Analysis of the Causes of Extreme Precipitation in Major Cities of Peninsular India Using Remotely Sensed Data

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Abstract

The frequent occurrence of Extreme Precipitation Events (EPEs) over the last decade has really created havoc in Indian cities. Anthropogenic emissions are one of the components that can influence the climatology over large urban conglomerates and cause the occurrence of EPEs. Aerosols are one of the emissions-related elements that can change the characteristics, production, and lifetime of clouds, leading to changes in precipitation dynamics. The goal of the current study is to investigate the influence of aerosols in causing EPEs by analyzing remotely sensed data of aerosols, clouds, and atmospheric features (K-index) from MODIS (Moderate Resolution Imaging Spectrometer) and precipitation from GPM-IMERG for major cities in Peninsular India. The last 10 days of remotely sensed data before the occurrence of an EPE event are analyzed. Along with Aerosol Optical Depth (AOD), cloud properties such as Cloud Fraction (CF), Cloud Top Pressure (CTP), and Cloud Top Temperature (CTT) are used in the analysis. The factors influencing precipitation in each city are analyzed through multiple linear regression models. For the major cities, the parameters that together caused extreme events are examined. All the observed EPEs had intensified precipitation due to a combination of middle-level clouds (CTP in the range of 440 hPa to 680 hPa), low AOD (0.4), with many thunderstorm states (K > 35°C), and CTT 0°C. Other elements that contributed to the occurrence of EPEs included low-level clouds (CTP > 680 hPa), an AOD in the range of 0.4–0.6, an isolated thunderstorm state (20°C < K < 25°C), and CTT > 0°C.

Keywords: Aerosol Optical Depth (AOD), Extreme Precipitation Event (EPE), Cloud Properties, GPM_IMERG, K-Index, MODIS Data

1. Introduction

Aerosols are anthropogenic emissions that can act as cloud condensation nuclei. The increase in the concentration of aerosols in the atmosphere can lead to global and regional climate variability, which is of prime concern in the recent scenario. Due to their significant influence on local and regional climate through effects on the radiation budget, physical characteristics of clouds, and the hydrological cycle, atmospheric aerosols have attracted a lot of scientific attention (Ramanathan et al., 2005; Kaskaoutis et al., 2009; Balakrishnaih et al., 2012; Sridhar et al., 2013; Kotrike et al., 2021). Aerosols may cause abrupt and severe precipitation when combined with favorable cloud characteristics and intense convection (Gryspeerdt et al., 2014).

Aerosols could increase rainfall from deep convection and potentially lead to catastrophic floods in localized areas while suppressing large-scale precipitation from shallow stratiform clouds (Andreae et al., 2004). In idealized simulations, rain suppression occurs during the early stages of polluted convective systems, but rain enhancement is observed as the system progresses (Tao et al., 2007). Similarly, observational analysis has found that heavy precipitation in polluted metropolitan areas is initially delayed. This delay is due to the scattering of radiation by aerosols, which reduces the amount of solar radiation reaching the Earth's surface and postpones the emergence of intense convection due to complimentary relations between land surface and atmosphere (Jaksa et al., 2015). Subsequently, precipitation increases as aerosol invigoration becomes predominant (Guo et al., 2016).

Extreme Precipitation Events (EPEs) pose a serious risk to human life, agriculture, and infrastructure by causing flash floods and landslides (Sujatha and Sridhar, 2021). With enhanced atmospheric moisture transport brought on by a warming climate, EPEs are anticipated to occur more frequently (Hamada et al., 2015; Kumar et al., 2019). Particularly in Asia, human activities have been correlated with more intense extreme precipitation events in recent years (Dong et al., 2021; Li et al., 2018; Sujatha and Sridhar, 2017). Focused attention is needed to mitigate the effects of EPEs and the resulting natural disasters in order to reduce societal and economic losses. Despite recent scientific advancements in numerical weather prediction capabilities, accurately forecasting EPEs at a regional scale and with longer lead times remains challenging due to uncertainties produced by various sources (Mao et al., 2018; Srinivas et al., 2018; Wang et al., 2021). However, there have been significant advancements in EPE forecasting with the improvements in satellite data (Fortelli et al., 2019).

The industrialization and increased mobility in major cities result in higher concentrations of aerosols in the atmosphere. The precipitation of high intensity and shorter duration has become evident in most metropolitan cities, leading to submergence and flooding in low-lying areas (Jenamani et al., 2006; Guhathakarta et al., 2011; Jasmine et al., 2022; Roxy et al., 2017; Sridhar et al., 2019). The current study focuses on analyzing the interplay of aerosol, cloud, and atmospheric variables to investigate their association with EPEs. This examination is conducted through spatial distribution and regression analysis. By employing regression techniques on aerosol and cloud properties, this study introduces a novel method for detecting the occurrence of EPEs.

2.0 Data and Study Area

The study area for the proposed work consists of four metropolitan cities that are undergoing rapid urbanization and industrialization in Peninsular India: Bengaluru, Chennai, Hyderabad, and Mumbai. The city of Hyderabad belongs to a warm semi-arid climate region, while the other cities belong to a Tropical Savanna climate region. Bengaluru, Hyderabad, and Mumbai receive most of their precipitation during the southwest monsoon season, while Chennai receives it from the northeast monsoon. Therefore, the chances of extreme events occurring in the first three cities are highest during JJAS (June-July-August-September), while for Chennai, the chance is in OND (October-November-December). The study area, along with the location graticules, is shown in Figure 1.

The data used in the study includes information on aerosols, cloud properties, and atmospheric stability states, specifically the K-index. All of these data products were obtained from the LAADS DAAC (Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Centre) (https://ladsweb.modaps.eosdis.nasa.gov/).

A database of aerosol-cloud-meteorological parameters with identical spatial resolutions was created by selecting reliable data sources. Various MODIS outputs had different spatial resolutions. For instance, the AOD used in this study had a spatial resolution of 10 km × 10 km, while the spatial resolutions for CTP, CTT, CF, and K index were 5 km × 5 km. Therefore, it was necessary to develop a database that standardized the spatial resolutions of these aerosol-cloud-meteorological parameters. The aggregate resampling method was employed to establish cloud and atmospheric profile characteristics with a resolution of 10 km × 10 km, as the AOD had the lowest spatial resolution.

2.1 MODIS AOD

The AOD is a quantitative measure of the presence of aerosols in a column of the atmosphere. The Moderate Resolution Imaging Spectrometer (MODIS) provides AOD data at a spatial resolution of 10 km × 10 km and a temporal resolution of 5 minutes. MODIS operates aboard the Terra and Aqua satellites at an altitude of 705 km, with overpass times of 10:30 and 13:30 (IST), respectively. Radiances are estimated at wavelengths of 470 nm and 670 nm based on lookup table values. The estimated satellite radiances are then used to calculate AOD at 550 nm using the Angstrom exponential law (Vijaykumar et al., 2018; Kotrike et al., 2021). In this study, we utilized the Level 2 AOD product from Collection 6.1 of MODIS.

