NMRF/TR/03/2023

TECHNICAL REPORT

Development of Real-time Quality Monitoring Module for ARG network over Mumbai: Results from Monsoon 2020-2021

Upal Saha, M. Das Gupta, Ashis K. Mitra and V. S. Prasad

March 2023

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA

Development of Real-time Quality Monitoring Module for ARG network over Mumbai: Results from Monsoon 2020-2021

Upal Saha, M. Das Gupta, Ashis K. Mitra and V. S. Prasad

March 2023

National Centre for Medium Range Weather Forecasting

Ministry of Earth Sciences

A-50, Sector 62, NOIDA-201309, INDIA

Ministry of Earth Sciences
National Centre for Medium Range Weather Forecasting
Document Control Data Sheet

1	Name of the Institute	National Centre for Medium Range Weather Forecasting
2	Document Number	NMRF/TR/03/2023
3	Date of publication	March 2023
4	Title of the document	Development of Real-time Quality Monitoring Module for ARG network over Mumbai: Results from Monsoon 2020-2021
5	Type of Document	Technical Report
6	No. of pages & Figures	57 & 15
7	Number of References	25
8	Author (s)	Upal Saha, M. Das Gupta, Ashis K. Mitra and V. S. Prasad
9	Originating Unit	NCMRWF
10	Abstract	Deployment and maintenance of the ground-based in-situ observing systems are one of the most important component of weather and climate monitoring system. Since, the automated rain gauge (ARG) and automated weather station (AWS) networks are established as the source of direct measurements of instantaneous rainfall, the availability of proper ground rainfall observation networks are in high demand. With the advent of technology and the growing demand of high density observations, a MESO-scale rain gauge NETwork (MESONET), comprising of ~ 142 automatic rain gauges scattered over the Mumbai metropolitan region, is established to provide rainfall information that would help the policy makers to cope with unforeseen situations caused by intense rainfall events over Mumbai. However, the rainfall data accuracy from such highly-dense ARG networks can be maintained only after a careful and strict monitoring with proper quality checking. The present study deals with the monitoring of rainfall observations from this high-density ARG network of Mumbai-MESONET by applying the Quality Control (QC) procedure for the monsoon months (June-September, JJAS) of 2020 and 2021. In this study, the 24-hourly accumulated rainfall observations of Mumbai-MESONET has been validated against the high-resolution satellite-retrieved rainfall along with gridded (in-situ and satellite–gauge merged) observations and rainfall from collocated neighbouring ARG sites during JJAS-2020 and JJAS-2021 respectively. Based on this procedure, a real-time quality monitoring method has been developed to assign Quality Flags to each ARG rainfall observations within Mumbai-MESONET network which could be useful for the possible utilisation of station rainfall data in operation and research purpose by the end users.
11	Security classification	Non-Secure
12	Distribution	Unrestricted Distribution
13	Key Words	Rainfall; rain gauge; monsoon; Mumbai; MESONET; quality control.

Contents

Abstract

Deployment and maintenance of the ground-based in-situ observing systems are one of the most important component of weather and climate monitoring system. Since, the automated rain gauge (ARG) network is established as the source of direct measurements of instantaneous rainfall, the availability of proper ground rainfall observation networks are in high demand. With the advent of technology and the growing demand of high density observations, a MESO-scale rain gauge NETwork (MESONET), comprising of ~ 142 automatic rain gauges scattered over the Mumbai metropolitan region, is established to provide rainfall information that would help the policy makers to cope with unforeseen situations caused by intense rainfall events over Mumbai. However, the rainfall data accuracy from such highly-dense ARG networks can be maintained only after a careful and strict monitoring with proper quality checking.

The present study deals with the monitoring of rainfall observations from this high-density ARG network of Mumbai-MESONET by applying the Quality Checking (QC) procedure for the monsoon months (June-September, JJAS) of 2020 and 2021. In this study, the 24-hourly accumulated rainfall observations of Mumbai-MESONET has been validated against the high-resolution satellite-retrieved rainfall along with gridded (in-situ and satellite–gauge merged) observations and rainfall from collocated neighbouring ARG sites during JJAS-2020 and JJAS-2021 respectively. Based on this procedure, a real-time quality monitoring method has been developed to assign Quality Flags to each ARG rainfall observations within Mumbai-MESONET network which could be useful for the possible utilisation of station rainfall data in operation and research purpose by the end users.

Keywords: Rainfall; rain gauge; monsoon; Mumbai; MESONET; quality control.

1. Introduction

It has been an increasing demand for accurate rainfall estimations both for real-time modelling and for scientific research. Despite the continuous progress and recent developments in rainfall estimations using remote sensing techniques to overcome spatial limitations of rain gauge data, ground level gauges remain the true references for any weather analysis. Proper ground rainfall observation networks are highly demanded for calibrating remote sensing quantitative precipitation estimation (QPE), generating national, regional, and location-specific maps, nowcasting, real-time initial conditions for numerical weather prediction, hydrological modeling validations, etc., as automated rain gauge (ARG) network serve as direct sources of instantaneous rainfall measurements (Saha et al., 2020, 2021; Ośródka et al., 2022). Thus, for several hydro-meteorological utilization, several rain gauges forming a rain gauge network is utmost necessary for providing rainfall information with high temporal and spatial resolution (Sunilkumar et al., 2022). In operational forecasting, low quality observational rainfall records, especially for unreasonably high or false zero rainfall values, can degrade model calibration and initialization, which can consequently lead to erroneous forecasts and misleading warnings (Borga et al., 2006). Due to various reasons, including power cut-off, server and internet facility down for transmission of data, sensor out of order, localised extreme weather events, system under maintenance, etc., some of the ARG stations from such a dense network might either having missing rainfall information or recorded data with large errors of various types that are hard to detect and correct, and even corrected records suffer from high uncertainty. Hence, it is extremely important to ensure quality checking (QC) of the recorded data, including both qualitative and quantitative corrections (Szturc et al., 2022). Thus, the data accuracy from such highly-dense ARG networks can only be maintained after a careful and strict monitoring and QC procedure, before they are applied as input data for any real-time hydrological modelling, in order to acquire reliable rainfall records. Previously, Saha et al. (2021) has developed a real-time monitoring and QC methodology using 24-hourly accumulated rainfall from IMD-maintained ARG network all over the Indian domain by assigning Quality Flags to each station based on the computed statistics of previous 15-day time-series of ARG rainfall with surface synoptic observations (WMO-SYNOP) and gridded/satellite-gauge merged rainfall.

The present work is also based on the high-density ARG network, named as MESO-scale rain gauge NETwork (MESONET), but over Mumbai (18.8^0N-19.35^0N, 72.8^0E-73.25^0E) region. Indian Institute of Tropical Meteorology (IITM), Pune, under the Ministry of Earth Sciences (MoES), India has taken the initiative to combine the rainfall measurements from four different agencies, namely, IITM, Municipal Corporation of Greater Mumbai (MCGM), India Meteorological Department (IMD), and System of Air Quality and Weather Forecasting and Research (SAFAR) under IITM and established a Mumbai-MESONET (Sunilkumar et al., 2022). The network started with ~124 ARG sites in 2019, which increased to ~ 147 sites in 2022. The rain gauges of MESONET are tipping bucket types manufactured by different companies. IITM maintains the rain gauges made by M/s. HyQuest Solutions Pvt. Ltd., Australia (Model No: TB4). Mumbai region has got a complex topography that comprises seacoast, flatlands, high-rise buildings, small hills, and mountains and as a result of which urban regions are much vulnerable to extreme rainfall events for several physical, dynamical, and topographical reasons leading to flood occurrences (Rana et al., 2012; Sunilkumar et al., 2015). During the southwest monsoon (June–September), Mumbai and surrounding regions receives copious amount of rainfall and drains overflowed causing local flooding, due to which significant transport disruptions like railways, road transport, and aviation services can be seen. High-resolution data along with quality information are thus of great importance for the data end users, for example, in crisis management during flood emergencies or in the issuing of dangerous weather warnings. Thus, it is very much necessary to daily monitor and check the quality of rainfall data from this high-density Mumbai-MESONET.

Thus, the present study deals with the monitoring of the high-density ARG network of Mumbai-MESONET and to perform the QC procedure for the monsoon months (JJAS) of 2020 and 2021. In this study, an attempt has been made to validate high-density ARG rainfall observations of Mumbai-MESONET against the high-resolution Integrated Multi-satellitE Retrievals for GPM-IMERG rainfall product, gridded observations from IMD, IMD-NCMRWF merged satellite-gauge rainfall product as well as rainfall data from neighbouring ARG sites (as buddy check). Based on the validation results, a methodology has been devised to delineate good quality ARG rainfall observations from the network and judicially using these high-density rainfall observations for its further utilisation in real time operation, weather monitoring as well as for verification of numerical weather prediction (NWP) model outputs. The study also attempts a real-time daily monitoring and QC for the Mumbai-MESONET rainfall data. This information is very crucial for all the stake holders, mainly, Disaster Management Department, Municipal Corporation, Western and Central Railways, Road transport, media and many others. This is also vital for the operational NWP-Centers, like NCMRWF or IMD or IITM, since the rainfall information from the quality-controlled high-density rain gauge stations may be utilized for the verification of different operational NWP-models. The present report is structured as follows: Following the Introduction in Section 1, Section 2 describes the in-situ (MESONET ARG rainfall data) and gridded rainfall observations (detailed in the section below) as well as the methodology applied for daily monitoring and QC; Section 3 presents the coverage of ARG sites during JJAS 2020-2021 based on rainfall observations reported by different agencies; Section 4 deciphers the methodology and its application for the assignment of QC Flags to each ARG sites within Mumbai-MESONET during monsoon; Section 5 indicates the overall status of the performance of these stations maintained by different agencies; Section 6 comprises of some case studies for extreme rainfall events over Mumbai region; Section 7 designates the methodology applied for real-time daily monitoring and quality checking of each of the sites under Mumbai-MESONET and finally the report has been wrapped up with Summary and Conclusions in Section 8.

