

# Investigating the Effect of Anthropogenic Fire Ritual on Cloud Microphysics in Current Scenario: A Novel Study on Aerosol-Cloud Interaction

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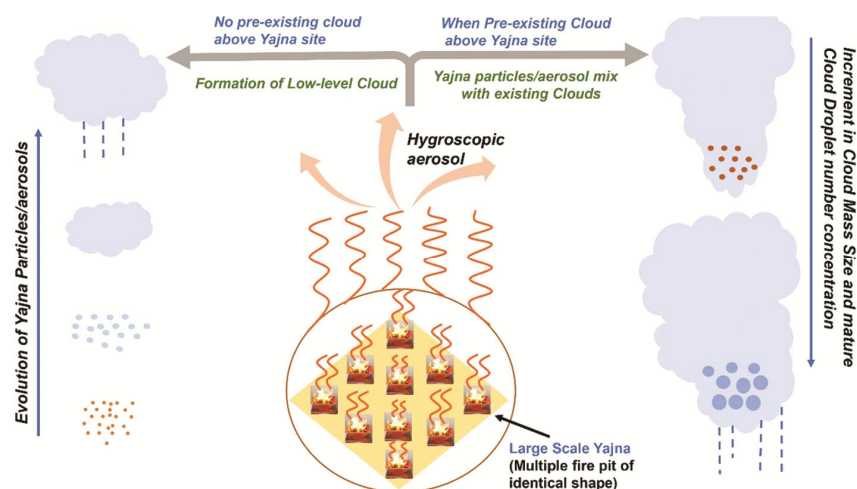
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The Indian anthropogenic fire ritual called Yajna has been practiced since ancient times. The production of a significant amount of aerosols is one aspect of large-scale Yajna that could increase the cloud condensation nuclei (CCN) in the atmosphere then subsequently enhance rain processes by creating low-level rain clouds and interacting with pre-existing clouds. In present study, we tried to explore the scientific basis of aforesaid hypothesis using satellite datasets. The chemical composition and hygroscopicity (estimated  $\kappa$ : 0.06-0.8) of the Yajna-induced particles led the formation of more cloud droplets, which in turn would have accelerated the collision-coalescence process and turned into raindrops. Meerut City in India is one of the cases where large scale Yajna was carried out for a week in March 2018. The Yajna event led to emission of  $\sim (8.4 \pm 1.5) \times 10^{19}$  to  $(3.08 \pm 2.5) \times 10^{20}$  CCN particles which gave rise to precipitation signature ( $\sim 0.4$  mm/day) of a very light rain category in the surrounding area based on satellite data. This precipitation could be due to i) initiation of collision-coalescence process even in a lower cloud liquid water path (LWP) i.e.  $20-86 \text{ g/m}^2$  and ii) formation of ice cloud with lower altitude centroid. Precipitation in such a condition is not a general phenomenon because the same has been earlier reported to be suppressed (especially in case of forest fires) in presence of high aerosol concentration and lower LWP. We have discussed micro scientific insights of Yajna that could be helpful to better understand its effect on the cloud microphysical processes. However, more such studies are required in future to validate aforesaid complex interactions.

**Keywords:** Fire, Cloud seeding, CCN, ACI

## 1 Introduction

The Earth's landscape has a carbon-rich vegetation, seasonal dryness, presence of oxygen, lightning and

volcano eruption make the Earth inherently flammable<sup>1,2</sup>. Fire is an exothermic chemical process of combustion that causes a material (called as fuel) to quickly oxidize, generating heat, light, and other reactive products<sup>3</sup>. Fire releases heat, gases, and

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materials (notably water vapor) at a combustion zone that quickly connects the hydrosphere, biosphere, and atmosphere. The biomass type, moisture content, and type of combustion play a role in products' composition, which is further regulated by oxygen availability and temperature<sup>1</sup>. In addition to altering surface albedo and releasing aerosols into the atmosphere, fires can have a regional impact on the climate because smoke plumes obstruct convective updraft and black carbon (BC) increase the temperature of surrounding air, which decreases convective updraft movement, precipitation, and the development of mature clouds<sup>4,5</sup>. Emissions from fires and related biomass burning (BB) include both gaseous and aerosol pollutants. The two most important aerosol species are BC and organic carbon (OC), while the most important gases released are carbon dioxide (CO<sub>2</sub>), non-methane volatile organic compounds (NMVOCs), carbon monoxide (CO), and nitrogen oxides (NO<sub>x</sub>)<sup>5-7</sup>. BB encompasses both living and dead flora found in the terrain, such as forests, grasslands, and agricultural waste and use of biomass as fuel (wood, charcoal, pellets, and sawdust)<sup>8</sup>. In this study, the gases and aerosols emitted from BB are assumed as fire particles.