2.2 Cloud Products

The optical and physical properties of clouds constitute the MODIS Level-2 Cloud product (MOD06_L2). These characteristics are computed from remotely sensed solar-reflected radiances in the near-infrared, visible, and infrared spectral ranges. During both daytime and nighttime conditions, cloud top temperature, cloud top height, effective emissivity, cloud phase (ice vs. water, opaque vs. non-opaque), and cloud fraction are determined using MODIS infrared channel radiances. Cloud optical thickness, effective particle radius, and cloud shadow effects are determined using MODIS visible radiances. In this study, we utilize Cloud Fraction (CF), Cloud Top Pressure (CTP), and Cloud Top Temperature (CTT) at a 5 km × 5 km resolution. The current study employs the International Satellite Cloud Climatology Product classification to identify low, middle, and high-level clouds based on CTP (https://isccp.giss.nasa.gov/cloudtypes.html) (Figure 2).

2.3 Atmospheric Profile Product

The MODIS Level-2 Atmospheric Profile product comprises total ozone load, atmospheric stability, temperature and moisture profiles, and atmospheric water vapor data. All these parameters are generated both day and night at a pixel resolution of 5 km × 5 km. The data files for the MODIS Atmosphere Profile product are labeled as MOD07_L2 and are obtained from the Terra platform. This study specifically utilizes atmospheric stability, represented by the K-index. The K-index is calculated using the vertical lapse rate of temperature, which is parameterized by the temperature difference between 850 hPa and 500 hPa. The moisture content in the lower atmosphere is indicated by the dew point at 850 hPa, while the difference between the temperature at 700 hPa and the dew point at 700 hPa signifies the vertical extent of the moist layer. The mathematical equation governing the K-index is provided in Equation (1) (Borbas et al., 2015).

$$K = (T_{850} - T_{500}) + T_{d_{850}} - (T_{700} - T_{d_{700}}) \quad - (1)$$

Where T_{850} is temperature at 850hPa, T_{700} is temperature at 700hPa, T_{500} is temperature at 500hPa, $T_{d_{850}}$ is dew point temperature at 850hPa, $T_{d_{700}}$ is dew point temperature at 700hPa.

2.4 Precipitation

The Integrated Multi-satellite Retrievals for the Global Precipitation Mission (IMERG) is one of the sources for precipitation data. The GPM Level 3 IMERG Final Daily dataset, with a spatial resolution of 10 km × 10 km (GPM_3IMERGDF), was generated from the GPM_3IMERGHH dataset collected every 30 minutes. The final estimate of daily accumulated precipitation is provided by the derived result. The parameter utilized in this study is PrecipitationCal, commonly known as complete calibrated precipitation. A comprehensive list of satellite products used for the analysis of extreme events is provided in Table 1.

3. Methodology

The methodology used for the analysis of EPEs in metropolitan cities is depicted in Figure. 3. EPEs are identified based on percentile calculations of precipitation data. The data is sorted in ascending order to compute percentiles, and the resulting distribution represents the frequency-intensity relationship of precipitation. The 95th percentile of precipitation is calculated using the R statistical software. This study utilizes daily GPM precipitation data from 2015 to 2021 for percentile calculations. Precipitation exceeding the 95th percentile threshold is considered an extreme event. Extreme events are identified for the metropolitan cities of Peninsular India from 2018 to 2020.

For each identified extreme event in the metropolitan cities, the data corresponding to aerosol and cloud properties for a period of 10 days prior to the event are visualized using ArcMap 10.2. In the present study, we have analyzed 6 events from Mumbai, 5 events from Chennai, 5 events from Hyderabad, and 2 events from Bengaluru, and the results are presented.

3.1 Percentile Calculation

The percentile helps to compare a score with other scores in the dataset, aiding in the identification of a threshold value. Data above this threshold value is considered an extreme event of precipitation. The steps involved in percentile calculation are as follows: Initially, the daily precipitation data from 2015-2021 are sorted in ascending order. The second step involves multiplying the required percentile, which is the 95th percentile for this study, with the total number of values and rounding it to the nearest integer. This gives us the threshold value. In the third step, we count the values from left to right in the dataset until we reach the number obtained in the previous step. The corresponding value is the 95th percentile of the dataset. Percentile calculation is performed over raster images corresponding to the metropolitan cities. This means that each pixel covering the metropolitan city has a different 95th percentile value.

3.2 Identification of Events

The series of raster data corresponding to precipitation is aggregated to match the resolution of the AOD data. The 95th percentile values are also aggregated to the same resolution. Each cell in the daily precipitation raster is then compared to the corresponding cell in the 95th percentile of precipitation using R statistical software. If the precipitation value is greater than the 95th percentile value, the data is retained; otherwise, the pixel value is classified as 'NA' (not available). The raster is saved to a folder if more than half of the pixels covering the area contain valid data.

3.3 Analysis of Parameters

For each identified extreme event in the metropolitan cities, the aerosol data for the 10 days leading up to the event is visualized. If aerosol data is available, other parameters, namely CF, CTP, CTT, and K, are averaged for the 10 days prior to the extreme event. The analysis includes examining the distribution of cloud properties and atmospheric stability during the extreme event. Additionally, the number of pixels experiencing moderate and heavy precipitation in the area is observed. The behavior of cloud properties and atmospheric stability in these pixels is analyzed, and the combination of parameters influencing precipitation occurrence is observed for each metropolitan city.

3.3.1 Multiple Linear Regression Analysis

The statistical analysis is conducted using Multiple Linear Regression Analysis (MLR), which is a type of analysis that examines the linear relationship between a dependent variable and two or more independent variables (Zain et al., 2009). In this study, MRA is employed with precipitation as the dependent variable and AOD, CF, CTP, CTT, and K as the independent variables. The regression is performed by extracting pixel values of each variable corresponding to Extreme Precipitation Events (EPEs) for each metropolitan city. The general form of MRA is represented by Eq. (2):

$$y = \propto + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n \qquad (2)$$

Where y is dependent variable, $\propto$ is intercept, $x_1, x_2, x_3 \ldots\ldots x_n$ are independent variables, $\beta_1, \beta_2, \beta_3 \ldots. \beta_n$ are coefficients

4. Results and Discussions

4.1 Mean Precipitation

The mean precipitation during EPEs in the metropolitan cities for the years 2018, 2019, and 2020 is depicted in Figure 4. Precipitation is highest in 2018 for all three cities, except for Mumbai. There is a decreasing trend in the magnitude of precipitation for Chennai and Bengaluru. However, mean precipitation is higher in 2019 for Mumbai and Hyderabad, and then it decreases in 2020. The increase in precipitation in 2019 in Hyderabad is also reflected in the increased number of EPEs in the city.

The number of EPEs increased in 2019 compared to 2018 for all three cities, except for Hyderabad (Table 2). However, EPEs also increased in Hyderabad in 2020. Most of the EPEs in 2019 occurred during the months of July, August, September, and October in the selected study area. In that year, a total of 110% of the "long-period average" (LPA), which is 880 mm, representing the national average of monsoon rains received in the 50 years prior to 2010, fell between June and September 2019 (Source: https://reliefweb.int/organization/govt-india).

