Chapter 9
Cloudburst—A Major Disaster in The Indian Himalayan States

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9.1 Introduction

Cloudbursts and related flash flooding are one of the Himalayan regions' utmost significant natural calamities. The cloudbursts result from monsoon clouds originating from the Bay of Bengal, bringing an immense amount of rainfall across the Gangetic Plain to the Himalayas, and under the topographic influence "bursting" into a torrential downpour [1]. In India, cloudbursts usually occur in steep orographic regions during the monsoon season, such as the Himalayan region, the north-eastern states, and the Western Ghats. Cloudburst usually occurs where a steep topography experiences a deep and fast uplift of the saturated thermodynamic unstable atmosphere [2]. Convective clouds formed may lie up to 15 km height in cloudburst-like systems and because of its extremely localized occurrence, and ground observation stations are barely able to capture the features of the storm [1]. Generally, cloudbursts occur in inaccessible hilly areas and are not reported until a significant socio-economic disturbance is caused by the subsequent flash flooding and landslides [3]. A cloudburst, also known as rain gush or rain gust, is an intense form of rainfall where a high rain intensity falls over a localized region of about 20–30 km^2 [2]. The India Meteorological Department (IMD) defines cloudburst as a 100 mm/h intensity rainfall event accompanied by lightning and strong winds. This excessive amount of rain falling within a short period further leads to an intense runoff in the form of flash-floods [4]. The conditions and physical processes leading to flooding in the Himalayas are extremely complex, involving multiple genes, and diverse atmospheric and terrestrial surface processes. Geological instability of the region, together with high atmospheric precipitation, is responsible for widespread landslide occurrences. Despite their devastating effects on human life and the Himalayan socio-economy,

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the hydro-meteorological analysis of the "cloudbursts" is given little consideration. [5] have illustrated the usage of remote sensing knowledge to link the space–time variability of the cloudbursts with precipitation, topography, and large-scale patterns of circulation.

In this paper, an attempt has been made to utilize the satellite-derived hydro-meteorological datasets for understanding the characteristics and spatiotemporal variation of cloudbursts over the Himalayan region, especially Uttarakhand. This would not only help in developing a more comprehensive understanding of the mechanism associated with these cloudbursts events but would also shed some light on the identification of these events in future.

9.2 Study Area

The Uttarakhand state is located from latitude 28.44–31.28 N, longitude 77.35 to longitude 81.01 E (Fig. 9.1). The area of this hilly state is 53,483 km^2, which makes up 1.63% of India's landmass. There are 13 districts and 95 development blocks in the State and the whole state is divided into two regions the eastern part, known as Kumaun and, the western part as Garhwal. Dehradun, in the district of Garhwal, is the state capital. Uttarakhand is the initial source of many perennial Indian rivers.
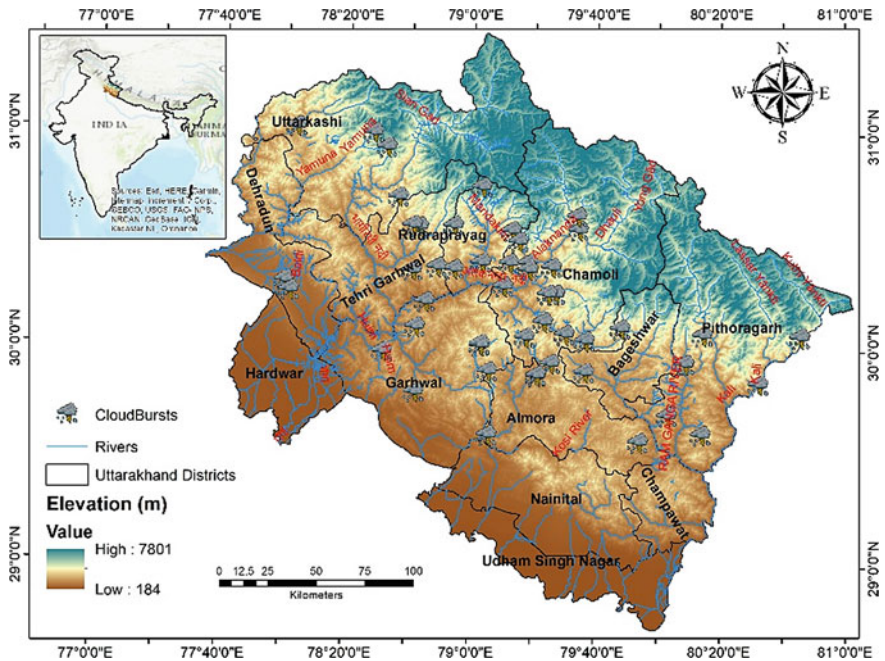