A unique BB, known as Yajna has been followed since the ancient time by the Indian community as a fire ritual. Here, ancient anthropogenic fire ritual denoted as Yajna. To perform Yajna, participants burn Samidha that includes various biomass i.e., woods (ficus religiosa, mango etc.), herbs, clarified butter along with other items, in a fire pit with a geometric design called Yajna Kund or Havan Kund while reciting Vedic mantras. The earlier studies have been found that Yajna purify the environment, specifically polluted air<sup>9</sup> and induce the precipitation process for rain<sup>10</sup>. A systematic approach of Yajna i.e., process, type and biomass ingredients make it unique BB. With several identically shaped Havan Kund, large-scale Yajna events are intended to emit a substantial amount of gases and particles that increase the CCN in the atmosphere at regional level<sup>10</sup>. Two situations may develop near the large scale Yajna site that are enhancing the precipitation process by formation of low level cloud in stable atmospheric condition and interactions with pre-existing cloud<sup>10</sup>. It is challenging to quantify the intricate relationship between aerosol-cloud interactions (ACI), which influences how BB aerosols impact clouds that impact climate and radiation. In an earlier study, two different scenarios of

ACI over Amazon forest fire have shown that cloud fraction increases in low aerosol concentration scenario and cloud fraction decreases in high aerosol concentration due to atmospheric stabilization brought by smoke particles' semi-direct effects<sup>11,12</sup>. Large scale Yajna is a case of low aerosol condition relative to magnitude of forest fires or wildland fires. In the scientific community, the health benefits of the Yajna have also been studied<sup>13-19</sup>; however very limited studies were reported, which links the implications of large scale Yajna on regional weather<sup>10</sup>. It is to be noted here that globally, large scale Yajna is being organized at a regular interval all over the World<sup>20</sup>. An earlier study has shown the necessity of researching these rituals and cultures in South Asia in order to improve the emission inventory<sup>21</sup>. According to the availability of satellite data products like aerosol optical and cloud properties, a large scale Yajna event at Meerut (28°59'15"N, 77°41'52"E) in North India has been considered in the present study.

## 2 Data and Methodology

### 2.1 Study Site

A continuous monitoring of the aerosol and cloud properties through satellite data products (SDP) were started in the beginning of 21<sup>st</sup> Century. According to All World Gayatri Pariwar database of large scale Yajna events, several sites were identified but continuous SDP were found only at one site (Meerut site). This large scale Yajna was happened at Bhaisali Ground (28°59'15"N, 77°41'52"E) from 18 to 25<sup>th</sup> March 2018 in Meerut city of Uttar Pradesh state in North India. The implications of emission from of large scale Yajna have been studied with the help of SDP. In this large scale Yajna, people burn Samidha which includes various biomass [i.e., mango wood (~ 50000 kg), mixture of medicinal herbs, cow's ghee (clarified butter) etc.]. This biomass fuel was used in 108 identical Havan Kunds to perform Yajna under a shaded area (~ 15625 feet<sup>2</sup>)<sup>22</sup>. The shaded area was used to protect participants performing Yajna from direct sunlight as shown in Fig. 1.

### 2.2 Data Collection

#### 2.2.1 Moderate Resolution Imaging Spectroradiometer (MODIS)

Moderate Resolution Imaging Spectroradiometer (MODIS) is a crucial instrument on board the Terra and Aqua satellites launched in late 1999 and in early 2002 respectively. The timing of Terra's orbit around