2. Data and Methodology

Daily rainfall observations (24 hourly accumulated from previous day 08:30 AM to present day 08:30 AM, i.e. 04Z-03Z) of stations from the "Mumbai-MESONET network" has been validated against neighbouring ARG sites and three gridded (one in-situ, one satellite and other satellite-gauge merged) rainfall datasets over Mumbai region during June-September for 2020 and 2021 respectively.

2.1 In-situ rainfall observations

The daily (24-hourly) accumulated in-situ rainfall observations are obtained from the high-density MESONET observations over Mumbai that cover the latitudes of about 18.8^0N-19.35^0N and longitudes of 72.8^0E-73.25^0E with a total area of about 2800 km^2, including Greater Mumbai, Thane, Kalyan-Dombivili, and Navi Mumbai Municipal Corporations. MESONET is the first dense ARG network established in Mumbai. The sub-daily and daily rainfall observations from these network are procured from a dedicated FTP server from IITM, Pune in excel (.xlsx) format during JJAS-2020 and JJAS-2021. The obtained data are then pre-processed for missing data checks, neighbouring collocated station look up and categorization of rainfall observations based on the maintained agency using Python 2.7 environment. The average number of ARG stations reporting daily rainfall observations was ~132 during JJAS 2020 and ~142 during JJAS 2021 over Mumbai. Most of the rain gauges are located within 10-25 km radius. Furthermore, Ministry of Earth Sciences (MoES) is making tremendous efforts in augmenting more and more rain gauges over Mumbai to get an overall rainfall picture of every locality. The coverage plots for the daily availability of reported rainfall stations will be discussed in the upcoming Sections.

2.2 Gridded rainfall observations

In this study, three gridded rainfall datasets – i) gauge-only (Pai et al., 2014), ii) satellite-based gridded (Huffman et al., 2019) and iii) satellite-gauge merged products (Mitra et al., 2013) are used for validation of Mumbai-MESONET ARG rainfall observations. First one is the daily gauge-only gridded rainfall dataset at 25 km spatial resolution over whole India generated by IMD (Pai et al., 2014). However, the temporal density of the station points was not uniform and on average, about 2600 stations per year with a maximum of 6955 stations over entire India were available for the preparation of daily grid-point data (Rajeevan et al., 2006, 2008; Pai et al., 2014). Out of 6955 rain gauge station records, 547 records from IMD observatory stations, 494 records from Hydro-meteorological observatories, 74 records from Agro-met observatories and 5845 records from stations maintained by the state governments (Pai et al., 2014; Singh et al., 2021). This IMD gauge-only gridded data is daily downloaded from IMD Pune website: https://imdpune.gov.in/cmpg/Realtimedata/Rainfall/Rain_Download.html. This data set has been widely used as a reference rainfall data for the evaluation of satellite-derived rainfall, validation of predicted rainfall by NWP models and various hydro-meteorological applications in India (Jena et al., 2020; Setti et al., 2020; Singh et al., 2021).

The other gridded dataset constitutes the high resolution (0.1° x 0.1° spatial resolution in half hourly time scale) Integrated Multi-satellitE Retrievals for GPM-IMERG satellite rainfall product, which is generated from the ten microwave imaging and sounding satellites in the GPM constellation (Huffman et al., 2019). This half-hourly real-time GPM-IMERG satellite rainfall product is then processed to generate 24-hourly daily (04Z-03Z) accumulated rainfall for JJAS 2020-2021 respectively, which is further used for the verification of highly-dense Mumbai-MESONET ARG rainfall data.

The other daily gridded set used in this study is NCMRWF merged satellite-gauge (NMSG) rainfall product, generated jointly by NCMRWF and IMD (Mitra et al., 2003, 2009, 2013). In this method rainfall is analysed using IMERG (GPM) satellite product as first guess and IMD in-situ gauge discussed above as observations, which corrects the satellite-estimated rainfall. The daily merged satellite-gauge rainfall data is downloaded from IMD Pune website: https://imdpune.gov.in/cmpg/Realtimedata/gpm/Rain_Download.html. This dataset is also extensively used in several studies (Prasad et al., 2016; Sharma et al., 2017; Sridevi et al., 2020; Saha et al., 2021, etc.) to validate the model forecast over Indian region. Both the qualities of IMERG (GPM) as well as NMSG rainfall data over the Indian were well documented in Reddy et al. (2019). This NMSG gridded rainfall is used as another background data for the verification and quality checking of ARG rainfall stations from this dense network over Mumbai during JJAS 2020-2021.

2.3. Methodology

Verification of the 24-hourly (8:30 AM previous day to 8:30 AM next day) accumulated rainfall from Mumbai-MESONET ARG network is carried out against neighbouring ARG sites (collocated within 3km radius from the base station) as well as GPM, IMD and NMSG gridded rainfall data following the steps discussed below:

1. Preparation of Rainfall Database: Mumbai ARG Rainfall Archive data for JJAS-2020 and JJAS-2021 has been downloaded from the dedicated FTP Server from IITM, Pune, while GPM Rainfall data is taken from NCMRWF Operational Observational Rainfall Data Archive and IMD as well as NMSG gridded rainfall data are downloaded from IMD Pune web page. As the daily reception of ARG rainfall observations is highly variable, only those stations with frequency of reported observations at least 50% (61 days) in the season (i.e. June to September comprising of 122 days), are used for the verification purpose. These stations are termed as “Regular Stations”. Those stations which reported less than 61 days are termed as “Irregular Stations”.

2. Missing Data: The prepared rainfall database are checked and made ready after filling the missing dates having missing data with ‘NaN’ or ‘-99’ values within each of the Station data.

3. Neighbourhood-Selection for each sites: Neighbouring stations of each ARG locations (collocated within 3 km radius) have been searched for both the monsoon months of 2020 and 2021.

4. Outlier Data Removal: The rainfall values from each collocated stations were passed through 2-Sigma Rule [Median ± 2 sigma] for the removal of any spurious or outlier data in particular days. Mean of the rainfall values from neighbouring stations have also been calculated after outlier removal technique applied.

5. Preparation of Rainfall Time-series: After the step of outlier data removal, the rainfall data from the sources of ARG, GPM, IMD and NMSG are made ready for time-series preparation of 122 days of individual monsoon (i.e. JJAS) season during 2020-2021.

6. Computation of Statistics: Various statistics, e.g. Pearson’s correlation co-efficient, root mean square error (RMSE), standard deviation, bias and mean of the rainfall observations for each ARG sites are computed against collocated neighbouring sites, GPM, IMD and NMSG rainfall data for the monsoon season during 2020 and 2021 respectively.

7. Quality Flagging: Based on the calculated statistics, each of the ARG stations within the network is attached with flags ranging from 0 to 9, with 0 as the best. Flag 0-5 are termed as “Regular and Usable Stations”, while Flag 6 is termed as “Regular but Non-Usable Stations” and Flag 7-9 are designated as “Irregular Stations”. Detailed discussion on quality flagging criteria will be presented in the later part (Section 4). Based on the verification statistics of previous 15-day time series, a real-time monitoring procedure has been developed for quality flagging each individual rainfall reporting stations. Depending upon the assigned Quality Flags, end user can decide which stations to be used for a particular application.

8. Coverage and Time-series plots: Coverage plots based on the reported rainfall observations by each agencies during the period are plotted with associated statistics. Rainfall Time series of each of the ARG stations are plotted against the rainfall sources from GPM, IMD, NMSG and mean of the collocated Neighbouring (NHBR) Stations.

3. Spatial coverage of ARG stations during monsoon over Mumbai

MESONET is the first-ever highly dense ARG network been established in Mumbai, having inter-gauge distance between 1-3 km. This section will describe the coverage and statistics of ARG stations within the network over Mumbai based on (a) daily accumulated rainfall observations reported by the maintenance agencies – IITM, MCGM, IMD and SAFAR, (b) actual reported days of rainfall observations, sub-divided into categories, (c) agency-wise actual reported days of rainfall observations during JJAS-2020 and JJAS-2021.

3.1. Based on daily accumulated rainfall observations reported by agencies

The daily rainfall observations by Mumbai-MESONET ARG network are being reported and stored every day by a remote server located at IITM, Pune. From Figure 1, it is seen that there were a totality of 132 stations during monsoon months (June-September, JJAS) of 2020, which has increased to 142 stations in JJAS-2021. During JJAS-2020, out of 132 ARG stations, 38 stations are maintained by IITM, 59 stations are maintained by MCGM, 7 stations by IMD and 28 stations by SAFAR, as can be seen from Figure 1a, while during JJAS-2021 rainfall data reported by all other agencies did not change except for IMD. 10 new stations started reporting rainfall observations in JJAS-2021, making a totality of 17 stations as maintained by IMD (Figure 1b).