Fig. 9.1 The elevation map of Uttarakhand with the cloudbursts location

The region is dominated by three major river systems, namely the Ganga system, the Kali River network, and the Yamuna-Tons river system. In high altitudes as well as in the lower Uttarakhand basins, the climate conditions are very distinct. The climate and landscape differ considerably with the elevation. The state has a high estimated annual precipitation of 1229 mm. Cloudburst is now a common problem in the high-altitude area of the Himalayas during the moon and pre-monsoon. In the past 20 years during the monsoon, the state alone witnessed more than 40 incidents of cloudbursts.

9.3 Datasets and Methodology

9.3.1 Cloudbursts Occurrences

To estimate the hydro-meteorological characteristics of the recent cloudbursts in the region, firstly, the collection of occurrences of the cloudbursts, which were documented by various agencies, authors, and news reports, namely National Institute of Disaster Management (NIDM), Uttarakhand State Disaster Management Authority (USDMA), [6, 7] and India Meteorological Department (IMD). Around 44 locations were identified, in which 14 incidents were reported in Chamoli, 5 in Pauri Garhwal and Pithoragarh each, 4 in Almora, Tehri, and Uttarkashi each, 3 in Rudraprayag, 2 in Bageshwar and Dehradun each, and 1 incident in Yamunotri. The detail of some major incidents (Fig. 9.2) and their estimated impacts are as follows:

a. August 11, 2001—Around 27 humans, 64 animals, 22 houses were lost due to the cloudburst-induced flash flood near the Phata village of Rudraprayag.
b. August 31, 2001—28 houses, 7 animals, and 7 humans were reported missing in the Gona village, Tehri.
c. September 15, 2010—Around 2 villages were washed away due to the cloudbursts induced flash-floods in Almora.
d. August 3, 2012—A cloudburst incident was reported in Pandrasu ridge of Uttarkashi. The resulting flash-floods affected around 35 humans, 436 livestocks and damaged around 591 houses.
e. September 12–14, 2012- A series of cloudburst occurred in the Rudraprayag district that resulted in the loss of about 66 peoples.
f. June 16–17, 2013—Numerous incidents of cloudbursts and resulting flash-floods were reported in Kedarnath, Rambada, Badrinath region of Uttarakhand. This incident killed more than 10,000 people, around 400 houses were damaged and more than 1 lakhs people were affected.
g. May 28, 2016—Around 120 houses and100 animals were lost in the cloudburst incident in Kemra village of Tehri.
h. July 2–19, 2018—Multiple incidents of cloudbursts and flash-floods were reported in the Uttarakhand at Garhwal, Pithoragarh, Dehradun, Chamoli, and

Fig. 9.2 Major cloudburst incidents in Uttarakhand followed by flash flooding caused huge damages at **a** Kedarnath, Rudraprayag-2013 **b** Thipak village, Chamoli-2016 **c** Pithoragarh-2018 **d** Uttarkashi-2019; Image Source: https://www.hindustantimes.com/; https://www.firstpost.com/; https://primenewslive.com/; https://www.indiatoday.in/

   Uttarkashi district. Near about 20 people, 15 houses, 15 shops, 4 roadway bridges, several vehicles, and cowsheds were damaged.

i.   August 8–18, 2019—Several cloudburst events were reported in Chamoli, Rudraprayag, Tehri, Garhwal, Bageshwar, Uttarkashi, and Pouri district of Uttarakhand. More than 30 people were reported dead.