4.2 Spatial Distribution Maps

4.2.1 Mumbai

The spatial distribution of precipitation, AOD, cloud properties, and the K-index is shown in Figureure 5 for the selected Extreme Precipitation Events (EPEs). The precipitation map indicates that EPEs typically have precipitation in the range of 30-250 mm/day. All the other parameters in the area represent averaged values for the 10 days prior to the occurrence of the extreme event. For example, isolated thunderstorm conditions ($20°C < K < 25°C$) accompanied by AOD in the range of 0.2-0.6 resulted in precipitation exceeding 110 mm in Mumbai. Additionally, a Cloud Top Temperature (CTT) greater than zero and a Cloud Fraction (CF) greater than 0.8 were observed in most of the EPEs in Mumbai. The distribution also shows that scattered thunderstorm conditions ($30°C < K < 35°C$) along with AOD in the range of 0.2-0.4 led to precipitation levels below 30 mm/day. From Figure. 5, it can be inferred that low-level clouds (CTP > 680 hPa), CTT > 0°C, AOD in the range of 0.2-0.6, and isolated thunderstorm conditions resulted in high precipitation levels exceeding 100 mm/day in the metropolitan region of Mumbai.

4.2.2 Chennai

The spatial distribution of precipitation, AOD, cloud properties, and the K-index is shown in Figure. 6 for the selected EPEs. Three out of five EPEs have experienced numerous thunderstorm states (K > 35°C) over most of Chennai city. The precipitation during those three events falls in the range of 25-85 mm per day, and AOD is in the range of 0.2-0.6. The CF appears to be greater than 0.9 in all the EPEs in Chennai. However, the CTP is low, implying that the area is covered by high-level clouds as the region extends toward the East coast of India. The CTT is less than zero in all five EPEs. But, the CTT is significantly lower in the observed three out of five EPEs that have experienced numerous thunderstorm states. Overall, it can be concluded that EPEs might take place during numerous thunderstorm states if AOD is in the range of 0.2-0.6, accompanied by low CTP and CTT being less than zero.

4.2.3 Hyderabad

The city of Hyderabad experienced 3, 9, and 22 EPEs in the years 2018, 2019, and 2020, respectively. AOD data was visualized for the 10 days prior to each event using ArcMap. If the data was available on those days, a stack of images was created, and the mean value was reported. The process of stacking and calculating the mean was carried out for both cloud and atmospheric products. If AOD data was not available, the consecutive EPE was visualized. Consequently, 2 and 3 events from 2018 and 2020 had the required data for analyzing the occurrence of EPE.

The spatial distribution of precipitation, AOD, cloud properties, and the K-index for the 10 days prior to the EPE is shown in Figure. 7. Isolated thunderstorm conditions (20°C < K < 25°C) were prevalent on May 03, 2018, and Nov 26, 2020, during the EPE. Among these, the precipitation was more pronounced on Nov 26, 2020, compared to all five EPEs in Hyderabad. However, AOD in four out of five EPEs falls within the range of 0-0.4. Numerous thunderstorm conditions (K > 35°C) were predominant in two out of five EPEs, specifically on June 03 and June 28, 2020. Nevertheless, the precipitation during these events was less than 40mm. Considering that the dates mentioned coincide with the lockdown phase in India due to the COVID-19 pandemic, it is possible that aerosols were trapped in the upper layers of the atmosphere, leading to the formation of numerous small cloud droplets.

Alternatively, this might also be attributed to the onset of the monsoon season in the metropolitan city of Hyderabad.

Considering the EPE with the most precipitation, which occurred on Nov 26, 2020 (Figure. 7e), the corresponding Cloud Top Pressure (CTP) was in the range of 450-600 hPa, and the Cloud Top Temperature (CTT) was in the range of -35°C to -15°C. The spatial pattern shows that more precipitation occurred in the presence of middle-level clouds when CTP was in the range of 500-600 hPa and CTT was in the range of -25°C to -15°C. Higher CTP (>680 hPa) and CTT (>0°C), accompanied by isolated thunderstorm conditions (20°C < K < 25°C), have resulted in lower precipitation (<30 mm), as evident from the precipitation (Figure. 7a) on May 03, 2018. Additionally, lower CTP (<680 hPa) and CTT (<0°C), coupled with isolated thunderstorm conditions (20°C < K < 25°C) and numerous thunderstorm conditions (K > 35°C), have resulted in precipitation ranging from 20-30 mm (Figure. 7b to 7d) in the city of Hyderabad. This may be attributed to the dispersion of Cloud Condensation Nuclei (CCN) from deep convective clouds. Thus, it can be inferred that higher CTP and lower CTT, along with lower Aerosol Optical Depth (AOD), may lead to higher precipitation in the metropolitan city of Hyderabad.

4.2.4 Bengaluru

The metropolitan city of Bengaluru experienced 14, 20, and 17 EPEs in 2018, 2019, and 2020, respectively. Unfortunately, data was only available for two events, namely, on June 07, 2019, and June 02, 2020. The spatial distribution of AOD, cloud properties, and the K-index is shown in Figure. 9. AOD values in the range of 0.4-0.6, along with CTP (400-600 hPa) and CTT (<0°C), during numerous thunderstorm conditions (K > 35°C), resulted in precipitation ranging from 40-60 mm, as evident from Figure. 8a. However, low AOD (<0.4), coupled with low CTP (<400 hPa) and CTT approaching 0°C, led to precipitation of less than 30 mm in the city of Bengaluru (Figure. 8b). Due to the limited number of EPEs available for analysis, it is not possible to conclusively determine the combination of parameters that result in low and high precipitation.

4.3 Regression Analysis

The pixel values of each variable for every EPE in the metropolitan city are extracted to Excel using R Statistical software. Blank cells, which represent missing data, were removed prior to the analysis. The Excel file was then read, including the column names, and multiple linear regression analysis was performed, considering precipitation as the independent variable and aerosol, cloud, and atmospheric stability parameters as the dependent variables. The coefficients of MLR models to predict precipitation depth (in millimeters) during an EPE for each metropolitan city are given in Table 3.

The results shows that AOD was highly significant in predicting precipitation depths during an EPE for Mumbai and Chennai. Assuming that all other components in the regression equation are constant, Chennai receives more precipitation with an increase in AOD because the coefficient is positive, while Mumbai receives less precipitation because the coefficient is negative. This might be due to the location of the Chennai and Mumbai towards east and west coasts respectively. Also, the latitudinal influence might result in different behavior in precipitation. Additionally, the regression analysis for Chennai City shows that K and CTT were equally significant. Chennai's climate is nearly constant throughout the year because of its proximity to the thermal equator. Chennai's average elevation above sea level is 6.7 meters, making the city nearly flat. As a result, the vertical lapse rate for any EPE does not vary significantly, as seen by K-index map in Figure 6. This could be the cause of the positive and substantial coefficient of K-index in the regression equation for Chennai. CTP has a positive influence on precipitation and was found to be significant in all cities except Chennai. The city of Mumbai is towards the windward side of the western ghats which receives precipitation from south-west monsoon from Arabian sea. The precipitation over the city is influenced by the maritime clouds. The variations in pressure due to undulating terrain of Mumbai, when the monsoon arrives could potentially be a cause of an EPE (Chakravarty et al., 2021). The present study demonstrates that the coefficient of CTP for Mumbai is positive and significant, as indicated by Table 3.