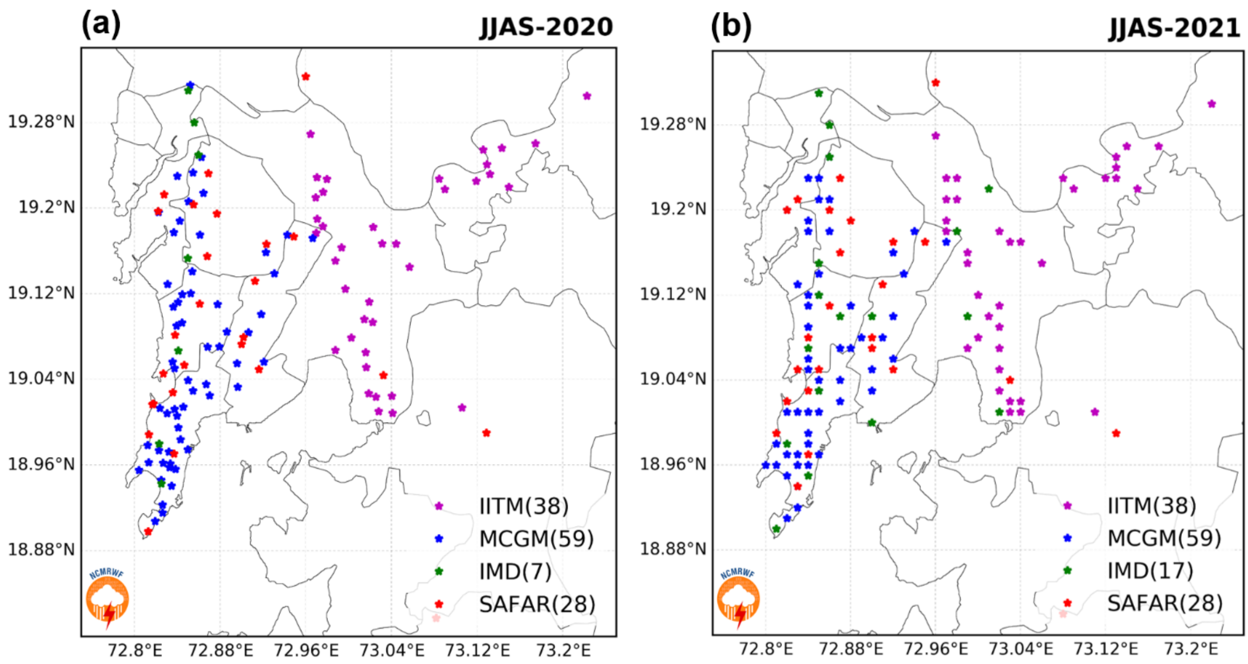


Fig. 1. Coverage of ARG stations maintained by IITM, MCGM, IMD and SAFAR agencies during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

3.2 Based on actual reported days of rainfall observations

Daily reported rainfall observations are categorized into six categories: i) 90% and above (>= 110 days), ii) 80-89% (98-109 days), iii) 70-79% (85-97 days), iv) 60-69% (73-84 days), v) 50-59% (61-72 days) and vi) less than 50% (< 61 days), on the basis of actual reported days of observations out of 122 JJAS-days. From Figure 2a and Figure 3a, it is evident that during JJAS-2020, the sixth category coverage (i.e. < 50%, shown in black stars) over Mumbai was maximum (67 in count) which indicates that out of 132 stations, 67 ARG stations (~ 50.76%) have reported less than 50% days of rainfall observations. This clearly shows that more than half of the ARG sites have not reported daily rainfall data during monsoon months of 2020. On the other hand, during JJAS-2021, the situation for sixth category coverage has improved significantly and only 19 stations (~ 13.38%) out of 142 stations have reported in this category (Figure 2b and Figure 3b). It is to be noted that Figure 3 shows the total count of ARG stations reported during JJAS-2020 and JJAS-2021 to be 132 and 142 respectively.

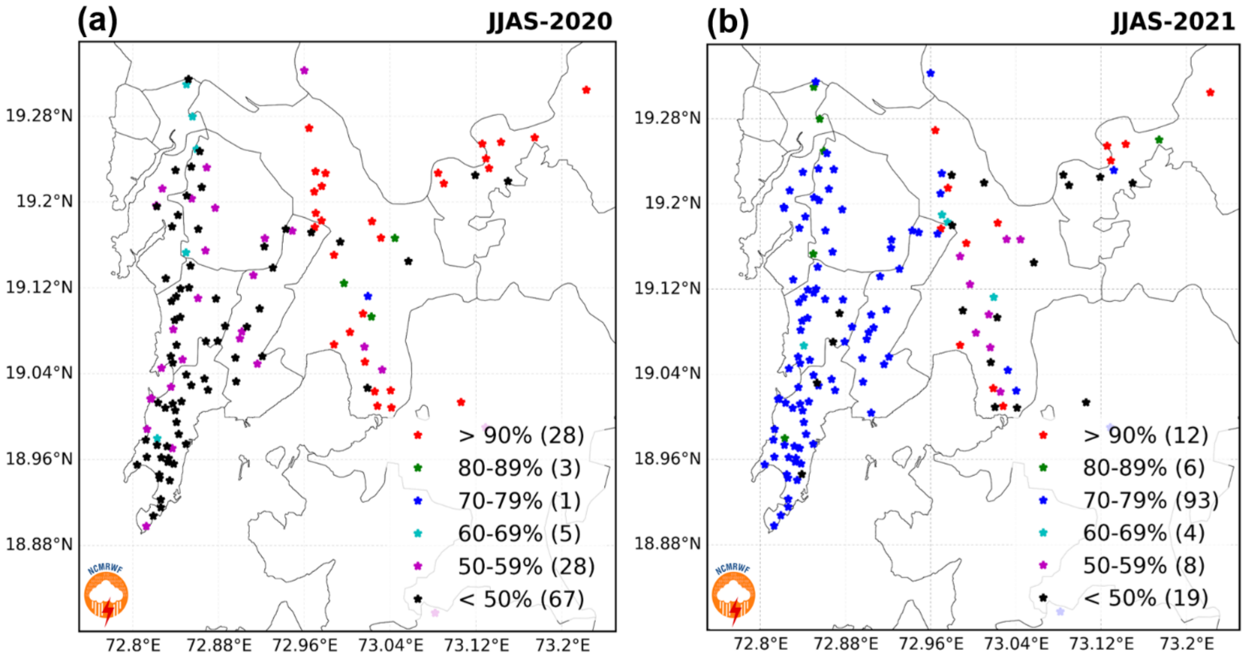
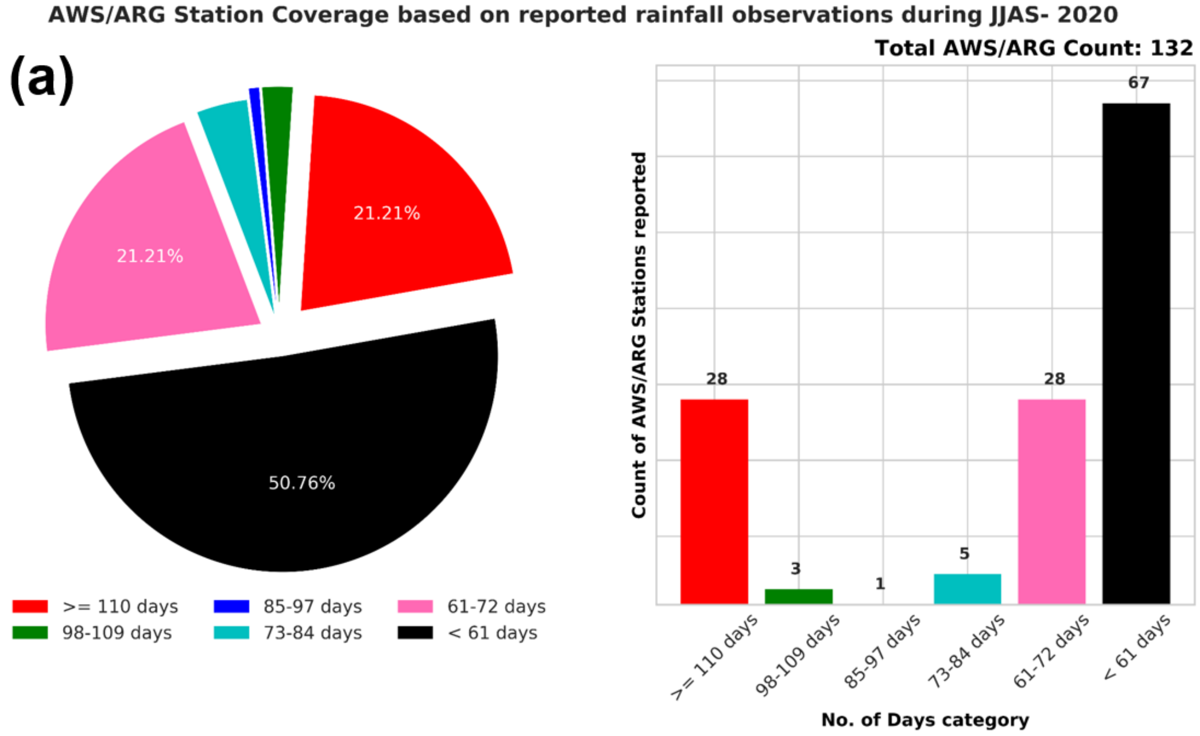


Fig. 2. Coverage and categorization of ARG stations based on the actual reported days of rainfall observations during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

Moreover, the first category (> 90%, shown in red stars) coverage are comparatively greater in count for JJAS-2020 (28 in count, ~ 21.21%) than JJAS-2021 (12 in count, ~ 8.45%), which indicates the stations reporting > 90% of the days of rainfall has reduced significantly in 2021 than 2020. On the contrary, the third category (70-79%, shown in blue stars) coverage was maximum in 2021 (93 in count, ~ 65.49%) than the previous year (1 in count, ~ 0.70%), which specifies a significant improvement in reported rainfall data coverage over Mumbai region during JJAS-2021. The spatial coverage of other categories and their percentage coverage statistics can be evident from Figure 2 and Figure 3. Those slices in the pie charts which remains unannotated indicates the coverage has been less than 10% out of total number of reported station observations.