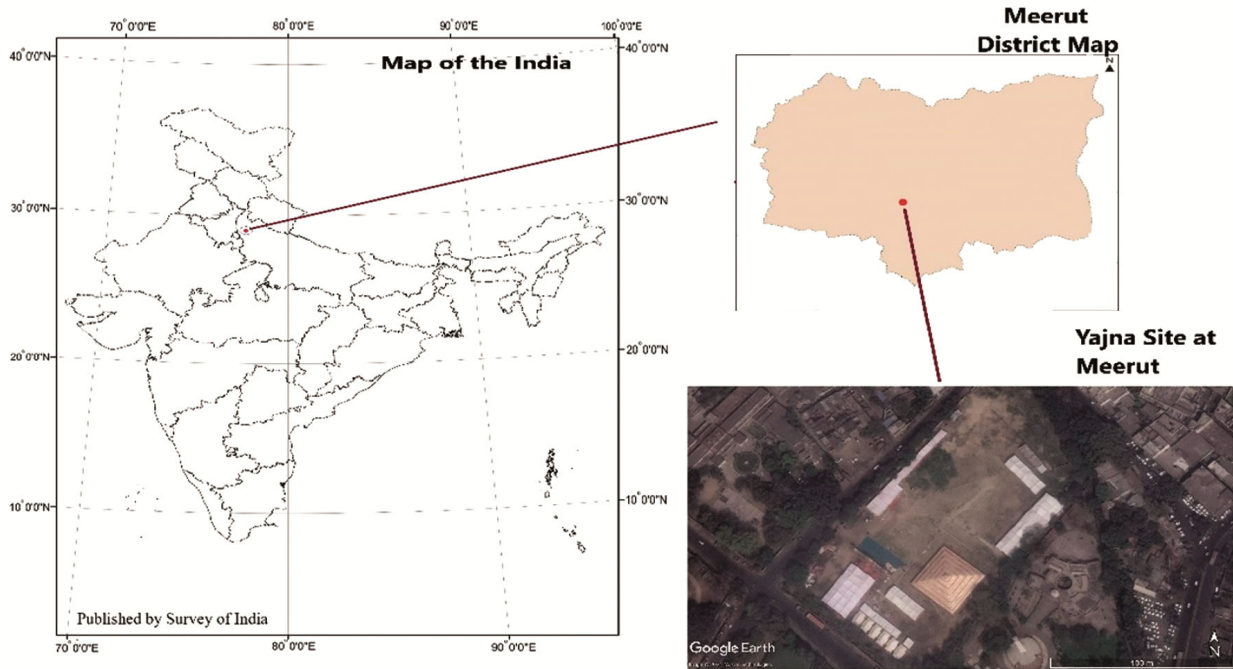


Fig. 1 — Yajna Site at Meerut, India

the Earth is such that, in the morning, it crosses the equator from north to south, whereas Aqua crosses it in the afternoon from south to north. Every one to two days, Terra MODIS and Aqua MODIS scan the whole surface of the planet. It is among the earliest passive satellite radiometers that was specifically intended to measure aerosols. It monitors terrestrial emission and reflected sun radiation in 36 wavelength bands with resolutions ranging from 250 m to 1 km while observing from about 700 km. With a nominal observation area of about 2300 km, it covers almost the whole world every day and each of its 5 minute segments, referred to as "granules," is around 2300 kilometers long<sup>23</sup>. The daily level 3 Collection 6.1 aerosol optical parameters & Cloud properties (MYD08 & MOD08) i.e., Aerosol Optical Depth (AOD) 550 nm, Angstrom Exponent(AE) (412-470 nm), Cloud Top Pressure (mean of daily mean), Cloud Optical Thickness (mean of daily mean), Liquid Water Cloud Effective Radius (CER), Cloud Liquid Water Path (LWP) are utilized in the present study and for the visualisation of CER, AOD, Cloud Fraction a joint atmosphere product MYDATML2 is used.

### 2.2.2 HYSPLIT Air Mass Trajectory

To establish source-receptor interactions, the Hybrid Single Particle Lagrangian Integrated

Trajectory (HYSPLIT) model uses geographically and temporally gridded meteorology data to simulate air parcel movement by wind advection<sup>24,25</sup>. A mix of the Lagrangian and Eulerian reference frames is used in the model computation process<sup>24</sup>. The movement of smoke has been extensively modelled using HYSPLIT<sup>24</sup>. The computation of forward and backward trajectories makes it possible to illustrate airflow patterns and interpret the movement of pollutants over various temporal and spatial ranges. The Global Data Assimilation System (GDAS) archive provides meteorological data with a 6-hour time step and a horizontal grid spacing of 0.5° latitude by 0.5° longitude, which are used to calculate two-day (48-hour) forward trajectories for the Yajna site.

### 2.2.3 Meteorological Data

The meteorological data i.e., precipitation, relative humidity (RH), temperature have been extracted from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2), the most recent atmospheric reanalysis of the modern satellite era created by NASA's Global Modeling and Assimilation Office (GMAO)<sup>26</sup>. The other precipitation data has been taken from the Near Real-Time 3-hourly Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis TMPA (3B42RT).

### 3 Results and Discussion

#### 3.1 Changes in aerosol optical properties over time along with meteorological parameters at Yajna site

A temporal variability in aerosol optical properties along with meteorological parameters have been studied at Yajna site for March month of 2018 as shown in Fig. 2. There has been a unique relationship observed between the aerosol optical parameters i.e., AOD, AE and meteorological parameters i.e., precipitation, temperature and RH during the Yajna period of 18-25 March 2018. For Yajna period, the optical properties of aerosol and meteorological parameters are almost inphase with each other. It is clearly evident from the Fig. 2 that both AOD and AE were higher during the Yajna period. This suggests relative dominance of fine-mode aerosols over the region. It is also evident from the Fig. 2 that the RH was relatively higher during the Yajna period when AOD and AE were higher. A precipitation signature of 0.4mm/day (very light rain category as per IMD) observed in nearby area during the Yajna period. This can be indicating that the particles generated during the Yajna activities had a unique physico-chemical characteristic in nature. These particles act as good CCN that may attract water vapor, and grow to form the rain-bearing clouds. In earlier study, it has been observed that the particles emitted from the forest fire act as a CCN with hygroscopic in nature, which can initiate the growth of precipitation particles through condensation and coalescence processes<sup>27</sup>.

Organic material (OM), BC, and a few inorganic components make up the majority of fresh biomass