The cloud properties (CTP and CTT) and K-index were significant for the city of Hyderabad. Hyderabad's terrain is undulating, with elevations between 456 and 650 meters. Precipitation falls on the city due to low pressure in the Bay of Bengal and Arabian Sea. Theoretically, the chance for occurrence of precipitation is due to high CTP and low CTT. The coefficients of CTP and CTT in the regression equation of Hyderabad is positive and negative respectively. It implies that increase in CTP and decrease in CTT might enhance the precipitation over the city of Hyderabad. As the terrain is undulating, the pressure difference develops within the city. Also, the surface heating invigorates the rate of evaporation from the water bodies. The changes in the pressure and the rate of evaporation might help in the formation of clouds that led to extreme precipitation in the city.

5. Summary and Conclusions

The study analyzed the potential influence of aerosol, cloud, and atmospheric stability properties on the occurrence of EPEs. The 95th percentile threshold value was calculated by arranging precipitation data from 2015 to 2021 in ascending order. Precipitation data exceeding this threshold value were identified as EPEs in the study. The number of EPEs for the metropolitan cities of Bengaluru, Chennai, Hyderabad, and Mumbai during the period 2018-2020 was determined using the R Statistical Software.

The number of EPEs was highest in 2019 for all four cities. The mean precipitation for the corresponding years of 2018, 2019, and 2020 was calculated. Mumbai had the highest mean precipitation in EPEs in 2019, followed by a decrease in 2020. Chennai and Bengaluru had their highest mean precipitation in 2018, followed by a consecutive decrease in 2019 and 2020. The city of Hyderabad experienced lower mean precipitation in EPEs in 2018 and roughly the same amount of precipitation in EPEs in 2019 and 2020.

The present study attempted to analyze the spread of AOD, cloud properties, and K-index for 10 days prior to the occurrence of EPEs. It was known that satellite AOD data might be contaminated with clouds during EPEs, so AOD greater than 1.5 was not considered in the analysis. Additionally, the availability of data for 10 days prior to EPE occurrences posed a major challenge in the analysis.

The spatial distribution indicated that AOD in the range of 0.2-0.6 influenced precipitation in Mumbai and Chennai. Furthermore, low-level clouds (CTP > 680 hPa) with isolated thunderstorm conditions (20°C < K < 25°C) and CTT > 0°C enhanced precipitation in Mumbai. Conversely, in Chennai, middle-level clouds (CTP < 680 hPa) with numerous thunderstorm conditions (K > 35°C) and CTT < 0°C intensified precipitation. This difference might be attributed to the coastal and marine influences on the cities of Mumbai and Chennai. Middle-level clouds (CTP in the range of 440 hPa to 680 hPa), along with AOD less than 0.3, amplified precipitation in Hyderabad.

In summary, it can be stated that a combination of middle-level clouds (CTP in the range of 440 hPa to 680 hPa), low AOD (<0.4), numerous thunderstorm conditions (K > 35°C), and CTT < 0°C led to intensified precipitation in all the observed EPEs. Low-level clouds (CTP > 680 hPa), AOD in the range of 0.4–0.6, isolated thunderstorm conditions (20°C < K < 25°C), and CTT > 0°C were other factors contributing to the occurrence of EPEs.

The regression analysis indicated that the spread of AOD was significant for the coastal cities (Mumbai and Chennai). CTP was found to be significant for three out of four cities, while CTT and K were significant in two out of four cities. This study provided initial insights into the relationship between aerosols, cloud properties, and extreme rainfall events.

The current study is limited to data between 2018-2020. The regression model may be strengthened by extending the duration for the identification of the EPEs. Also, the coarse resolution of the datasets may have impact on the results significantly. Since most Indian cities are experiencing frequent extreme rainfall events with longer duration which are causing damage to property, economic losses and disturbing the city life, more research in this area is necessary. It may be possible to uncover additional reasons for the occurrence of EPEs by incorporating Precipitable Water Content (PWV) and cloud phase into the research to examine the formation of clouds with water content. The construction of robust frameworks for city that can endure EPEs will be aided by these studies.

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Conflicts of Interest:

The authors declare no conflict of interest.

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Data Availability Statement:

Datasets will be made available upon request to the authors.

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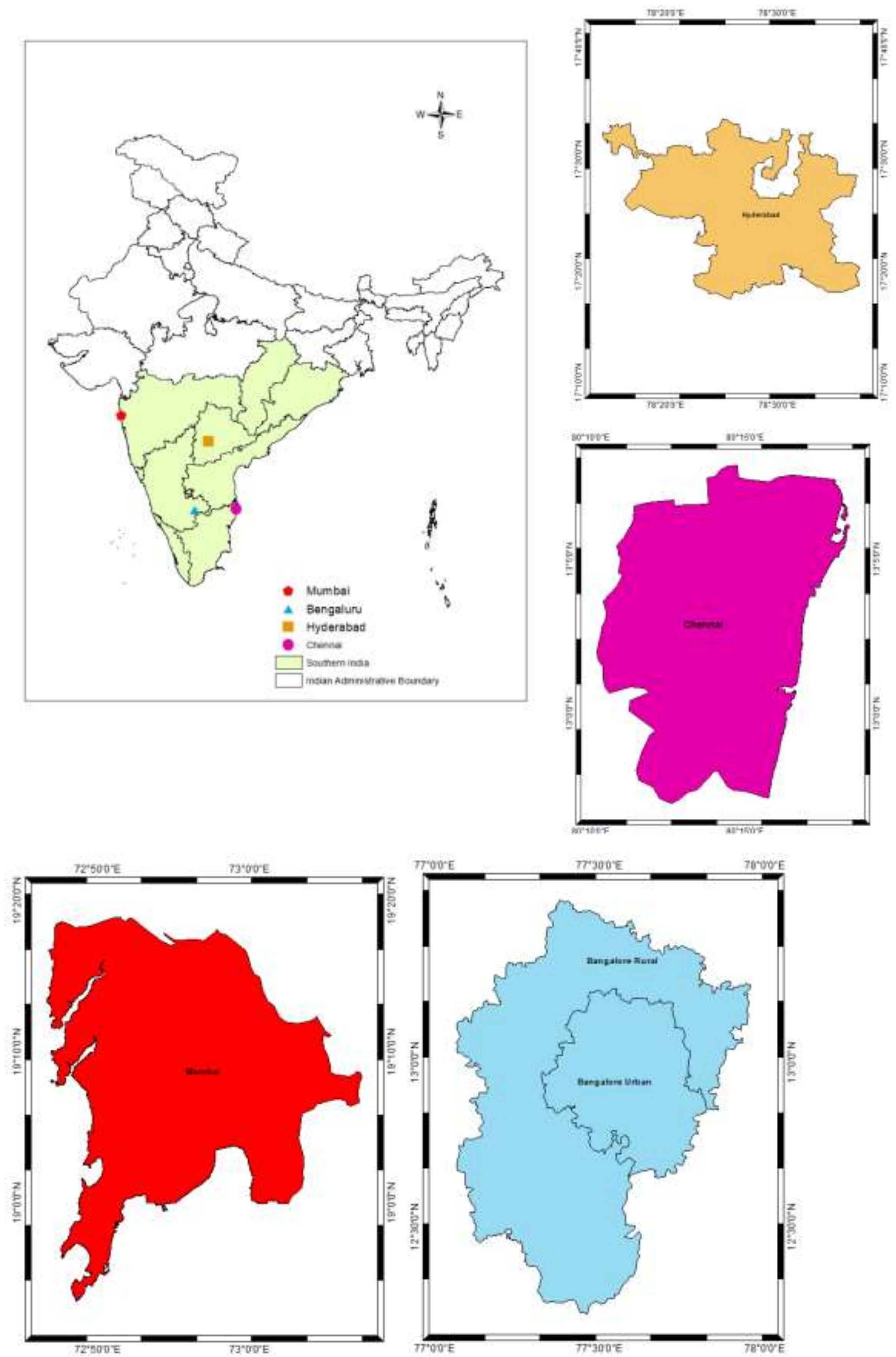

