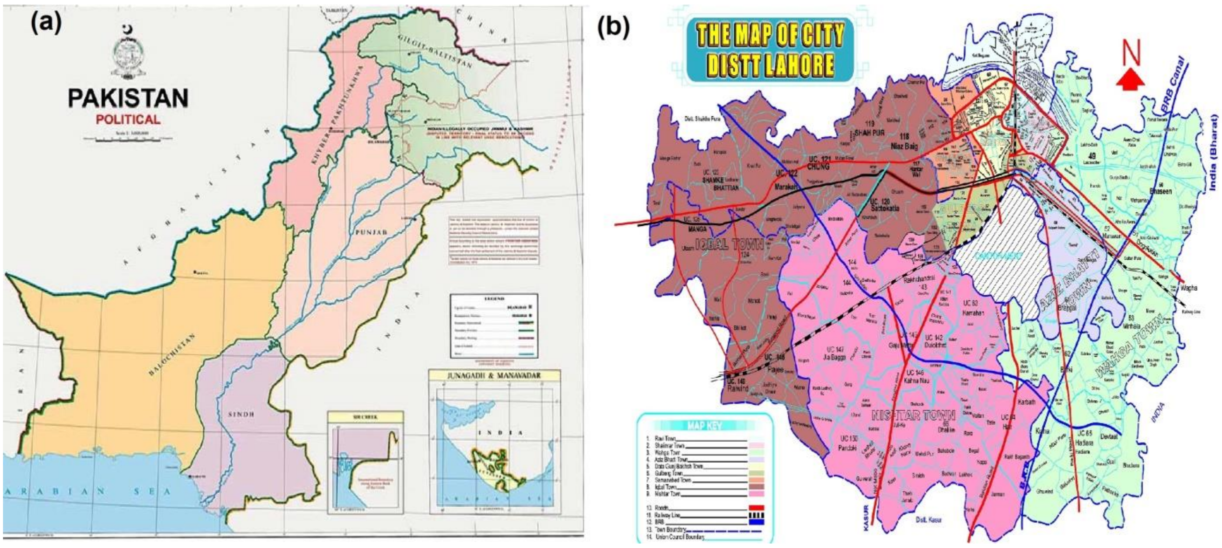

Fig. 3. Political map of Pakistan (source*: the news international*, 2020; *Ali et al.*, 2015).

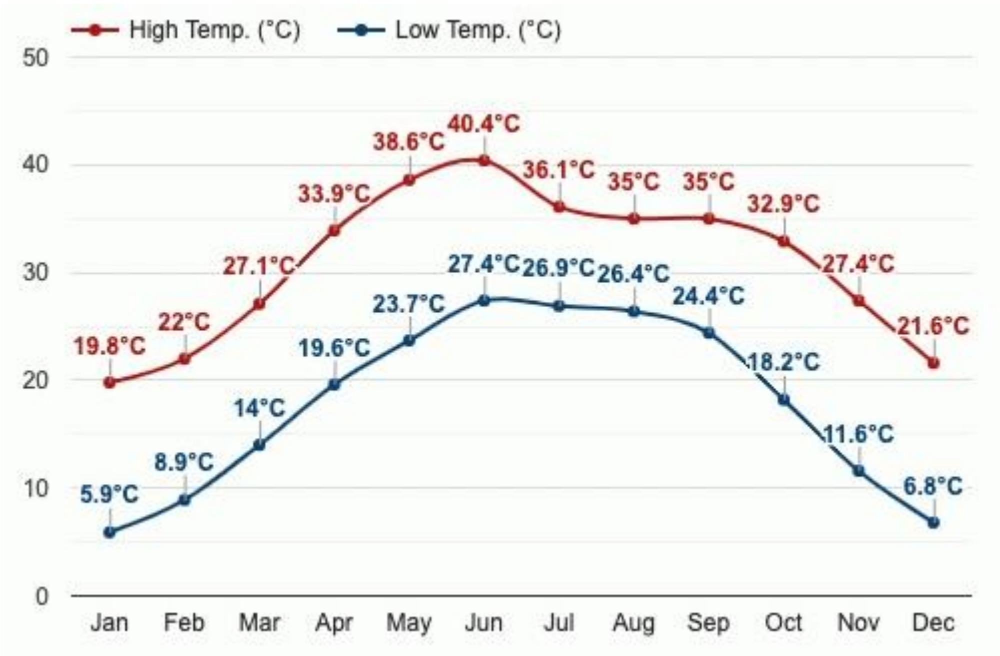

Fig. 4. Maximum and minimum values of average monthly temperatures of Lahore (Source: PMD, 07/12/2020).