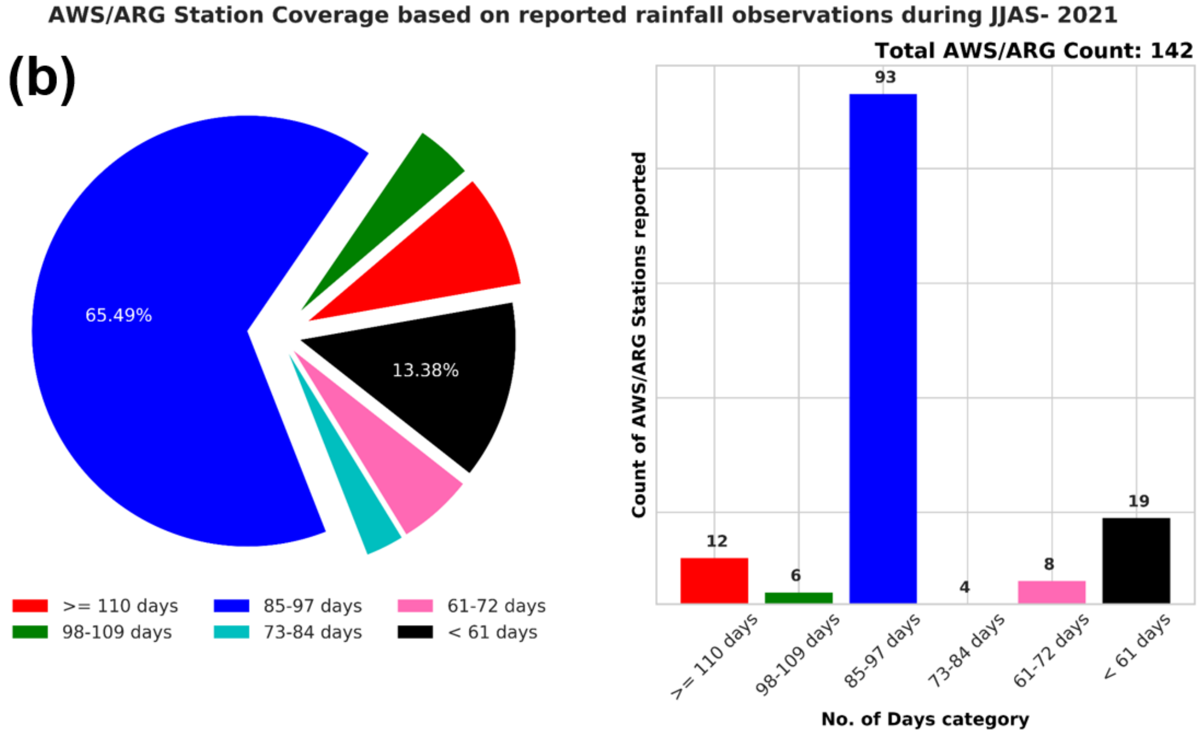


Fig. 3. Statistics for the ARG station coverage based on the reported days of rainfall observation during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

3.3 Based on agency-wise actual reported days of rainfall observations

This sub-section will demonstrate the coverage of different agency-maintained ARG stations from the highly dense Mumbai-MESONET according to the reported days of rainfall observations, alike the previous sub-section 3.2, with the statistics based on the percentage count as well as the reported count of rainfall data during 2020-2021 monsoon months. Figure 4 deciphers a single-frame qualitative information for the coverage of ARG sites based on the categorization percentage of reported rainfall observations by each agencies (IITM, MCGM, IMD and SAFAR) for both JJAS-2020 and JJAS-2021 respectively. This figure will not indicate the exact count of reported rainfall observations but it will definitely showcase the regular and irregular ARG stations maintained by each agencies. IITM, MCGM, IMD and SAFAR-maintained stations are marked with “circles”, “diamond”, “triangle” and “star”-shaped markers respectively. It is to be noted that the first category (i.e. the stations reporting > 90% of days within 122 days of JJAS) are color-encoded with “red”, second category (80-89% or 98-109 reported days) with “green” color, third category (70-79% or 85-97 days) with “blue”, fourth category (60-69% or 73-84 days) with “cyan” color, fifth category (50-59% or 61-72 days) with “pink” and final sixth category (< 50% or < 61 days) with “black” color. During JJAS-2020, the stations which have reported less than 50% of the days are in a huge number operated by MCGM agency, while the stations that reported greater than 90% of the days are mostly maintained by IITM agency (Figure 4a). SAFAR-maintained stations are mostly clustered within the fifth category while IMD-maintained stations mostly lie within fourth category in JJAS-2020. Irrespective of JJAS-2020, most of the stations maintained by MCGM were restored and revived during JJAS-2021 and reported under the third category while some of the stations maintained by IITM stopped reporting daily and lie into sixth category (Figure 4b).

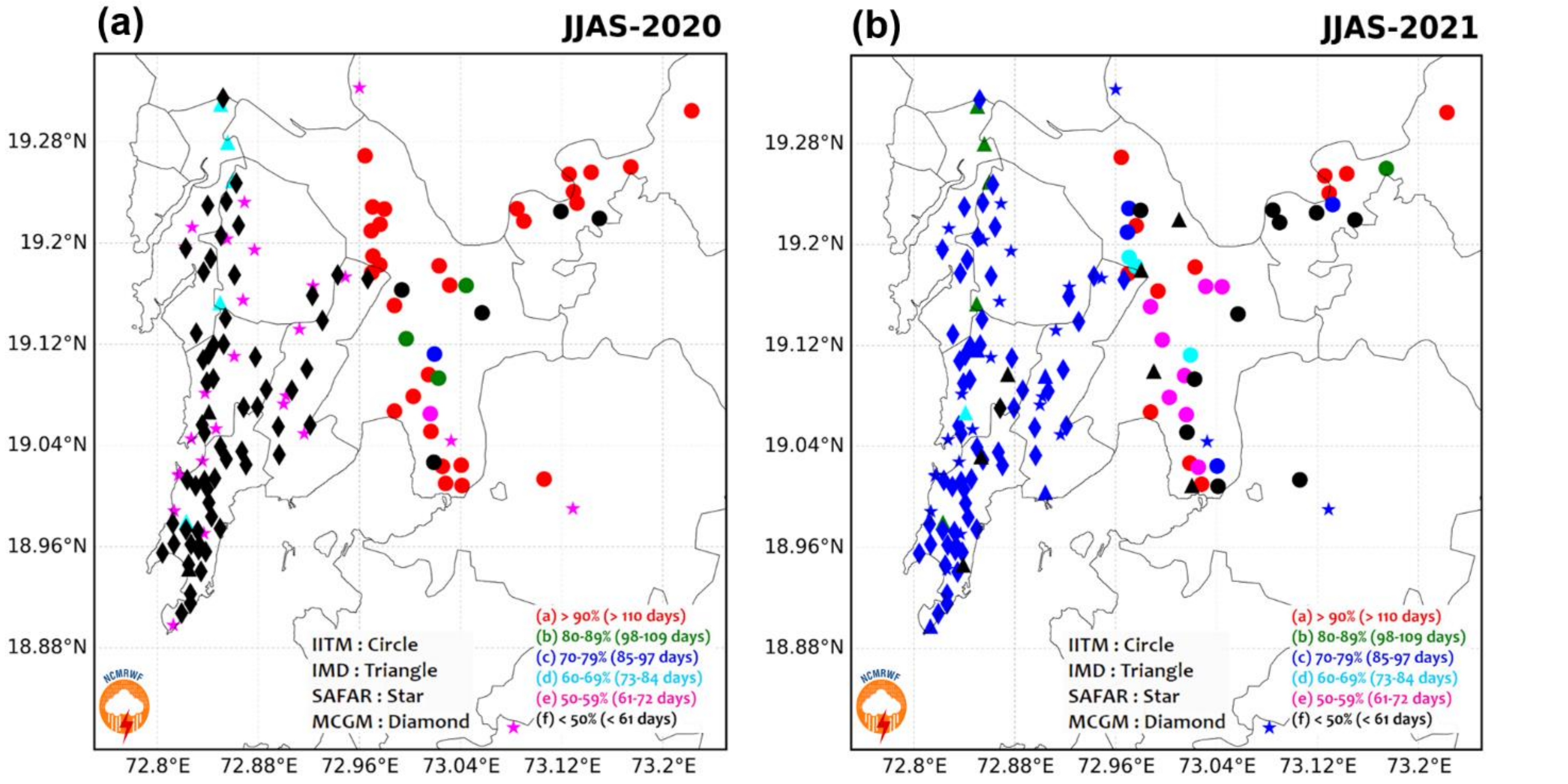


Fig. 4. Coverage of ARG stations maintained by IITM, MCGM, IMD and SAFAR agencies with categorization (based on reported days of rainfall observations) in a single frame during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