Figure 1: Study Area Study Area - Metropolitan Cities of Bengaluru, Chennai, Hyderabad, and Mumbai

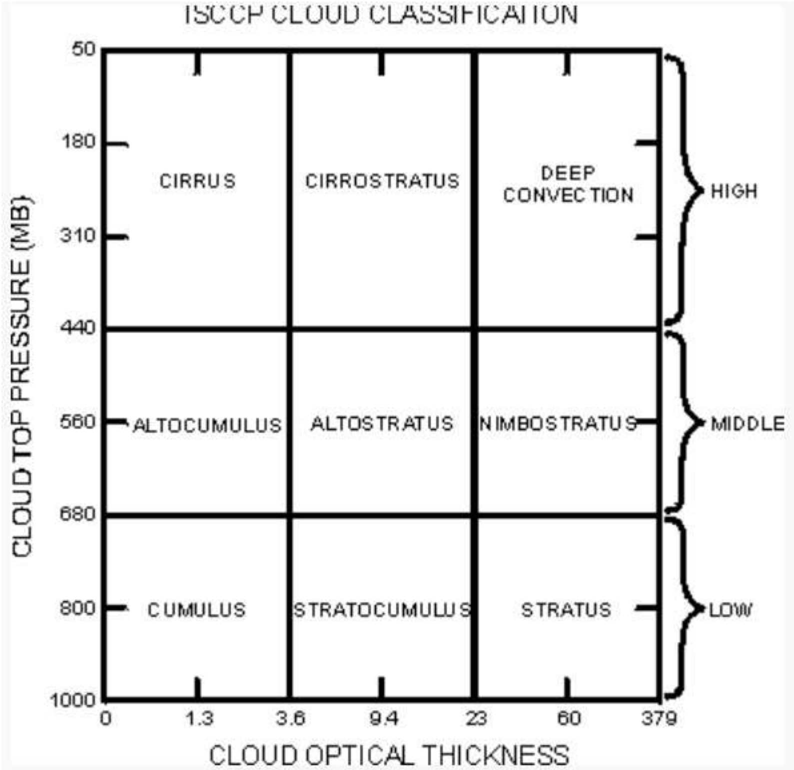

Figure 2: Cloud Classification based on the International Satellite Cloud Climatology Project (ISCCP) Data. Source: ISCCP Official Website (Source: https://isccp.giss.nasa.gov/cloudtypes.html)