9.3.2 Dataset Collection

To evaluate the trends and correlation of various cloudbursts influencing factors, the satellite observations were incorporated. The datasets were retrieved using various algorithms in Google Earth Engine [8]. The datasets used in this study are as follows:

- The Digital Elevation Model has obtained from Shuttle Radar Topography Mission (SRTM) satellite datasets at 30 m resolution.
- The European Centre for Medium-Range Weather Forecasts (ECMFW) ReAnalysis (ERA5) from year 2001 to 2019 at 0.25° was used for the analysis of air temperature, dew point temperature and pressure.
- The Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) from year 2001 to 2019 at 0.05° resolution was used for the analysis of rainfall.

- The Land Aerosol Optical Depth Daily (MCD19A2.006: Terra and Aqua) at 1000 m resolution from the year 2001 to 2019 was used to study the Aerosol Optical Depth.

9.4   Methodology to Assess the Cloudbursts

The study of the characteristics of the cloudburst requires the identification of numerous influencing factors. These factors have been categorized into three division, each representing a vital cause for the occurrence of cloudbursts. They are, namely Climatic, Orographic, and Anthropogenic cause. The climatic factor being the primary cause, includes precipitation, air and dew point temperature, surface pressure over a region, and their interaction with the environment.

The orographic factor mainly includes the elevation of the region. In the Himalayan regions, the orography along with the hydro-meteorology generates large-scale forcing leading to synoptic-scale extreme events that further lead to flooding. The anthropogenic cause includes the changes in the land-cover patterns and aerosols and its impact on the natural and atmospheric environment. The monthly time series of these factors were evaluated and correlations were plotted to study their variability with the topography. The overall methodology to assess the cloudbursts for the region is shown in Fig. 9.3.
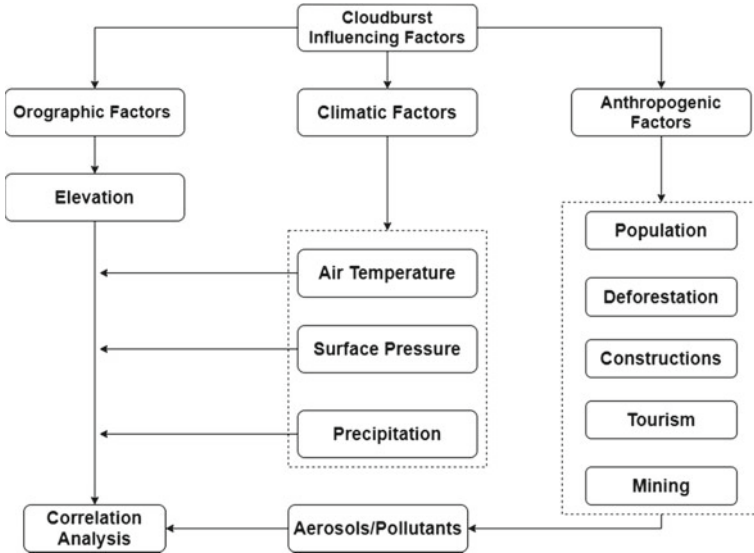

Fig. 9.3   The overall methodology adopted to assess the cloudburst impact over the region

9.5 Results and Discussion

Extreme rainfall associated with cloudbursts and resulting in flash-floods over the Himalayan region is a result of numerous complex and non-linear processes. The atmospheric flows together with orographic forcing interactions invigorate flash-floods. The GFI-Global Flood Inventory by [9], shows that most of the floods (64%) events occur due to heavy rainfall of shorter duration, followed by torrential rains (11%). These heavy rain occurrences are primarily attributed to regional factors such as lake outbursts, cloudbursts, orographic forcing, and landslides.

9.5.1 Climatic Factors

The climate of India is generally governed by the summer and winter monsoon. On account of varying elevation and rugged topography, the climate of the Himalayas differs across the regions [10, 11].

Precipitation Active monsoon is the most common extreme rainfall events in the Himalayas that occur every year. The winds from the southwest cause rainfall during the summers while during winters the region receives the rainfall and snowfall from the Mediterranean region.