Temperature and rainfall data was collected from Pakistan Meteorological Department, Lahore, for the months July-September, 2019. Graphs were plotted for daily maximum and minimum temperatures and rainfall of Lahore. Satellite images for the cloud top temperature were also taken from Pakistan Meteorological Department. For cloud top temperature, European Meteorological Satellite (EUMETSAT) was used.

3. Results and discussions

Rainfall is due to the result of two processes: condensation and evaporation. In summer, the process of evaporation increases because of heat from the sun which results in the gathering of more vapors in the atmosphere. These gathered vapors form tiny water droplets, and the process is called condensation. Ultimately, these droplets result in rain.

3.1. Temperature and rainfall analysis from July to September, 2019

A decreased trend was shown in the daily minimum and maximum temperatures of Lahore for July and September, while August exhibited an increased trend (*Figs. 5* and *6*). Two daily rainfall peaks were recorded for July (92 mm and 75.8 mm), August (57.8 mm and 63 mm), and September (22.2 mm and 14.4 mm), respectively (*Fig. 7*).

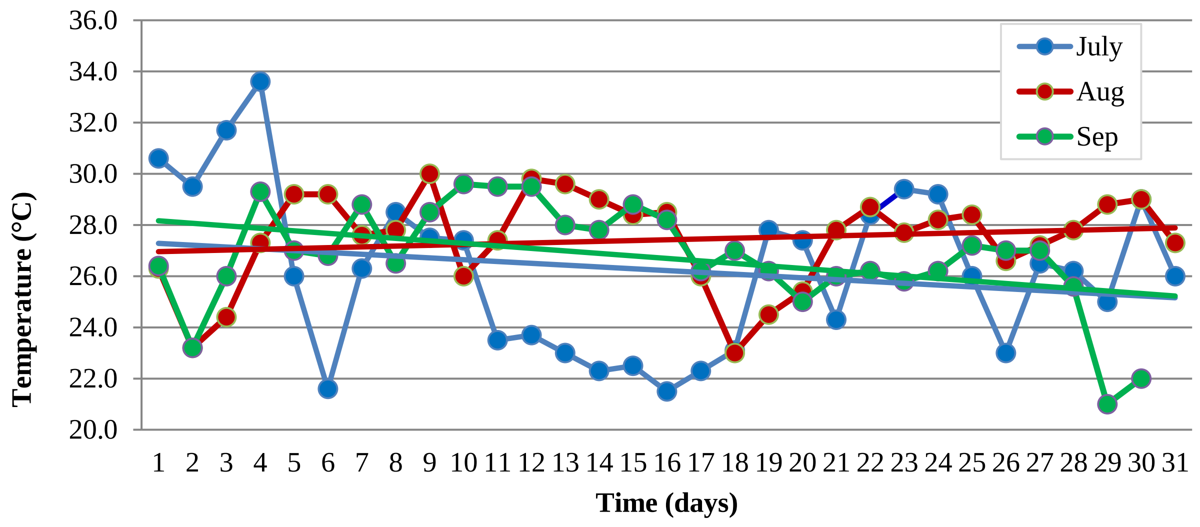

Fig. 5. Daily minimum temperature of Lahore from July to September, 2019.