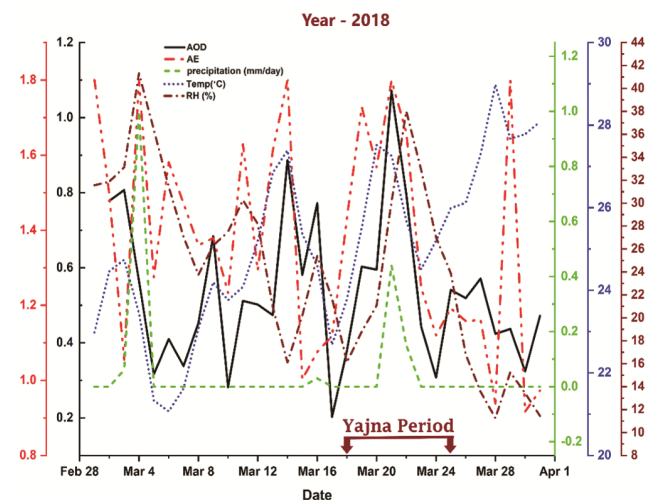


Fig. 2 — Temporal Variation in Aerosol optical parameters along with meteorological parameters over Yajna site in March month of 2018

burning particles<sup>28</sup>. The hygroscopicity parameter ( $\kappa$ )<sup>29</sup> of fresh biomass burning particles of different biofuel varied between 0.06 -0.622<sup>30,31</sup>. Fresh biomass burning particle  $\kappa$  is largely determined by the type of biomass fuel and, to a lesser extent, combustion conditions<sup>32,33</sup>. An earlier study found that smokes with high inorganic fractions (whose  $\kappa$  decreases with aging) and carbonaceous-dominated smokes (whose  $\kappa$  increases with aging) converged to midrange  $\kappa$  values after photochemical aging<sup>30</sup>. It has been noted that the kappa (K) value of smoke or fire particles is often low but not negligible<sup>29</sup>. The range of  $\kappa$  varies between 0.02 (indicates weakly hygroscopic) and 0.8 (indicates highly hygroscopic) for emitted particles from various type of biomass fuel and individual smokes<sup>34</sup>.

The biomass materials used in Yajna activity are mainly organics and structure of fire pit causes a complete combustion of the biomass. This may give rise to very low emission of BC leading to the hygroscopicity of emitted particles from Yajna in the range of 0.06-0.8 as per our earlier discussions. The hygroscopicity of OM increases with oxidation in the sub-saturated relative humidity regime<sup>35,36</sup>. The relative humidity was also in sub-saturated regime during the Yajna period, so a hygroscopicity of organic rich Yajna particles may increase due to oxidation. Inorganic rich particles are more sensitive to size than composition, but organic rich particles are sensitive to both size and chemical composition and fine organic particles are found more hygroscopic<sup>37</sup>. BB particles are usually in the accumulation mode with mean diameters  $>100$  nm<sup>28</sup>, so they have the potential to be CCN at modest supersaturations. The Ultrafine particle number emission from three stone cooking fire which uses typically wood is  $\sim (4.2 \pm 1.5) \times 10^{15}$  to  $(8.8 \pm 2.5) \times 10^{15}$  particles/kg of unimodal distribution with  $\sim 30$ -40 nm nucleation mode peak<sup>38</sup>. So, a total emitted particle during whole Yajna period might be in the range of  $(2.1 \pm 1.5) \times 10^{20}$  to  $(4.4 \pm 2.5) \times 10^{20}$  particles. It is noteworthy to mention that most of the fresh particles can serve as a reasonable CCN at a 0.2 % supersaturation level for a particle having activation diameter is in 114-125nm range<sup>39</sup>. In general, the mass, size and hygroscopicity of the biomass burning particles have been reported to increase after atmospheric aging<sup>40</sup>. It has also been reported that around 40–70% of the fresh particles from biomass burning after aging can activate as CCN at 0.2% supersaturation<sup>39</sup>. Therefore, the estimated

CCN released during the Yajna event might be in range of  $(8.4 \pm 1.5) \times 10^{19}$  to  $(3.08 \pm 2.5) \times 10^{20}$ .

A negative correlation has been reported between fine-mode AOD (fAOD) and precipitation over the tropical biomass burning areas. In earlier reported work while in higher latitudes, some exceptions are found where fAOD and precipitation are partially positively correlated during biomass burning period but it is coincidental and temperature was found to play a critical role<sup>41</sup>. The Boreal forest fires in higher latitudes typically occur during warmer seasons, but in the tropics, where the air is consistently warm, temperature is unlikely to be a limiting influence<sup>41</sup>. The Yajna site at Meerut comes under the Indo-Gangetic Plane (IGP) in the mid-latitude subtropical region of North India. A footprint of Yajna on AOD and Precipitation have been shown as a hotspot of higher AOD (in yellow color & circled in green color) and Precipitation rate (yellow + red color) are

observed near and downwind to Yajna site in the Fig. 3. It again emphasized the potential of Yajna as a cloud seeding agent in present scenario.

### 3.2 Temporal Variation in Cloud Optical Properties during Yajna Period

The smoke or fumes or fire particles loading in atmosphere from large scale Yajna is low in comparison to forest fire or wildland fires because lesser burning area, less amount of biomass burned. Figure 4 (a) depicts a temporal variation in cloud optical properties i.e., CER, LWP along with the precipitation have been studied at Yajna site for a March month of 2018. In this study, a continuous emission of fire particles from Yajna were happening, which may increase the aerosol concentration in the surrounding atmosphere. According to previously published work, higher aerosol concentrations cause liquid clouds' cloud droplet number concentration