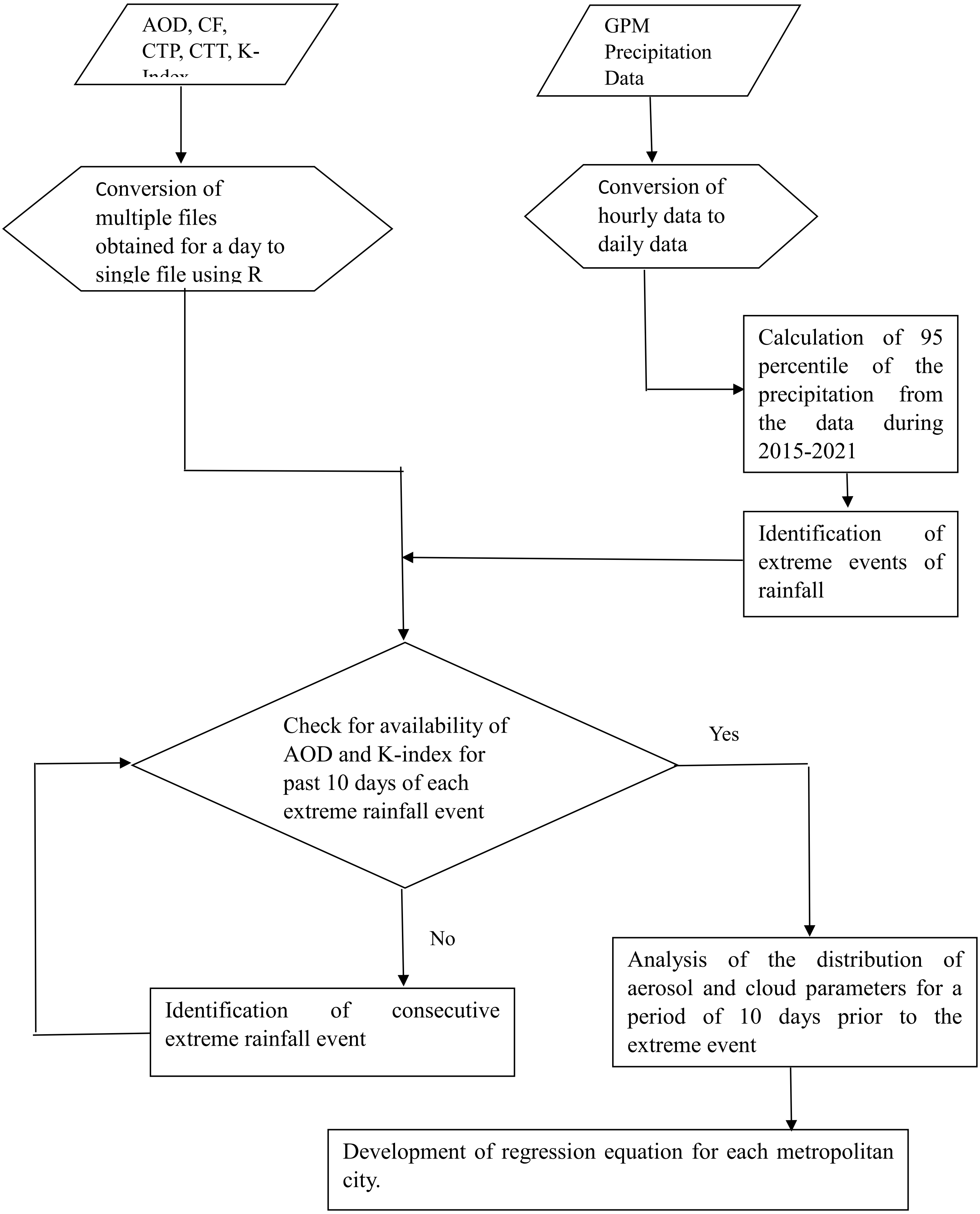

Figure 3: An Overview of the Research Approach and Methods Employed in the Study

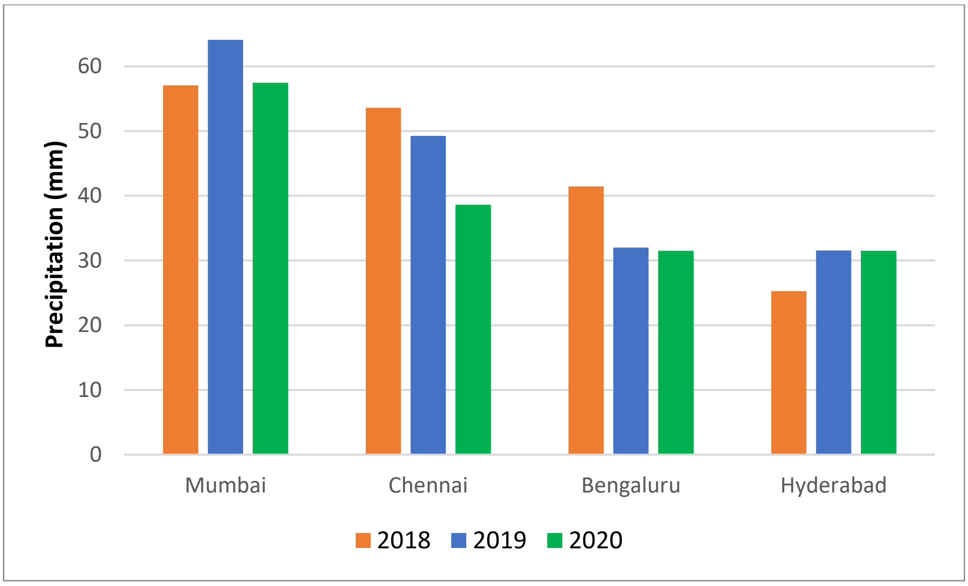

Figure 4: Mean Precipitation of Extreme Precipitation Events (EPEs) in the Study Area for the Years 2018, 2019, and 2020

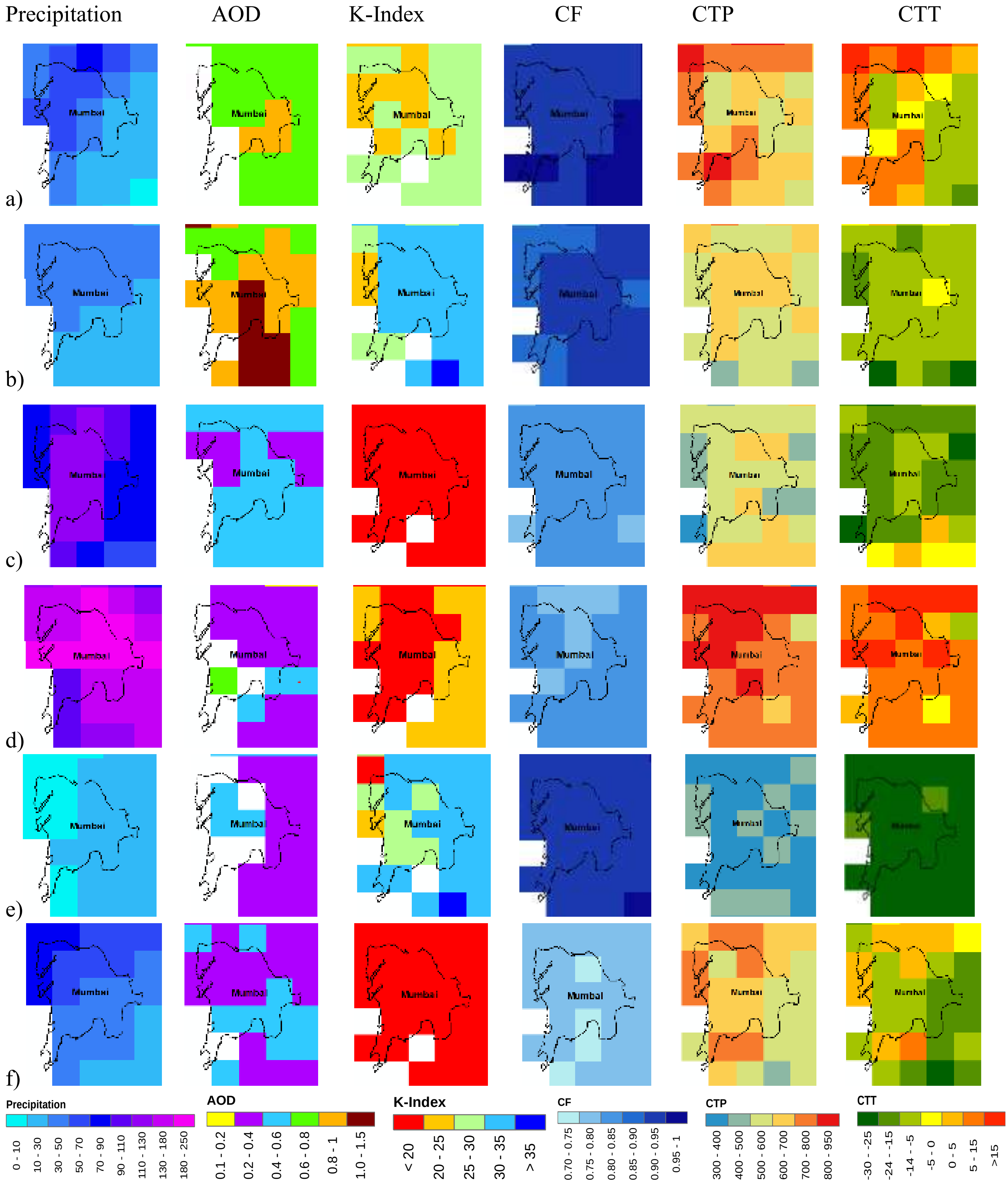

Figure 5: Spatial Distribution of Precipitation(mm), AOD, K-index(ºC), CF, CTP(hPa) and CTT(ºC) (Left to Right) for EPEs in Mumbai on a) May 25, 2018 b) Oct 4, 2018 c) Dec 3, 2019 d) May 31,2020 e) June 22,2020 f) Nov 19, 2020