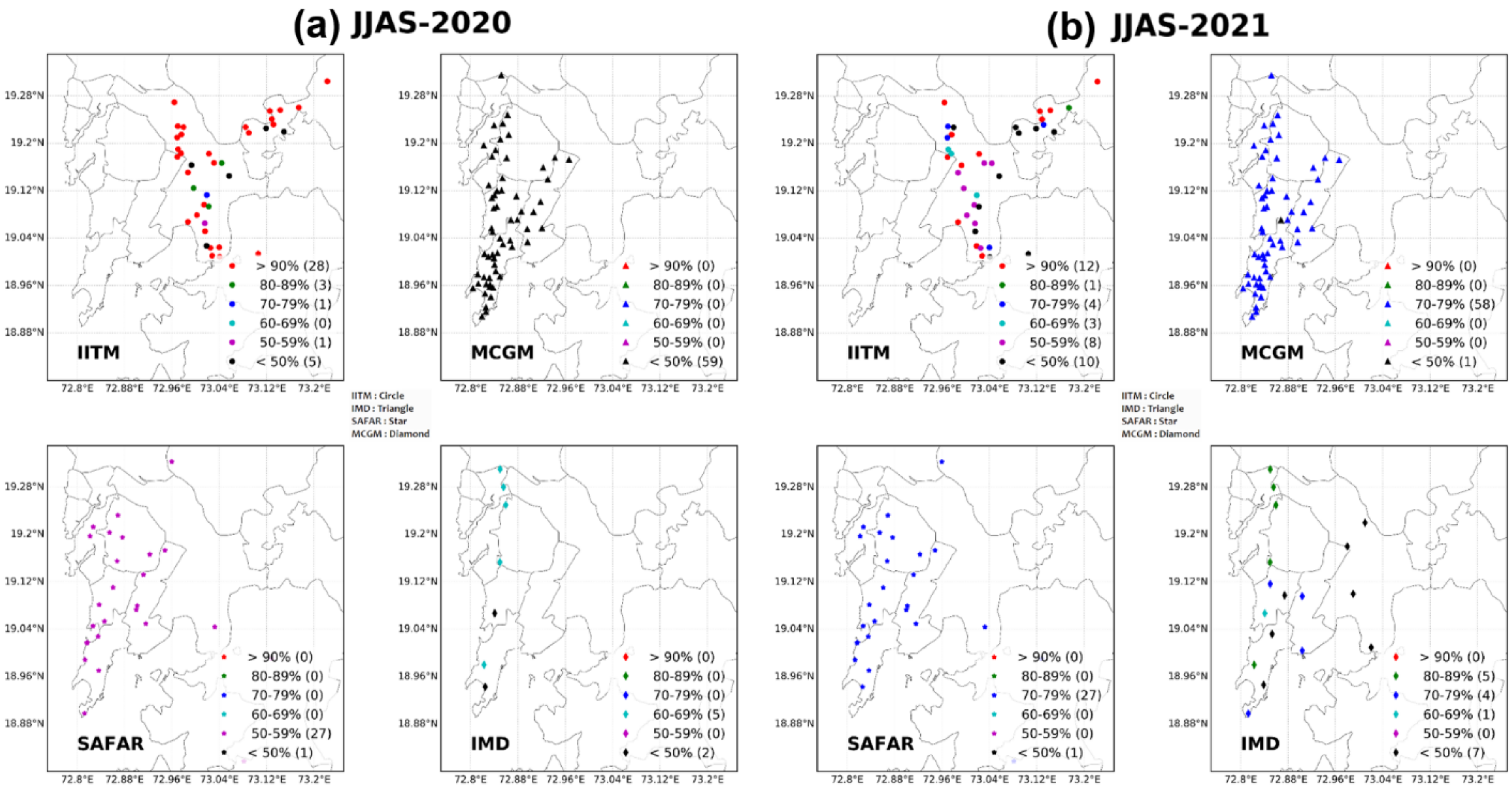


Fig. 5. Panel plots for the coverage of ARG stations (as maintained by IITM, MCGM, IMD and SAFAR agencies) based on reported days of rainfall observations categorization during the monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

Now, Figure 5 demonstrated the quantitative panel plots for the coverage of different agency-maintained ARG stations, based on the category created through reported days of rainfall observations, during the monsoon 2020-2021. The upper-left panel of Figure 5a indicates that 28 ARG stations maintained by IITM have reported > 90% days of the total monsoon (JJAS, i.e. 122 days) length, while 5 of the stations have reported < 50% days out of 122 days in JJAS-2020. Similarly, the upper-right panel of Figure 5a indicates that all the ARG stations maintained by MCGM have reported less than 50% of the reported rainfall observations, which is also seen in the qualitative picture of Figure 4a. SAFAR-maintained stations were also not so regular and 27 of such stations out of 28 count have reported under 50-59% category as evident from the lower-left panel of Figure 5a, while 5 of the IMD-maintained ARG sites have reported 60-69% of the days in JJAS-2020 and rest in less than 50% category as seen from lower-right panel of Figure 5a. Likewise, the upper-left panel of Figure 5b indicates that 12 ARG stations maintained by IITM have reported > 90% days and 10 of the IITM-stations have not reported more than 50% days of the total monsoon length in JJAS-2021, which is a clear picture of deteriorated functioning of IITM-maintained ARG stations than JJAS-2020 as evident from Figure 5a. Correspondingly, the upper-right panel of Figure 5b indicates that 58 out of 59 MCGM-maintained ARG stations have reported 70-79% days of the total monsoon length in JJAS-2021, which is actually a very good improvement in terms of the functioning of ARG sites than JJAS-2020. Similarly, the lower-left panel of Figure 5b shows that 27 out of 28 number of SAFAR-maintained stations have reported 70-79% days (i.e. 85-97 days) out of 122 days of monsoon 2022. These SAFAR stations too have shown improvement in terms of reporting rainfall observations more frequently in 2021 than in 2020. Finally, lower-right panel of Figure 5b depicts IMD-maintained stations have also shown improvement in JJAS-2021 and a total of 9 stations out of 17 stations have reported in second and third category of reported days of rainfall data, which was really absent in JJAS-2020.

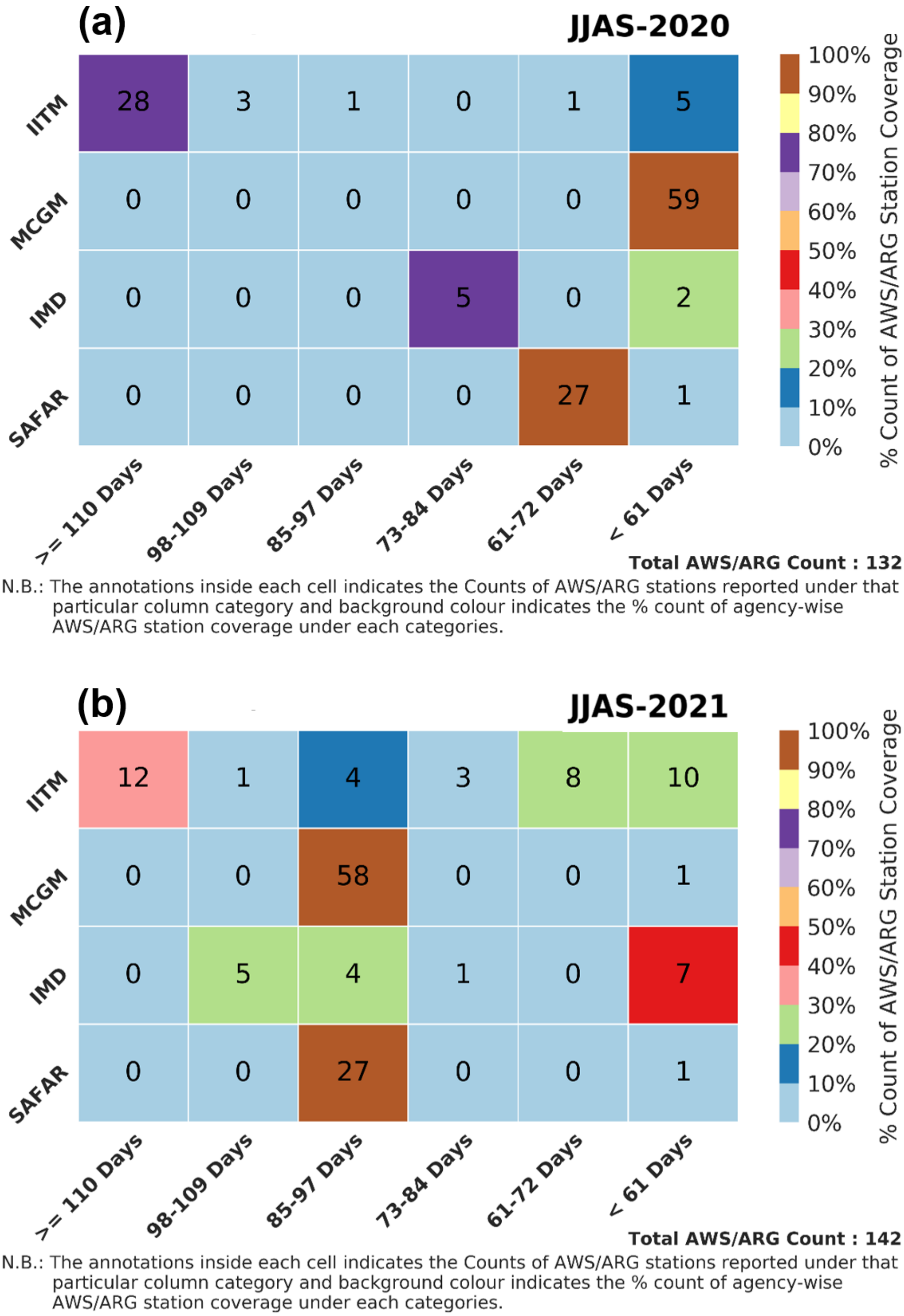


Fig. 6. Heatmap Statistics based on the percentage count as well as the reported count of rainfall observations by ARG stations as maintained by IITM, MCGM, IMD and SAFAR agencies during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