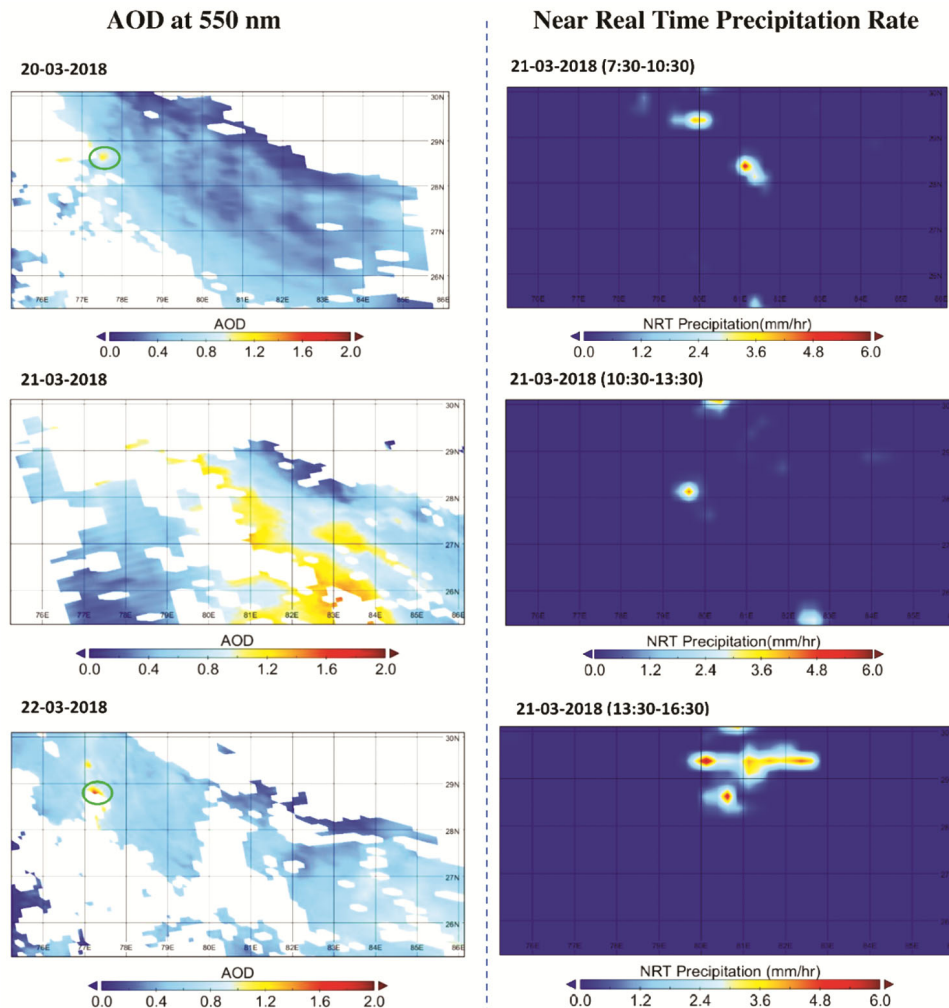


Fig. 3 — Implications of Yajna event on AOD and Precipitation

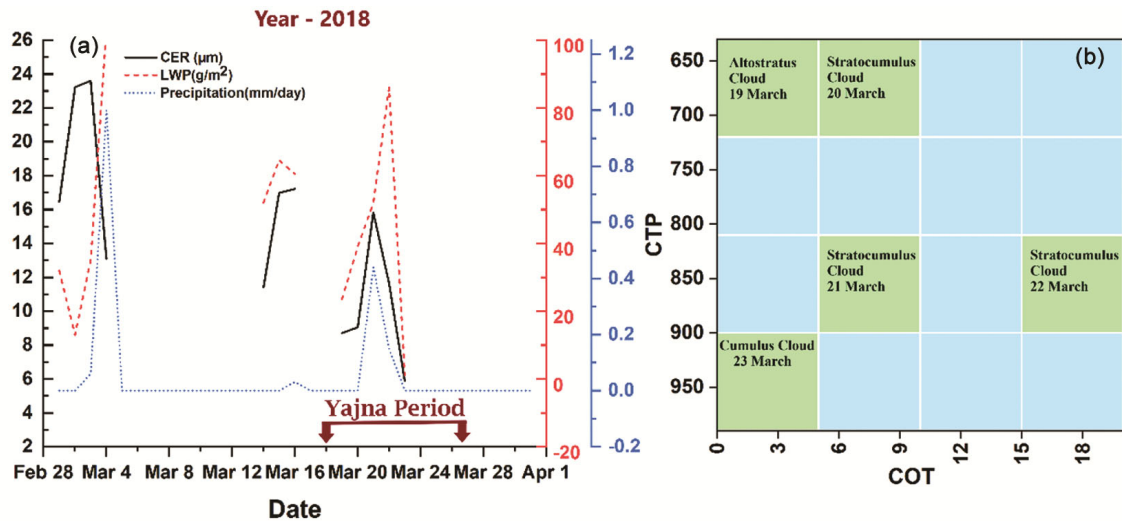


Fig. 4 — (a) Temporal variation of CER, LWP and Precipitation over Yajna site; (b) Cloud types during Yajna period over Yajna site