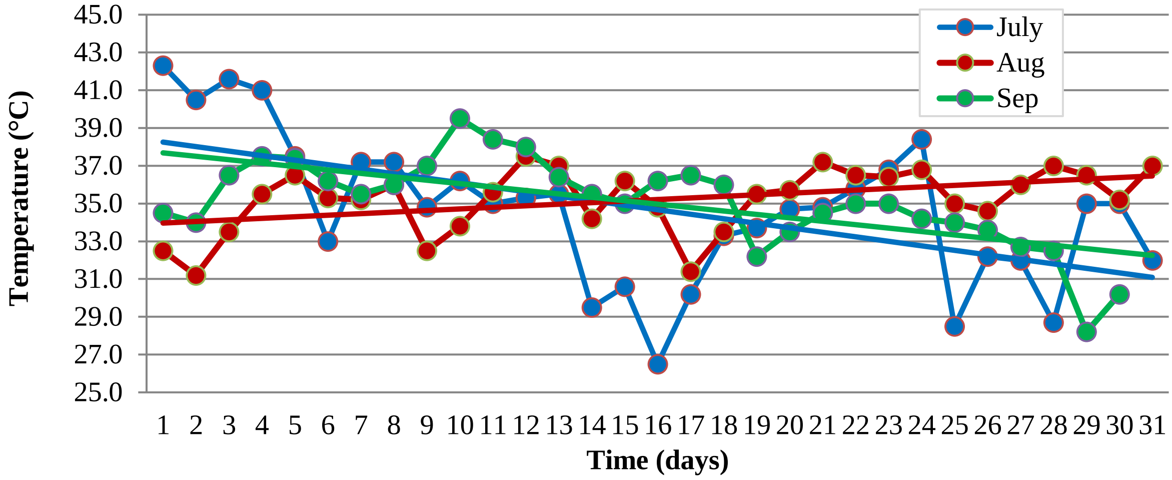

Fig.6. Daily maximum temperature of Lahore from July to September, 2019.

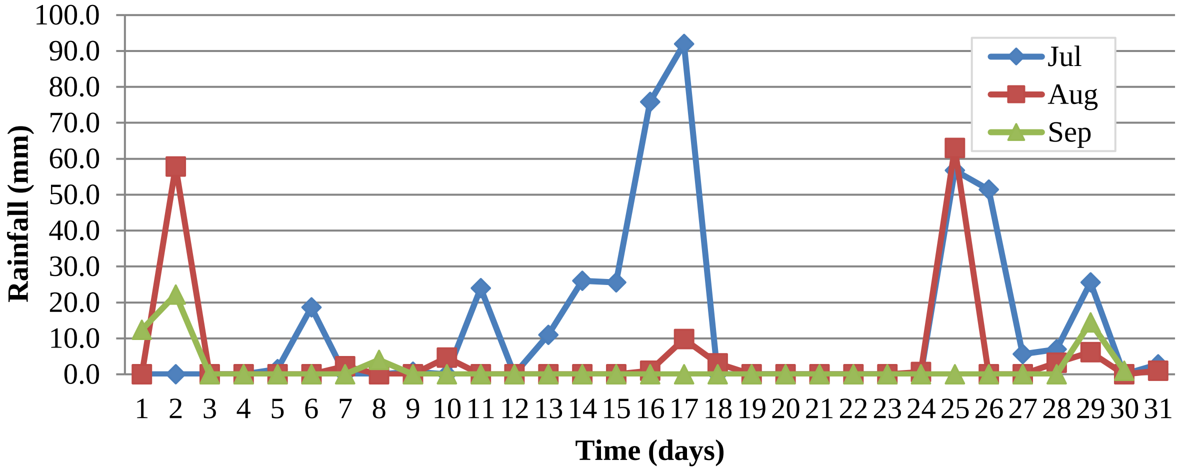

Fig. 7. Daily rainfall of Lahore from July to September, 2019.

3.2. Cloud top temperature

Satellite cloud top temperatures were also taken for moderate to heavy rainfall days of the monsoon months (July-September, 2019) to establish a relation between cloud top absolute temperature and surface rainfall over Lahore during the monsoon period, 2019. Selected days of July and August months were taken on the basis of their rainfall and corresponding cloud top temperatures (*Figs. 8a-f* and *9a-f*). Rainfall results after the process of evaporation and condensation. Vapors condense in the upper atmosphere shaping in water droplets and ice crystals to form clouds. The temperature of rainy clouds varies from 0 °C or below 0 °C. During the month of July, 424.3 mm rainfall was recorded, while a total of 152.4 mm rainfall was recorded in the month of August.