Figure 6 demonstrates the cumulative statistics based on the percentage count as well as the reported count of rainfall observations by ARG stations as maintained by IITM, MCGM, IMD and SAFAR agencies during monsoon 2020 and 2021 in terms of Heatmap. Thus, this figure clearly indicate the counts of reported rainfall observations, by agency-wise ARG stations, annotated within each cell. Each cell indicates the categorization (as discussed in earlier sections) as per reported data by each of the agencies. The background color inside each cell indicates the percentage count of ARG station coverage reported by each agencies under those particular categories. Figure 6a depicts ~ 70-80% (28 out of 38 stations) of the IITM-maintained stations reported rainfall observations greater than equal to 110 days within 122 monsoon days of 2020. Likewise, 100% of the MCGM-maintained stations (59 out of 59 stations) have reported less than 61 days of rainfall observations. Similarly, 5 out of 7 IMD-maintained stations (~ 70-80%) have reported within 73-84 days category, while 27 out of 28 SAFAR-maintained ARG stations (~ 90-100%) have reported 61-72 days out of 122 JJAS days (Figure 6a). In the same way, the other annotated values and color with each cell can easily be depicted from the figure for JJAS-2020. Also, Figure 6b depicts the same as Figure 6a but for JJAS-2021. From this figure, it can be seen that 30-40% of the IITM-maintained ARG stations (12 out of 38 stations) reported rainfall observations greater than 110 days out of 122 days in JJAS-2021, which actually gets deteriorated from JJAS-2020. Out of 38 stations, 18 stations (8 + 10) maintained by IITM (~ 25% + ~ 25% = ~ 50% respectively) in 2021 reported rainfall data in the last two categories. MCGM-maintained stations were found to report 90-100% of the stations were actually functional and 58 out of 59 stations have reported 85-97 days of rainfall data in JJAS-2021 (Figure 6b), which was absent in JJAS 2020 (Figure 6a). Likewise, almost 20-30% of the IMD-maintained stations have reported in the second (98-109 days) and third (85-97 days) category of the reported rainfall observation days and 7 stations (~ 40-50%) have reported less than 61 days and were basically irregular stations. Similarly, almost 90-100% of the SAFAR-maintained stations (i.e. 27 out of 28 stations) reported 85-97 days of rainfall observations and have shown improvement in JJAS-2021 than the previous year. Thus, this Heatmap statistics decipher a bird's eye view of the status of the ARG stations maintained by each agencies which were actually reporting regular or irregular rainfall observations during monsoon.

4. Assignment of Quality Flags to each ARG stations: Coverage over Mumbai

As discussed in the previous sections, it has now been obvious that some of the ARG stations report rainfall observations regularly and some stations have missing rainfall data or stations reporting less than half of the monsoon length. Since, Mumbai has an orographic influence on the rainfall process, the region not only experiences heavy rainfall cases but also high tidal events almost every year (Jenamani et al., 2006; Pattanaik and Rajeevan, 2010; Rana et al., 2014; Singh et al., 2017; Sunilkumar et al., 2022). The region is very much vulnerable to intense rainfall events due to the formation of offshore trough or northward moving mesoscale vortices over west coast or north-east Arabian Sea, movement of low pressure systems and depressions along the monsoon trough (Jenamani et al., 2006; Singh et al., 2017). Hence, all of the Mumbai-MESONET ARG sites has to realize such extreme weather phenomena almost every year, which may result in the disruption of rainfall data acquisition in most of the cases and leads to erroneous data quality in some cases. Thus, it is very much important to monitor the quality or performance of these ARG stations from such a high-density urban network and establish a quality checking framework. A similar framework has been established by Saha et al. (2021) previously for the IMD-maintained ARG network over the pan-Indian region for assigning rainfall quality flags in real-time. Rainfall reported by each ARG stations is attached with the Quality Flags ranging from 0 to 9, with 0 as the best. Flag 7-9 are assigned to irregular stations.

Flags 1-6 indicates different qualities and the rainfall data with these flags can be chosen by end-user for particular applications. As described in the Methodology section, after the step of "Outlier Data Removal", various statistics, including Pearson's correlation co-efficient, relative bias and mean of the rainfall observations for each ARG sites are computed against rainfall data from collocated neighbouring sites, GPM retrieved rainfall, IMD gridded and NMSG merged rainfall data, respectively, for JJAS 2020 and 2021. Similar to Saha et al. (2021), based on the calculated statistics (maximum correlation and minimum relative bias) for each ARG stations, different Quality Flags were assigned to each stations. Flag 0-5 are termed as "Regular and Usable Stations", while Flag 6 is termed as "Regular but Non-Usable Stations" and Flag 7-9 are designated as "Irregular Stations". The methodology that was adapted for assigning the quality flags has been described in a step-wise diagram in the Appendix.

Now, Figure 7 deciphers the coverage of ARG stations that are assigned with Quality Flags, ranging from 0 to 9 over Mumbai region during the monsoon months of 2020 and 2021 respectively. During JJAS-2020, out of 132 stations, 47 stations ranges from Flag 0 to Flag 5, 18 stations lie in Flag 6 category and 67 stations have been assigned to Flag 7 to Flag 9 (Figure 7A). This actually indicates 47 ARG stations were actually "Regular" and may be utilized by the end user for particular applications (Figure 7Aa), while 18 stations lying in Flag 6 category were "Regular but Non-Usable" (Figure 7Ab) and 67 stations were designated as "Irregular" stations (Figure 7Ac) during JJAS-2020. Similarly, during JJAS-2021, out of 142 stations, 82 stations were of "Regular and Usable" category (Figure 7Ba), while 41 stations were "Regular but Non-Usable" (Figure 7Ab) and 19 stations were simply "Irregular" ones (Figure 7Ac). Figure 7 showed much improvement in JJAS-2021 than JJAS-2020 in terms of Quality Flagging, since there has been a significant increase in "Regular and Usable" Stations (Flags 0-5) while a significant decrease in stations with "Irregular" (Flags 7-9) category.

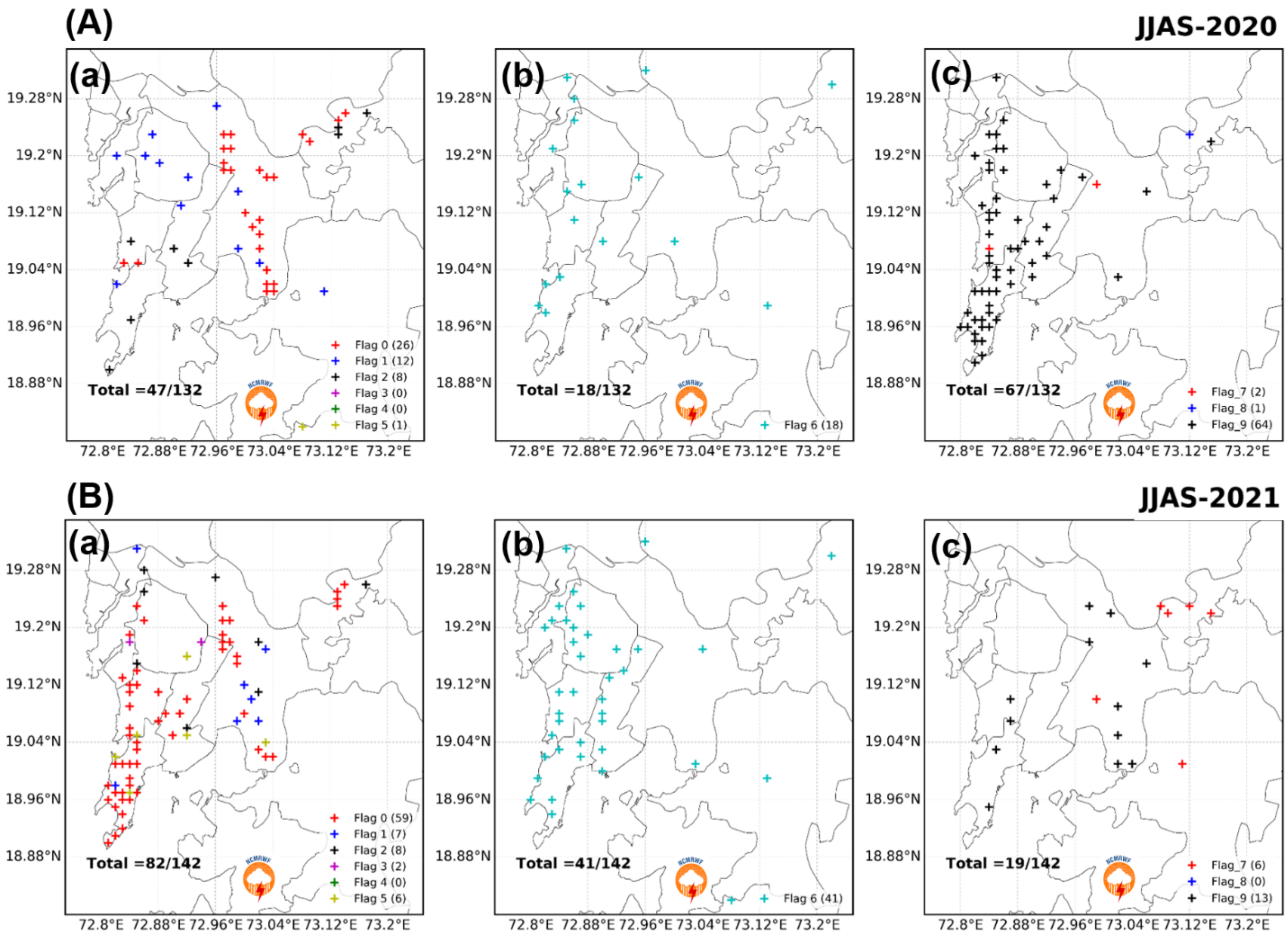


Fig. 7. Coverage of ARG stations assigned with Quality Flags with (a) "Flag 0" to "Flag 5", (b) "Flag 6", and (c) "Flag 7" to "Flag 9" during monsoon (June-September, JJAS) months of (A) 2020 and (B) 2021.