The annual precipitation time series of Uttarakhand from 2000 to 2019 shows that the minimum and maximum annual rainfall ranged from 1535 to 2338 mm in the year 2001 and 2011, respectively, with a mean annual rainfall of 1865 mm. The maximum, minimum and mean precipitation curve was plotted (Fig. 9.4) and it was
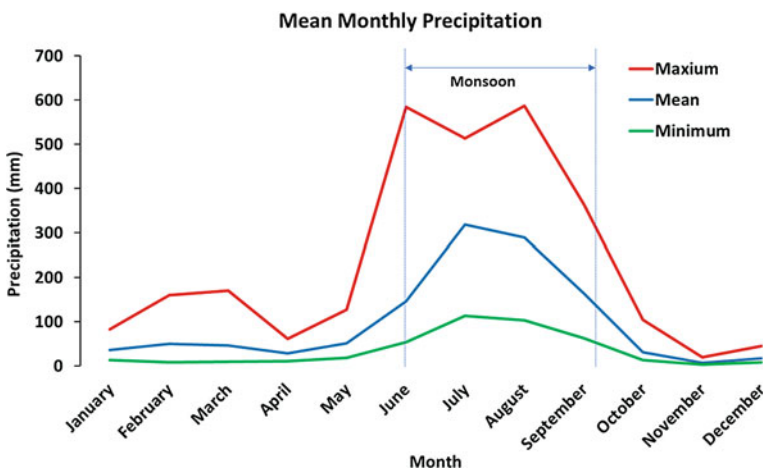

Fig. 9.4 The minimum, maximum, and mean monthly rainfall curve for Uttarakhand

found that in the monsoon season, the monthly precipitation ranges from 364 to 586 mm, which may cause the occurrences of frequent flashfloods.

Air and Dew Point Temperature Increase in temperature increases the atmospheric humidity and leads to extreme rainfall occurrences [12]. During a rainfall event, the temperatures can decrease due to the movement of cold air associated with the rainfall event and evaporative cooling. Also, the distribution of rainfall also varies throughout the months as shown in Fig. 9.5. In this study, the region was divided into six seasons based on the air temperature statistics, viz, pre-summer, summer, post-summer, pre-winter, winter, and winter as shown in Table 9.1.

The amount of moisture and humidity in the air is indicated by the dew point temperature. The increase in dew point temperature increases the moisture content of the air, such that when it becomes equal to the air temperature, precipitation occurs [13]. From the time series analysis of the air temperature from 2000 to 2019 for Uttarakhand, it was found that the mean air temperature ranges from −4.72 °C
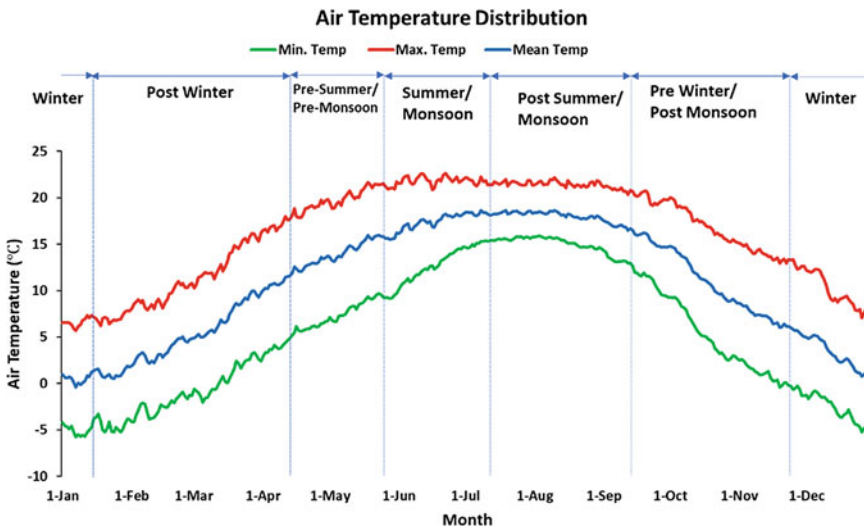