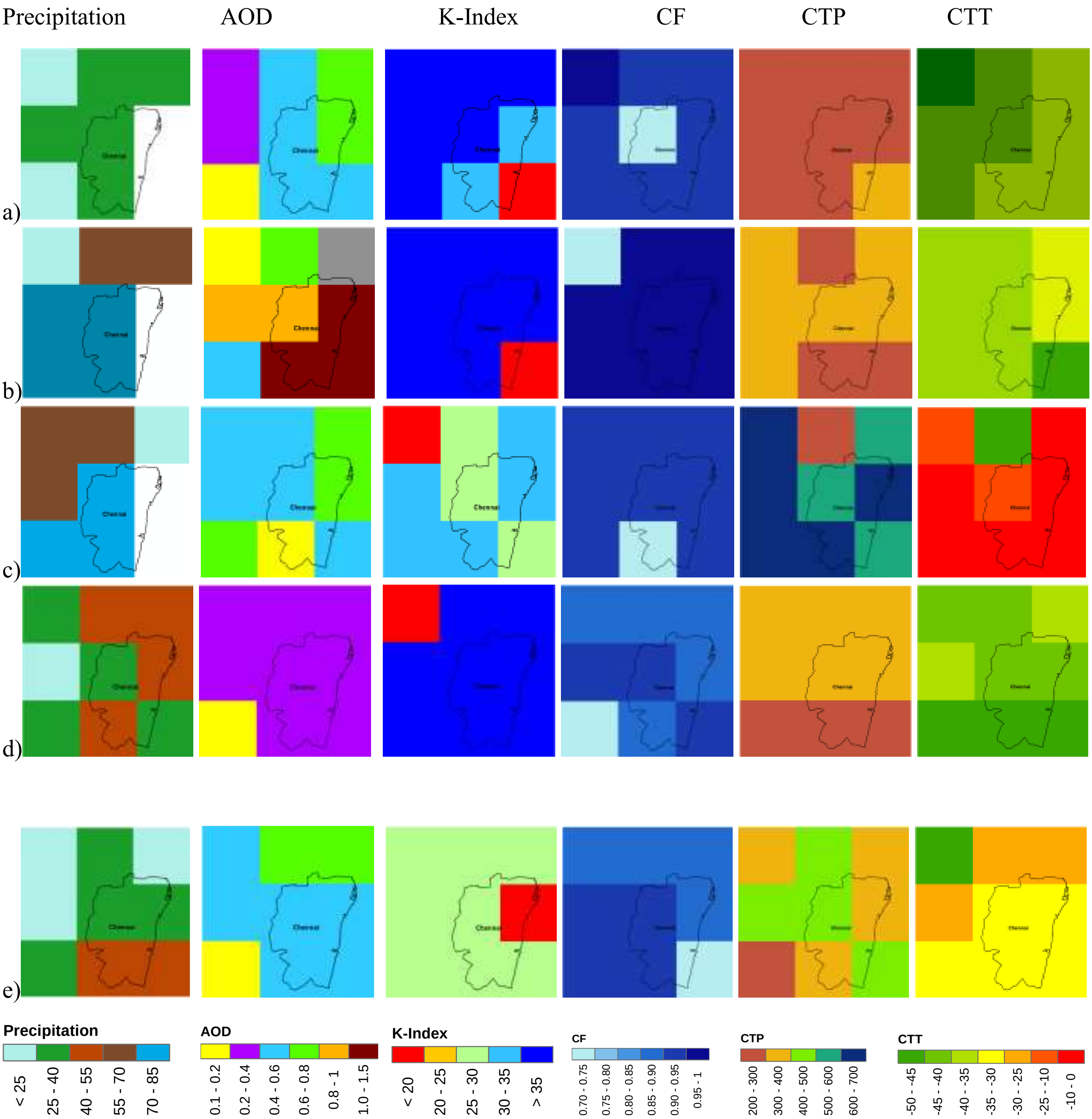

Figure 6: Spatial Distribution of Precipitation(mm), AOD, K-index(ºC), CF, CTP(hPa) and CTT(ºC) (Left to Right) for EPEs in Chennai on a) June 11, 2018 b) Aug 20, 2018 c) Sep 20, 2018 d) June 10,2020 e) Oct 10, 2020