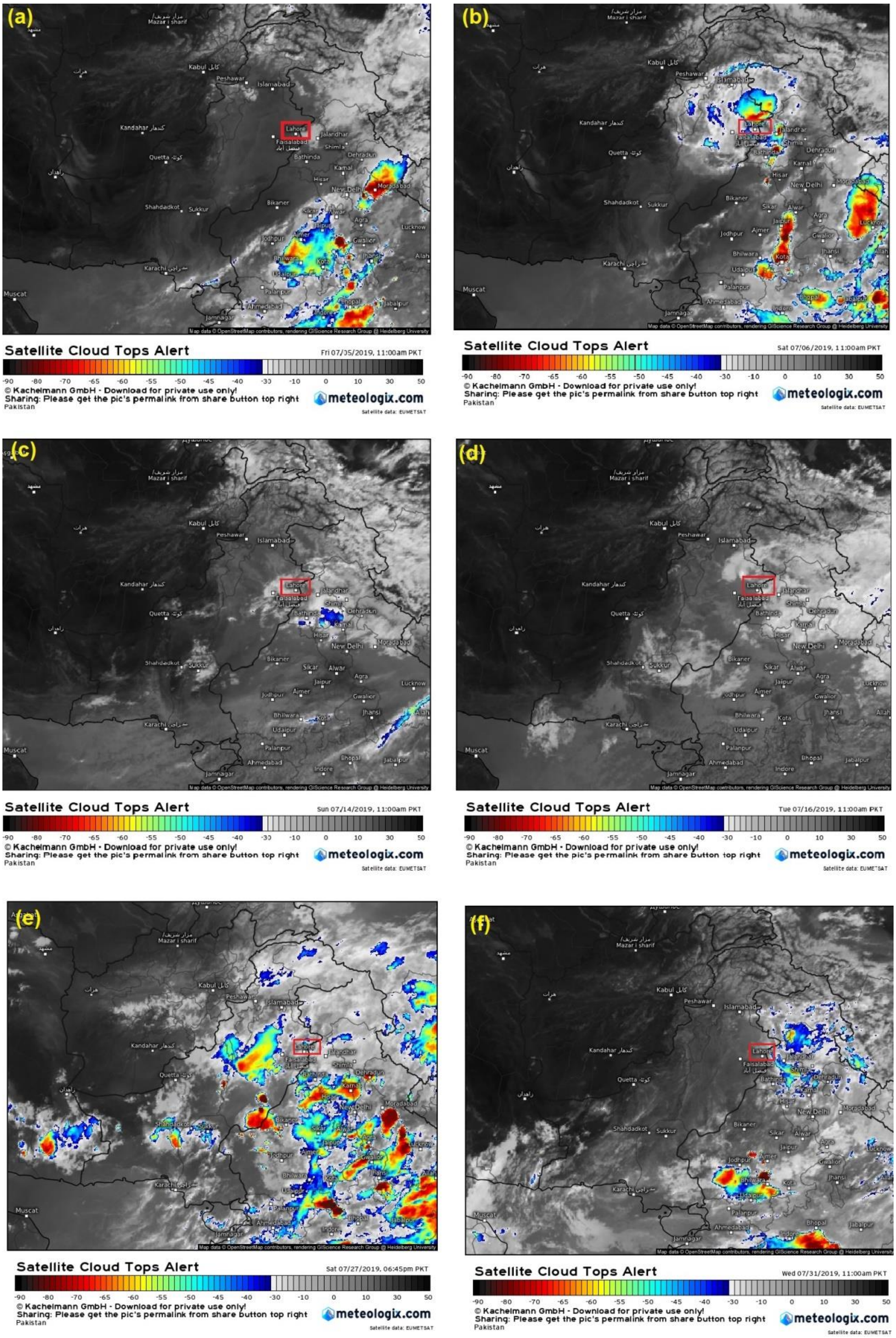

Fig. 8. Cloud top temperatures for the July monsoon spell: (a) July 5, 2019; (b) July 6, 2019; (c) July 14, 2019; (d) July 16, 2019; € July 27, 2019; (f) July 31, 2019.