Fig. 9.5 The distribution of Air temperature w.r.t. the seasons for Uttarakhand

Table 9.1 Distribution of seasons based on Air Temperature

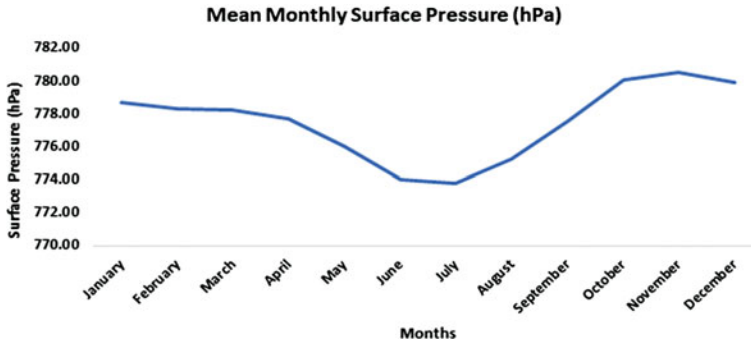| Pre-summer/pre-monsoon Mean 14.3 °C /Min 12.0 °C/Max 16.2 °C		Summer /monsoon Mean 17.8 °C/Min. 16.4 °C/Max 18.7 °C		Post-summer /monsoon Mean 17.9 °C/Min 16 °C/Max 18.6 °C	
16-Apr	31-May	1-Jun	15-Jul	16-Jul	15-Sep
Pre-winter /post monsoon Mean 10.2 °C/Min 5.0 °C/Max 16.2 °C		Winter Mean 2.1 °C/Min − 0.4 °C/Max 5.2 °C		Post-winter Mean 5.7 °C/Min 0.5 °C/Max 12.6 °C	
16-Sep	30-Nov	1-Dec	15-Jan	16-Jan	15-Apr

Fig. 9.6 The mean monthly surface pressure distribution for Uttarakhand

to 21.86 °C in the months of January and June, respectively, and the mean dew point temperature ranges from −5.42 °C to 15.94 °C in the months of January and July, respectively.

Pressure

Owing to the presence of temperature variations in the environment, temperature differences between the atmosphere and the water within oceans and lakes, the effect of the high-level disturbances, and the amount of solar heating or radiation cooling of a region the high- and low-pressure system develops. Pressure mechanism triggers local weather phenomena. Air rises in areas where the pressure at the surface is low. The clouds, precipitation, and bad weather are mainly associated with the low-pressure systems. The mean monthly variation of surface pressure from 2001 to 2019 (Fig. 9.6) indicates that the pressure varies over the months and the minimum pressure mostly occurs in the months of June and July, which results in the frequent occurrences of cloudbursts in this region.

9.5.2 Anthropogenic Activities

The region's vulnerability to disasters has increased due to unscientific development and patterns of land use, deforestation, increased pressure on humans and cattle populations, poor socio-economic conditions, increased tourism. According to the census, the population increased to 100.86 lakhs in 2011 from 84.89 lakhs in 2001 and the average population density in Uttarakhand rose to 189 in 2011 from 159 in 2001 (19%). The extensive population growth over a decade has adversely affected the already fragile hill state environment by increasing demand for development and forcing people to engage in more agriculture and other developmental activities in sensitive areas. As the tourist influx has increased, many multistoried hotels and other amenities were built even in the environmentally sensitive areas of the city.
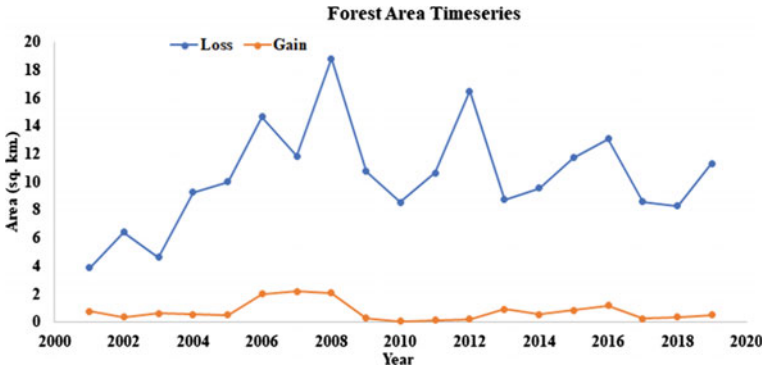
Fig. 9.7   The timeseries forest cover change for Uttarakhand from 2001–2019