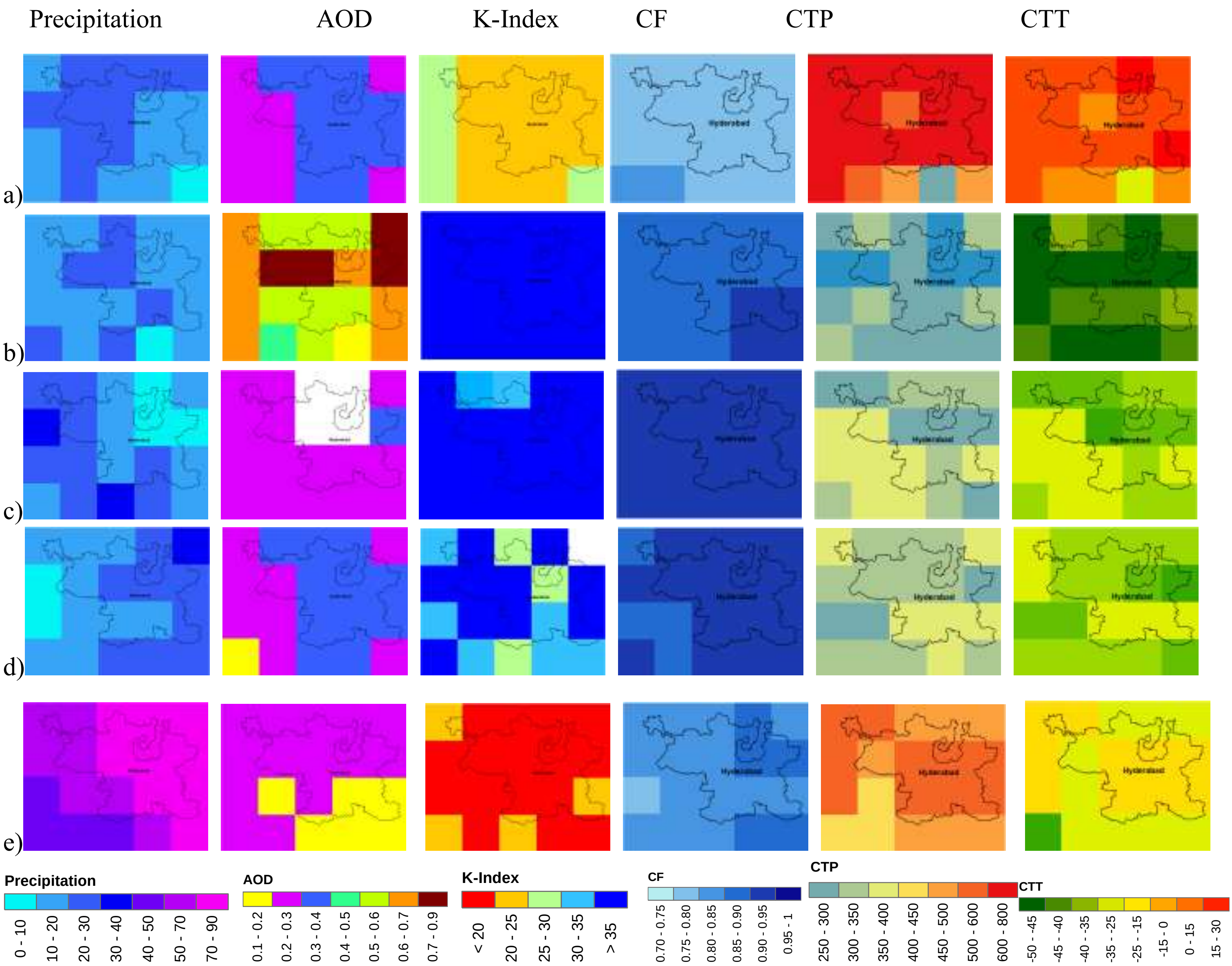

Figure 7: Spatial Distribution of Precipitation(mm), AOD, K-index(°C), CF, CTP(hPa) and CTT(°C) (Left to Right) for EPEs in Hyderabad on a) May 03, 2018 b) June 03, 2018 c) June 28, 2020 d) Oct 11, 2020 e) Nov 26, 2020

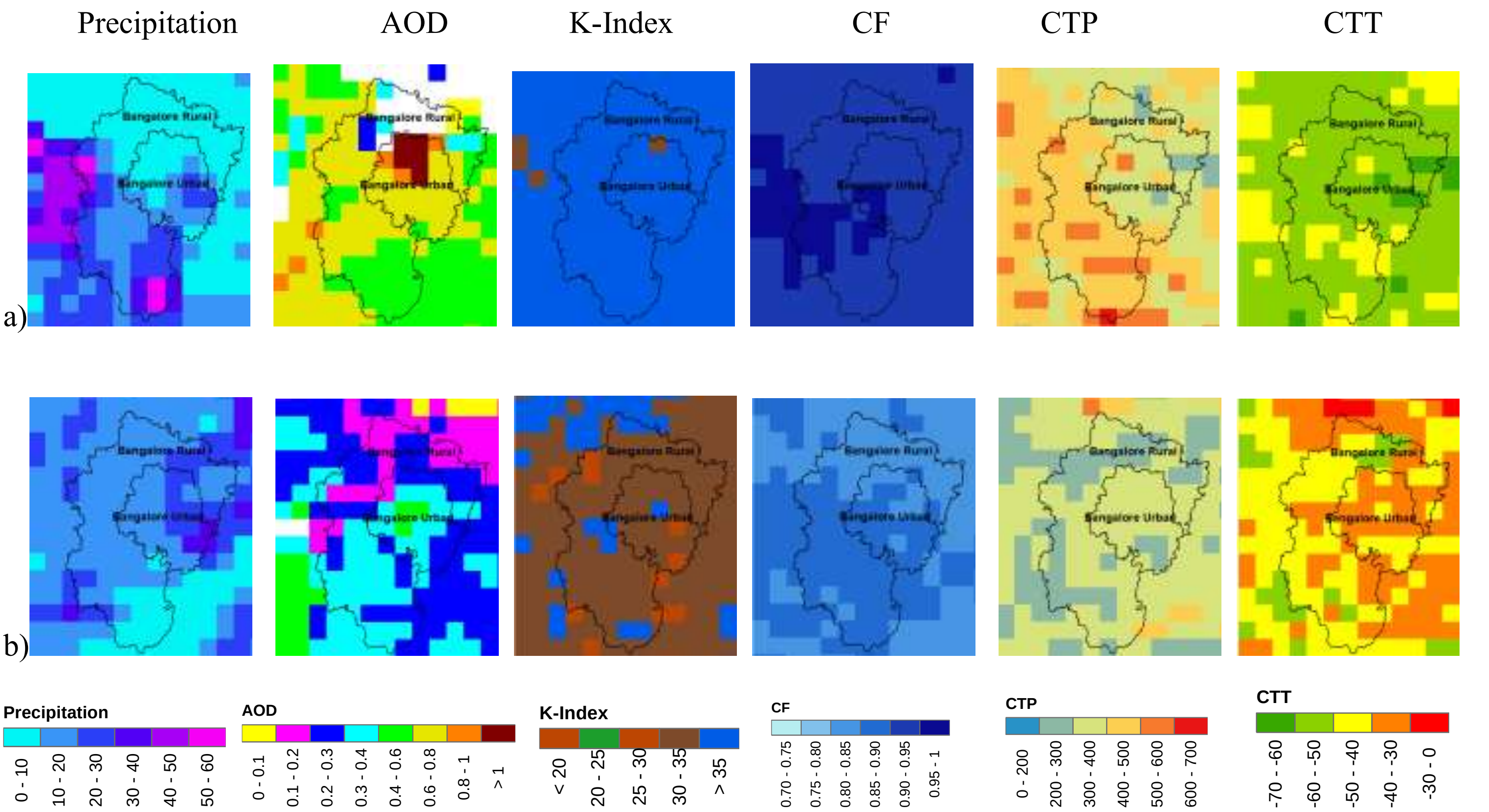

Figure 8: Spatial Distribution of Precipitation(mm), AOD, K-index(°C), CF, CTP(hPa) and CTT(°C) (Left to Right) for EPEs in Bengaluru on a) June 07, 2019 b) June 02, 2020

Table 1: Details of Satellite Data: MODIS and GPM

S.No	Source of Data	Parameter	Spatial Resolution
1	Moderate Resolution Spectrometer (MODIS) Terra (MOD04_L2) (https://ladsweb.modaps.eosdis.nasa.gov/)	Optical Depth Land and Ocean	10KmX10Km
2	Moderate Resolution Spectrometer (MODIS) Terra (MOD06_L2) (https://ladsweb.modaps.eosdis.nasa.gov/)	Cloud Fraction	5 Km X5Km
		Cloud Top Pressure	5 Km X5Km
		Cloud Top Temperature	5 Km X5Km
3	GPM IMERG Final Precipitation L3 (https://disc.gsfc.nasa.gov/)	Precipitation	10Km X10Km

Table 2: Enumeration of Extreme Precipitation Events (EPEs) in the Study Area

City	No. of EPEs		
	2018	2019	2020
Mumbai	8	55	23
Chennai	15	22	22
Bengaluru	14	20	17
Hyderabad	3	9	22

Table 3: Multiple Linear Regression (MLR) models for the four metropolitan cities of Mumbai, Chennai, Bengaluru and Hyderabad to predict precipitation depth during an EPE (Significance level: '***' 0.001 '**' 0.01 '*' 0.05)

City	**Mumbai**	**Chennai**	**Bengaluru**	**Hyderabad**
Parameter				
AOD	**-99 (***)**	**62 (***)**	3.95	-15.40
CF	6.81	115.32	**-59.41(*)**	-21.30
CTP	**0.29 (**)**	-0.16	**0.029(**)**	**0.33(***)**
CTT	-0.65	**2.53 (*)**	-0.04	**-2.70(***)**
K	0.13	**2.26 (***)**	0.18	**-0.74(**)**
Intercept	-81.50	-24.11	48.04	-139.25