4.1 Statistical overview of the stations reporting rainfall observations: Heatmap

As mentioned earlier, Heatmap generates a clear statistical overview of each features in a bird's eye view. Hence, Figure 8 demonstrates the cumulative statistics showing the features of percentage count as well as the reported count of rainfall observations by ARG stations assigned with Quality Flags with maintaining agencies (IITM, MCGM, IMD and SAFAR) in a single frame during monsoon 2020 and 2021 in terms of Heatmap. Thus, this figure clearly indicate the counts of reported rainfall observations, by agency-wise ARG stations, annotated within each cell. Each cell indicates the assigned Quality Flag as per the statistics computed by rainfall data from ground-based in-situ (i.e. ARGs), neighboring ground-based ARG sites, satellite-based GPM, gridded IMD and merged satellite-gauge NMSG. The background color inside each cell indicates the percentage count of ARG station coverage reported by each agencies under those particular quality flags. From Figure 8a, it can found that ~ 60% (23 out of 38 stations) of the IITM-maintained stations have been assigned with Quality Flag, "Flag-0", during JJAS-2020 which indicates that these stations are regular and rainfall data from these stations are usable for other particular applications by end-users of the in-situ data. 2 stations (~ 0-1%) are assigned as Flag-6 and these IITM stations are regular but cannot be usable while Flag-7 to Flag-9 has been assigned to 5 stations and are designated as irregular stations during JJAS-2020. Similarly, 100% (59 out of 59 stations) of MCGM-maintained stations are assigned as Flag-9 and were of irregular category, while ~ 70% (5 out of 7 stations) of the IMD-maintained stations were designated as Flag-6 and the rest were in Flag 7 and Flag 9 category respectively. Last but not the least, 15 stations (3+7+5) of SAFAR-maintained stations were assigned to Flag-0 to Flag-3 and 11 more stations were found to be in Flag-6 category during JJAS-2020 (Figure 8a). Now, on the contrary, during JJAS-2021, it can be obtained from the Heatmap that 16 (~ 40%) and 41 (~ 70%) stations maintained by IITM and MCGM respectively assigned as Flag-0 and were designated as

“Regular and Usable” stations (Figure 8b). MCGM-maintained stations showed a huge improvement in reporting correct rainfall observations in a regular basis in 2021 than in 2020. 6 (2+2+2) of the IMD-maintained stations were assigned to first three Quality Flags categories, while 4 stations were lying in Flag-6 and 6 of the stations were assigned as irregular. But almost 80% (22 out of 28 stations) of the SAFAR-maintained stations do report regular rainfall observations but were not usable since most of these stations either report zero rainfall while in actual case rainfall is there or report haphazard rainfall values, which were discarded during outlier check process (Figure 8b). One can easily identify the “Regular” and “Irregular” type stations with this color encoded Quality Flags.

4.2 Statistical overview of the regular, usable and irregular stations: Pie Chart

These Heatmap statistics, as discussed in previous section, are well supported by Pie-Chart analysis also for the ARG stations that were being assigned with different Quality Flags during monsoon 2020 and 2021. Figure 9a indicates that during JJAS-2020, 81.58% of the IITM-maintained ARG stations were designated as “Regular and Usable” (Flag-0 to Flag-5), while 13.16% of the stations were reported to be of “Irregular” types and the rest were under Flag-6 category, which were “Regular but Non-Usable” stations. Similarly, 100% of the MCGM stations were found to be “Irregular” category, which also conforms from Heatmap statistics too from previous section. There were no “Regular and Usable” category stations for IMD during JJAS-2020, as 71.43% of the stations were found to be “Regular and Non-Usable” under Flag-6 category and the rest 28.57% of the stations were “Irregular” types. Stations maintained by SAFAR has got 57.14% of the stations which were “Regular and Usable”, while 39.29% lying in Flag-6 category and the rest in “Flag7 to Flag-9” category during JJAS-2020. Similarly, from Figure 9b, one can easily demonstrate the category of ARG stations during JJAS-2021.

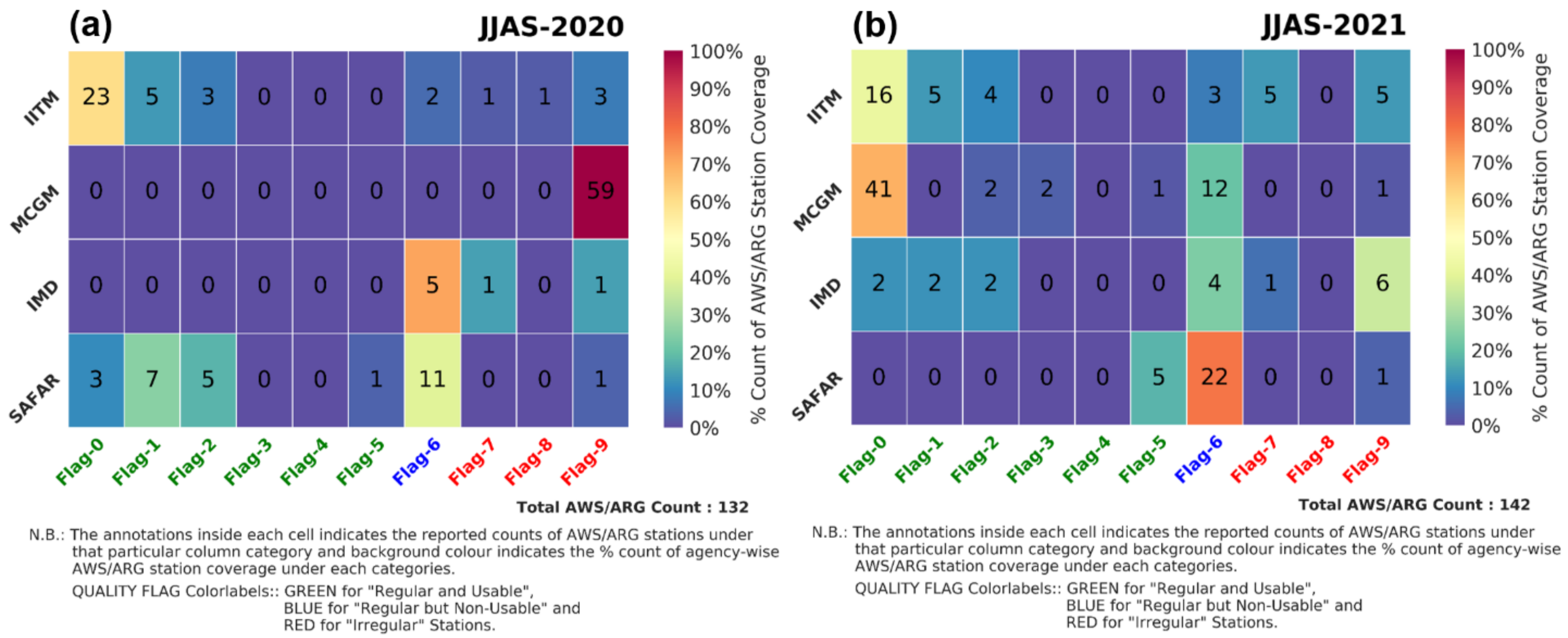


Fig. 8. Heatmap Statistics showing the features of reported count and percentage count of rainfall observations by ARG stations assigned with Quality Flags (Flag-0 to Flag-9) with maintaining agencies (IITM, MCGM, IMD and SAFAR) in a single frame during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