(CDNC) to rise that suppresses precipitation and lengthens the cloud lifetime at a fixed LWP<sup>42</sup>. During the Yajna period, AOD and AE are found to be relatively higher, which confirm the higher aerosol concentration that may increase CDNC in the cloud. Here, CER is showing an increasing trend and cross the precipitation droplet threshold of  $14 \mu\text{m}^{43}$ , the mechanism behind this may be initiation of collision-coalescence process due to increased aerosol concentration<sup>44,45</sup>. In our study, an existing cloud interacted with fire particles from Yajna that may invigorated the precipitation during Yajna period. It is to be noted here that the CCN from smoke plumes might decrease precipitation efficiency and droplet size at low cloud levels<sup>46</sup>, whereas there are other ways that precipitation can be enhanced at higher elevations<sup>47</sup>. This happens for higher smoke loading case that initially suppress precipitation because smoke reduces the riming and collision-coalescence processes, but eventually results in an invigoration of precipitation<sup>45</sup>. Precipitation has been found to increase in response to increased aerosol concentrations at higher LWP, whereas precipitation is reduced in lower LWP scenario<sup>48</sup>. During the Yajna period, the LWP was in the medium range of  $20\text{-}86 \text{ g/m}^2$  and majority of low level cloud were observed over the Yajna site as in Fig. 6. Here, the precipitation happened even in medium LWP that may be a novel effect of Yajna on microphysical properties of clouds.

It has been reported earlier that, aerosols suppress deep convection, producing ice clouds with lower altitude centroid in a light smoke environment<sup>49</sup>. In

present work Yajna is a case of light smoke which means fire particles from Yajna can also produce ice clouds with lower altitude centroid; a higher CER and Cloud Fraction indicates the presence of ice crystals in clouds on 21<sup>st</sup> March 2018 as shown in Fig. 5 & 6. It may happen that smaller cloud droplets that form in the presence of aerosols are more likely to freeze and may form Ice crystals within warm clouds when cloud top has a more negative temperature. So, when aerosols produce ice clouds with lower altitude centroid, it means that the clouds are forming lower in the atmosphere as stratocumulus cloud is found on 21<sup>st</sup> March 2018 in Fig. 4 (b). The daily variation of cloud fraction, CER and cloud type are shown in Figs. 5 & 4 (b). The 20<sup>th</sup> March was mostly cloud free sky but on 21<sup>st</sup> March, significant amount of cloud was present that interacted with the fire particles of Yajna. An increased level of LWP as visible in Fig. 4 (a) might favour a raindrop formation from the cloud droplets. In the current study, cloud type is identified using cloud top pressure (CTP) and cloud optical thickness (COT) data in accordance with International Satellite Cloud Climatology (ISCC) guidelines<sup>50</sup>.

### 3.3 Validation of Yajna Feedback through HYSPLIT Forward Trajectory

The HYSPLIT forward trajectory run for 48 hours along with rainfall has been shown in Fig. 7 for 20<sup>th</sup> March 2018. The majority of air parcel movement in the downwind direction towards the eastern IGP region of Uttar Pradesh (U.P) state of India and few air parcel movements towards the Western part of the