Some of the hotels are designed for tourists/pilgrims on the banks of rivers and even in flora of the plain [14, 15]. The forest degradation due to these activities has led to increase in the events of landslides and soil erosion which further silts the reservoirs. The time series analysis of forest cover from 2001–2019 using Global Forest Change datasets [16] revealed that in the Uttarakhand region, every year around 9.63 km^2. of forest loss occurs on an average (Fig. 9.7). This loss in forest cover hinders the evapotranspiration and thus leads to disturbance in the water cycle and affects the precipitation pattern throughout the region.

All these anthropogenic activities lead to the development of aerosols. The connection between aerosol clouds and precipitation is a concern in the field of aerosol and has a direct impact on the atmosphere. The rise in anthropogenic aerosol emissions in recent years and the aerosol-cloud-precipitation interaction analysis has become increasingly relevant in the study of atmospheric pollution. The aerosols directly influence earth-atmosphere layer radiation by absorbing and scattering sun radiation; the indirect effect of aerosols relates to the presence of cloud condensation nuclei (CCN) or ice nuclei (IN) in aerosols. In addition, mesoscale weather patterns, such as cloudbursts and thunderstorms, create changes in the properties of atmospheric aerosols over short time scales, either by removing them from the environment or by spatially redistributing them.

9.5.3   Orographic Influence

The mountains act as a barrier to the winds carrying moisture and force them to ascend. The windward side of the mountains receives the maximum precipitation. The interaction of mountains with the large-scale atmospheric flow and localized events determines the rainfall amplitude. The Indian Summer Monsoon (ISM) generates strong rainfall on the southern slopes of the Himalayas, while ISM precipitation is deprived in the northern Himalayas. Due to the altitudinal variation, the rainfall
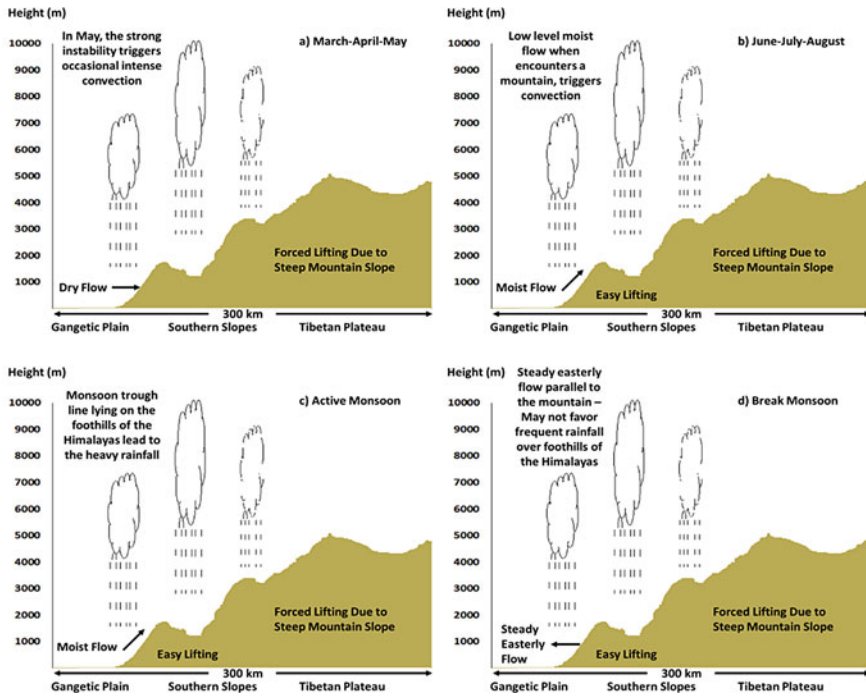
Fig. 9.8 Schematic illustrations of spatiotemporal variation in rainfall for **a** pre-monsoon (March–April-May), **b** summer monsoon (June-July–August), **c** active monsoon, and **d** break monsoon modified from [19]

distribution becomes complex. Some studies indicate that the trend of rainfall rises with altitude up to around 2500 msl and then starts to decrease. Studies the Himalayas relating to rainfall characteristics during the monsoon season suggest that rainfall decreases with altitudes between 2800 and 4500 m for Nepal [17, 18]. The seasonal spatiotemporal distribution of rainfall is shown in Fig. 9.8.