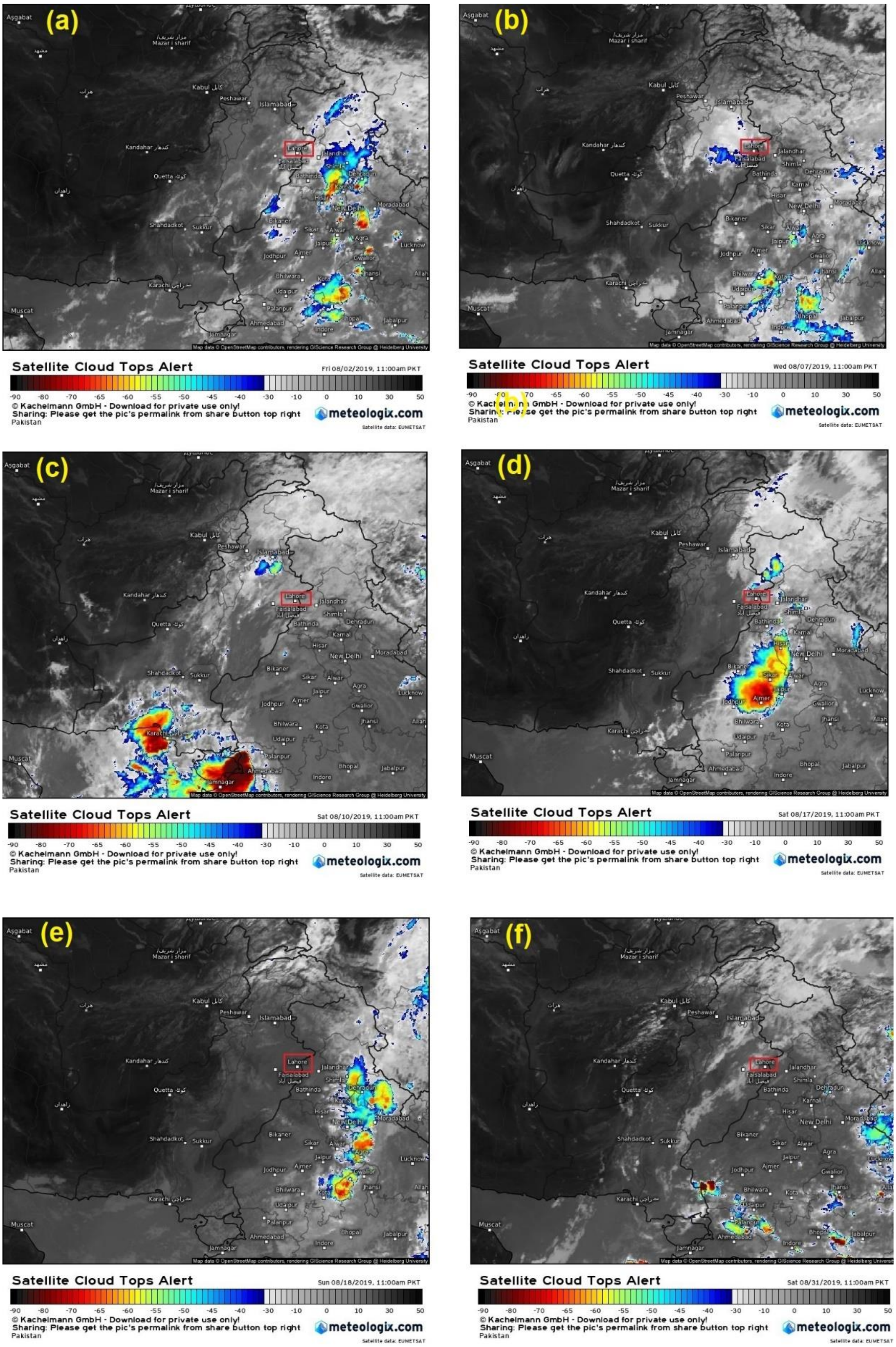

Fig. 9. Cloud top temperatures for the August monsoon spell: (a) August 02, 2019; (b) August 7, 2019; (c) August 10, 2019; (d) August 17, 2019; € August 18, 2019; (f) August 31, 2019.

3.3. *Cloud top temperature and rainfall relation*

Relations between the rainfall and cloud top temperature on the study area are shown in *Figs. 10* and *11*. The graphs clearly show as the cloud top temperature decreases and in accordance with the Bergeron Findeisen theory, where super cooled water droplets and ice crystals having high vapor pressure exist together, the rainfall becomes heavy and falls down as precipitation. The low cloud top temperatures in July and August have higher cloud tops resulting in more growth of cloud vertical column being the cause of rainfall. The saturation of water vapors is due to the influence of moist/humid air coming from Bay of Bengal and Arabian Sea resulting in precipitation.