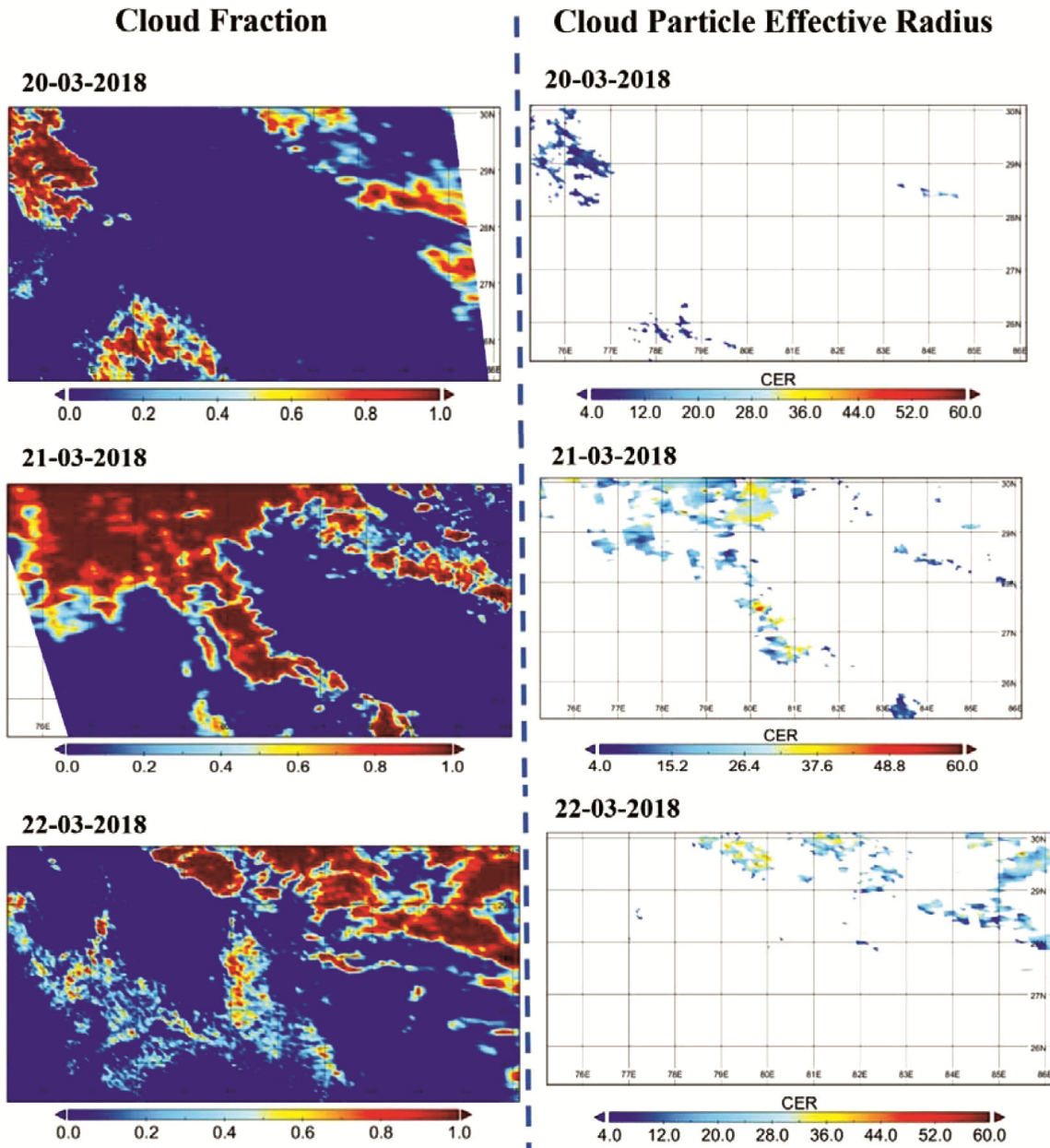


Fig. 5 — Daily Variation of cloud fraction and cloud particle effective radius over Yajna site based on MODIS data

IGP. The precipitation signature was observed around 36 hours later the air parcel emerged on 20<sup>th</sup> March (which is around mid of 21-22 March 2018) in blue, green and aqua color of wind trajectories (Fig. 7). Since the emitted particles from Yajna are carbonaceous in nature, therefore these aerosols could last in the atmosphere till seven days<sup>51</sup>. The constituents of BB plume evolved with time that may be affected by plume dilution due to atmospheric processes like gas-phase oxidation and the phase-to-

phase partitioning of primary and secondary organic aerosol that directly depend on concentration of constituents<sup>52</sup>. According to reported study, chemical oxidation of aerosols and the loss of volatile species happen more quickly in low-concentration environments; this is especially true near the edges of plumes as opposed to the centers, and minor flames as opposed to large ones<sup>53,54</sup>. A fresh emitted carbonaceous particle from Yajna may readily oxidise in low concentration environment which decrease