In the present study, around 500 random points were taken over Uttarakhand, and the scatter plots of Elevation vs Mean precipitation, Air temperature, Surface pressure, and Aerosol Optical depth were plotted for 2000–2019. The scatter plot of mean precipitation vs elevation (Fig. 9.9a) range shows that the mean precipitation showed negative correlation with the elevation and most of the precipitation was concentrated in the elevation range of 1000–2000 m. A scatterplot between air temperature and elevation (Fig. 9.9b) also follows strong negative correlation, which explains the presence of higher temperature at lower elevated areas. Also, the scatter plot of surface pressure vs elevation (Fig. 9.9c) also follows a negative correlation which indicates that at higher elevation the presence of low-pressure causes increases in evaporation which further leads to cloud formation. Furthermore, the scatter plot of aerosols optical depth vs elevation (Fig. 9.9d) follows negative correlation, and
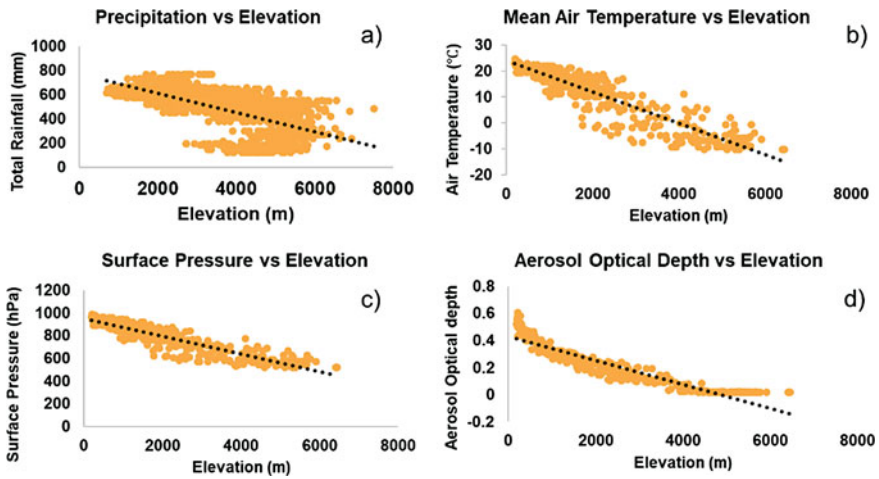
Fig. 9.9 The variation of **a** Precipitation with Elevation **b** Air temperature with Elevation **c** Surface pressure with Elevation **d** Aerosol Optical Depth with Elevation

most of the aerosols are concentrated at 100–1500 m elevations that facilitate the clouds forming mechanism.

9.6 Conclusion

Cloudburst and associated disaster are prominent in the Uttarakhand region of the Himalayas, affect thousands of people every year, and cause loss of life, property, livelihood, infrastructure, and environment. Most of the cloudburst events are concentrated during the monsoon months, and majority of these incidents occur during night times. The southwest and Mediterranean winds along with regional moisture are dominant during this period, and they descend over the low-pressure region and combine with the local humidity are further orographically lifted and cause cloudburst and consequently flash-floods. The region's vulnerability to disasters has also increased due to poor patterns of land use & socio-economic conditions, deforestation, increased pressure on humans and cattle populations, and increased tourism. These activities in these areas have further led to the development of aerosols, which influence the earth-atmosphere layer radiation by absorbing and scattering sun radiation and further impacts the cloud formations. While cloudburst events are difficult to predict, a dense network of rain gauges, especially in areas prone to cloudburst, is needed to better understand this phenomenon. The ground stations datasets coupled with satellite imageries can prove to be a powerful tool for the assessment of cloudbursts.

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