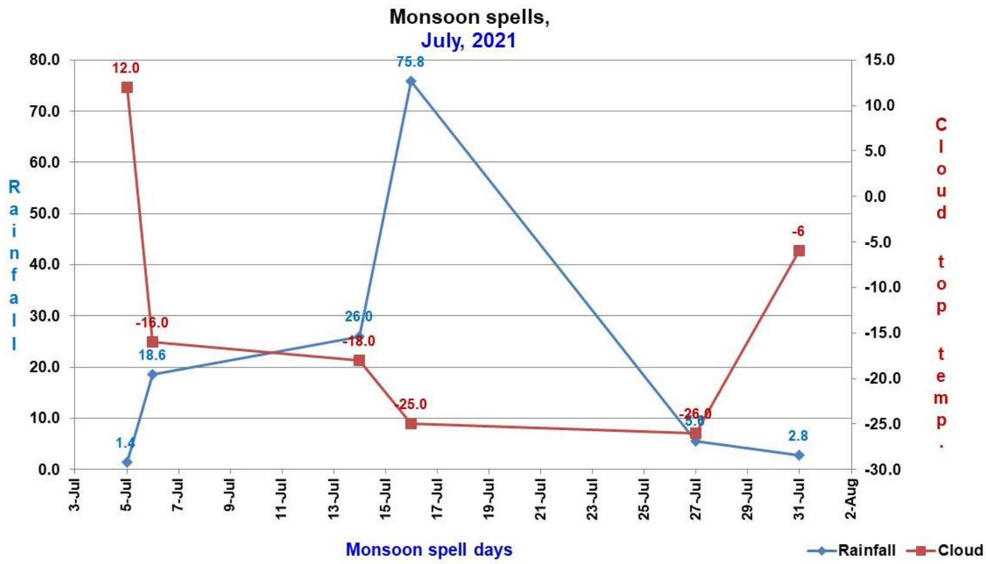

Fig. 10. Relation between cloud top temperature and rainfall (July, 2019).

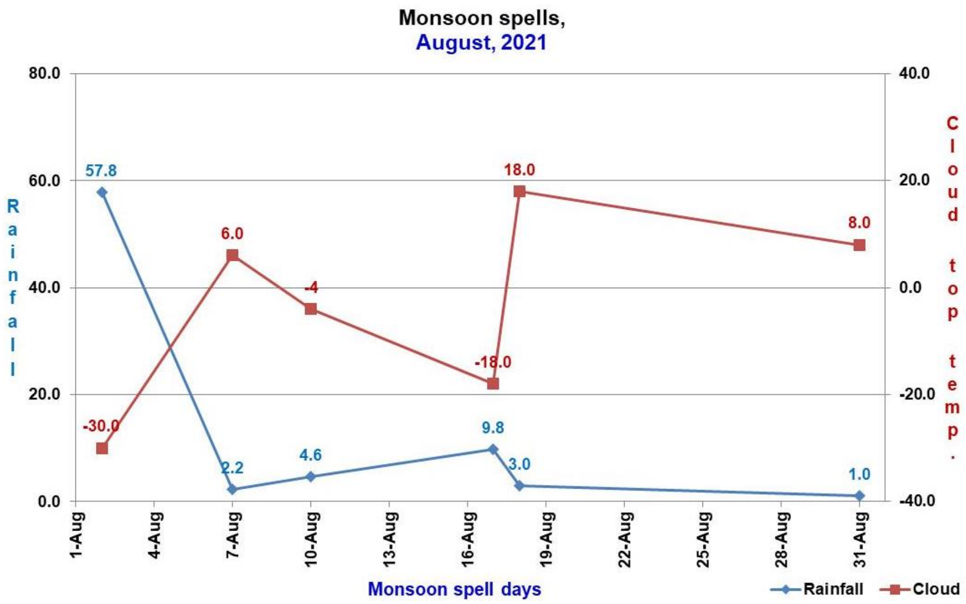

Fig. 11. Relation between cloud top temperature and rainfall (August, 2019).

4. Conclusions

In general, heavy rainfall occurs during the monsoon season over Pakistan, that normally lasts from mid-July till mid-September. This monsoon rainfall is a result of the depressions and low pressures originating over Bay of Bengal and Arabian Sea. July and August revealed a direct relation between temperature and rainfall, while a reverse trend was observed between these two parameters during September. Least rainfall was recorded during September, 2019 which means very few depressions originated over Bay of Bengal or Arabian Sea. In July, the moisture inflow was from moist sources, i.e., BoB and Arabian Sea resulting in precipitation, whereas in August, the saturation of water vapors is due to the condensation of the air lowering the cloud top temperature resulting in precipitation. It is recommended that a study may be made for the winter monsoon period (western disturbances) to observe the trend for that period. A detailed study can be made over the northern, central, and southern regions of Pakistan authenticated by satellite images (IR color code image, 6 GMT).

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