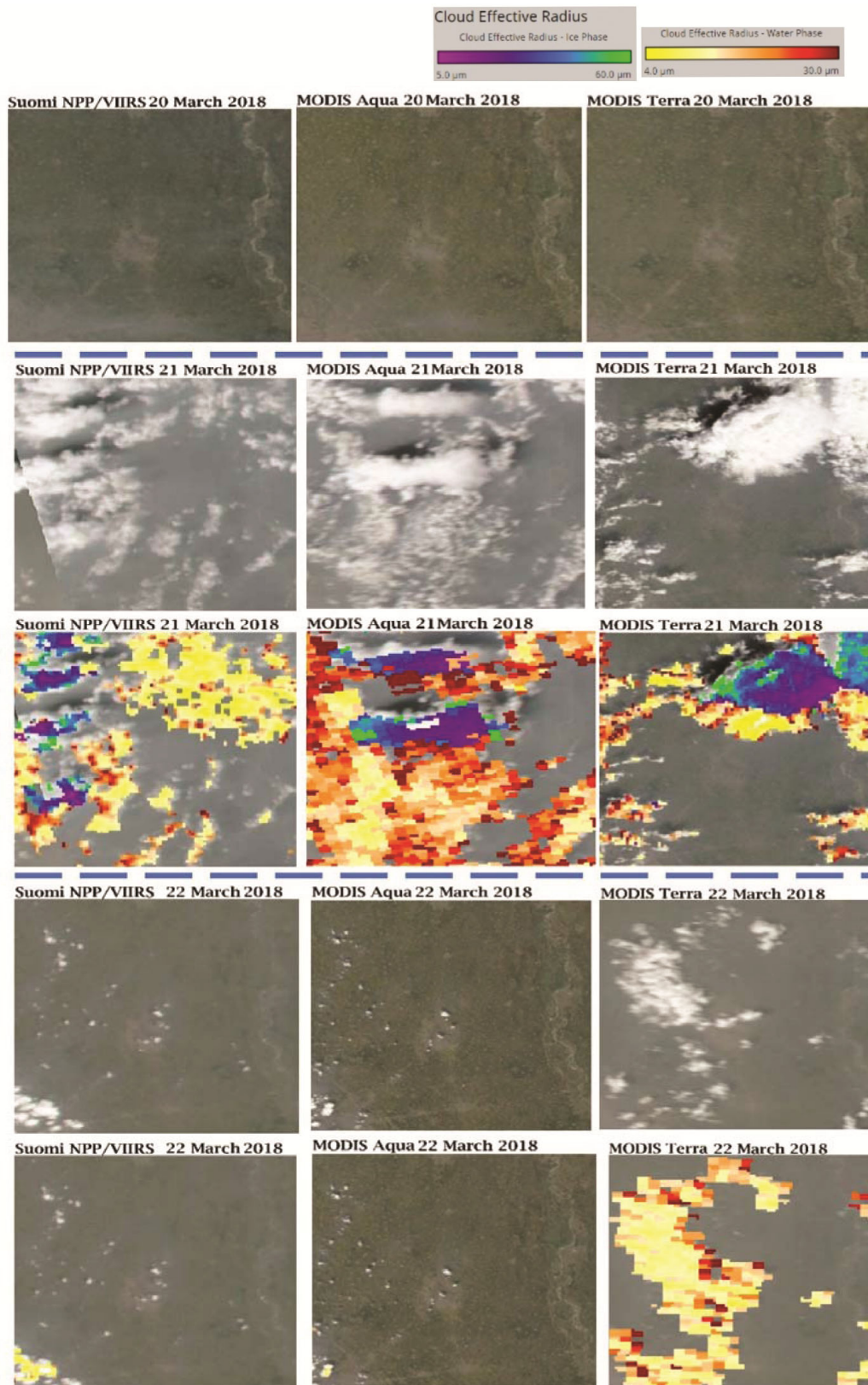


Fig. 6 — Daily imagery of Clouds cover over Yajna site

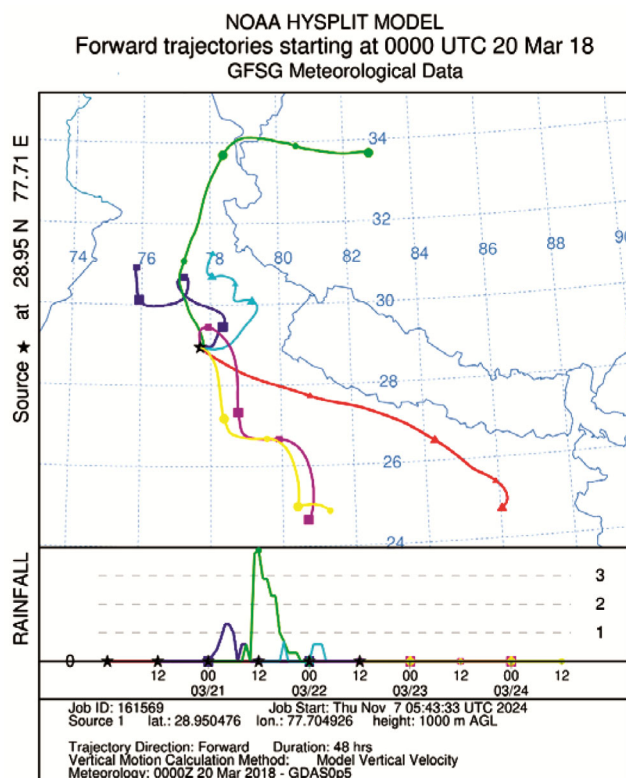


Fig. 7 — Forward Trajectory of 20th March air parcel at Yajna site along with rainfall

their residence time. So, accurate plume behavior and dispersion by HYSPLIT may help in understanding an implication of Yajna on microphysical properties of clouds.

#### 4 Conclusion

The Yajna is being followed by the Indian community since ancient time at a small as well as large scales on occasionally and daily basis for the betterment of environmental harmony. In this study, a large scale Yajna, conducted at Meerut city in North India during 18-25<sup>th</sup> March, 2018 was considered according to availability of satellite derived aerosol and cloud products along with the meteorological parameters among other cases. Among all possible outcomes of large scale Yajna, an increase in precipitation probability is one of them. The precipitation is suppressed in low level clouds in the presence of smoke but Yajna period has shown a small amount of precipitation even in mid-RH and lower LWP conditions. The low level and immature clouds are interacted with the emitted particles from Yajna. An increment in the collision-coalescence process and unique physicochemical properties of fire

particles from Yajna played a major role in modifying the microphysical properties of clouds; the estimated hygroscopicity of Yajna Particles come in the range of 0.06-0.8. In low smoke scenario precipitation is suppressed; it is invigorated only in high smoke scenario where ice clouds exist. However, in the present study, a mixed cloud in a low smoke scenario of Yajna has shown positive feedback of aerosol-cloud interactions that increase chances of precipitation due to intervention of large scale Yajna as visualized in Fig. 3

There are some limitations in this study that could not be addressed. Here, the result shown is based on one large scale Yajna event, however, the incorporation of more events could have been better. More large scale Yajna events could not be considered in present work due to non-availability or non-continuous satellite data products for that period/Yajna sites. The *in-situ* observations of large scale Yajna is necessary to determine a physicochemical characteristic of emitted particles through real-time & offline instruments to estimate its interactions with clouds and how it alters the microphysical properties of cloud.

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