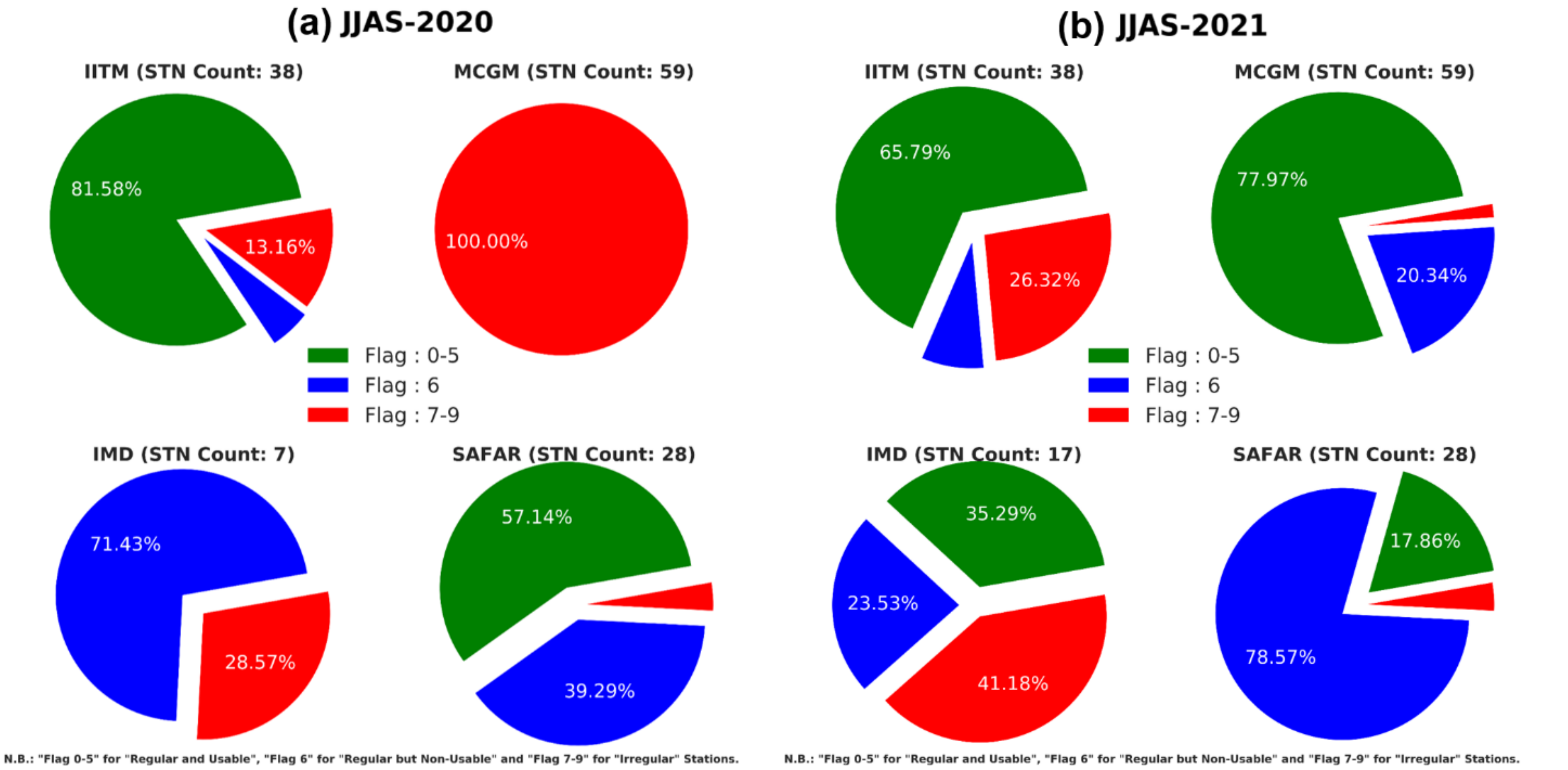


Fig. 9. Pie-chart statistics showing the percentage count of assigned Quality Flags for ARG stations over Mumbai during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

5. Regularity and Usability of each of the ARG station rainfall observations

This section will be dealing with the functional or non-functional status and henceforth, the usability of rainfall observations from each of the ARG sites maintained by IITM, MCGM, IMD and SAFAR respectively from the highly-dense Mumbai-MESONET during monsoon months of 2020 and 2021 respectively.

5.1 IITM-maintained stations

The actual status regarding the regularity of the IITM-maintained stations reporting rainfall or the usability of those station rainfall data can easily be depicted from Figure 10A and Figure 10B. As discussed in earlier sections, the regularity of the stations can be categorized into six categories based on the reported days of rainfall data. And the usability of these station rainfall data can be obtained from the assigned Quality Flags to each of those stations. Now, Figure 10Aa shows during JJAS-2020, most of the IITM-maintained stations reported >=110 days (i.e. 90-100% of the days) of rainfall observations and are designated as "Regular stations", except 3 stations, namely, "Airoli-Gaon", "Darave" and "Netvli", which reported less than 61 days (< 50% of the days) of rainfall data. "Sanpada" station reported data of almost 50-60% (67 days in count) of the days and "Kopar-Khairane" station has reported 70-80% (94 days in count) of the days in JJAS-2020. It can also be mentioned that, there were 12 such stations, namely, "Bhoirwadi", "Chiraknagar", "Dhokali", "Dombivli-East", "Greater Khanda Panvel", "Jahu-nagarwashi", "Jui-nagar", "Kasarvadavali", "Kopri", "Manpada-Thane", "Mumbra" and "Washi Village", which reported 122 days of rainfall data out of 122 days (100% of days) in JJAS-2020, i.e. these stations have not missed a single day for reporting rainfall observation (Figure 10Aa). It is also to be noted from the figure that not even a single day of rainfall observations has been reported by the stations, "Daighar" and "Vitthalwadi" in JJAS-2020.

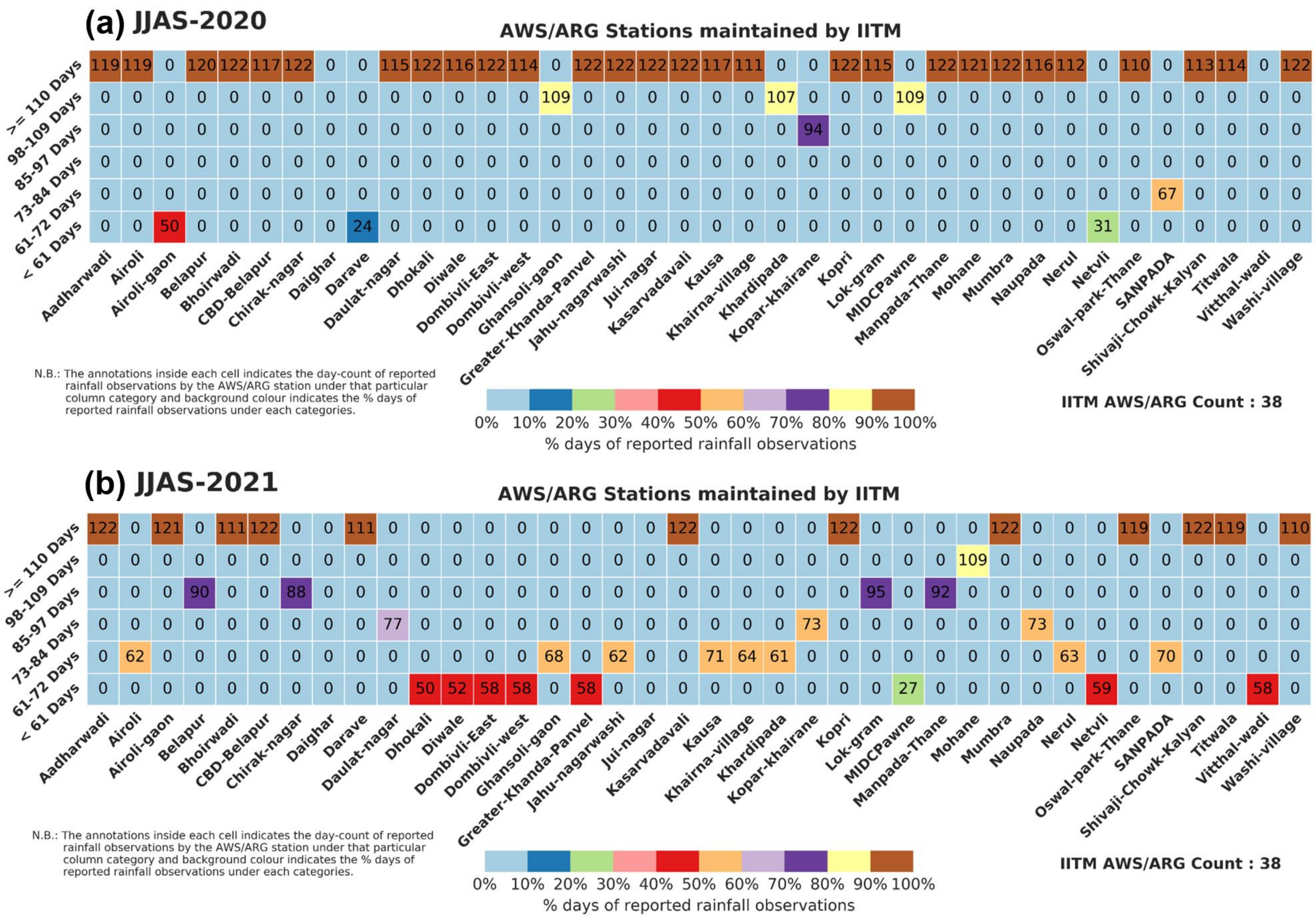


Fig. 10A. Heatmap statistics, for each ARG sites, based on the percentage days as well as the reported day-count of rainfall observations by ARG stations as maintained by IITM during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

Similarly, during JJAS-2021 from Figure 10Ab, the regular as well as irregular stations can be identified easily from the Heatmap. It can be noted that, 100% regularity of the IITM-maintained stations in JJAS-2021 has decreased significantly whereas the stations reporting rainfall data less than 50% of the days have significantly increased (Figure 10Ab). The stations, “Dhokali”, “Dombivli-East”, “Greater Khanda Panvel” and “Netvli”, which reported 100% of rainfall data in JJAS-2020, have reported rainfall less than 50% of the days of total monsoon length in JJAS-2021. Most interestingly, the station, “Jui-Nagar”, which also reported 100% of the rainfall data in JJAS-2020, have not reported a single day of rainfall observation while the station “Daighar” remains dry again in JJAS-2021 alike the previous monsoon year.

On the contrary, regarding the regularity as well as usability of the station rainfall data, the stations must be assigned with “Flag-0 to Flag-5” Quality Flags while the other stations assigned with Quality Flags ranging from Flag-6 to Flag-9 are either non-usable or irregular. Figure 10B interprets that the green-dots are “Regular and Usable” stations, while blue-dots are “Regular but Non-Usable” ones and the red-colored dots indicates “Irregular” stations. As deciphered from Figure 10Aa, out of the 12 stations that reported 100% of the days of rainfall observations during JJAS-2020, only 7 stations namely, “Bhoirwadi”, “Chiraknagar”, “Dhokali”, “Dombivli-East”, “Kopri”, “Manpada-Thane” and “Mumbra” were assigned to “Flag-0”, i.e. these are the bestest quality stations reporting rainfall while the other stations, namely, “Jui-nagar”, “Greater Khanda Panvel”, “Kasarvadavali”, “Washi Village” were assigned to “Flag-1”. 19 other IITM-maintained stations assigned with “Flag-0 to Flag-5”, were also designated as “Regular and Usable” for JJAS-2020 (Figure 10Ba). Most interestingly, it can be noted that the station “Jahu-nagarwashi”, although reported 100% of the days of rainfall observations, has been flagged with “Flag-6”, indicating the station data may be regular but the reported rainfall data by this station were not usable during JJAS-2020. Thus, this actually serves the purpose of Quality Flagging.

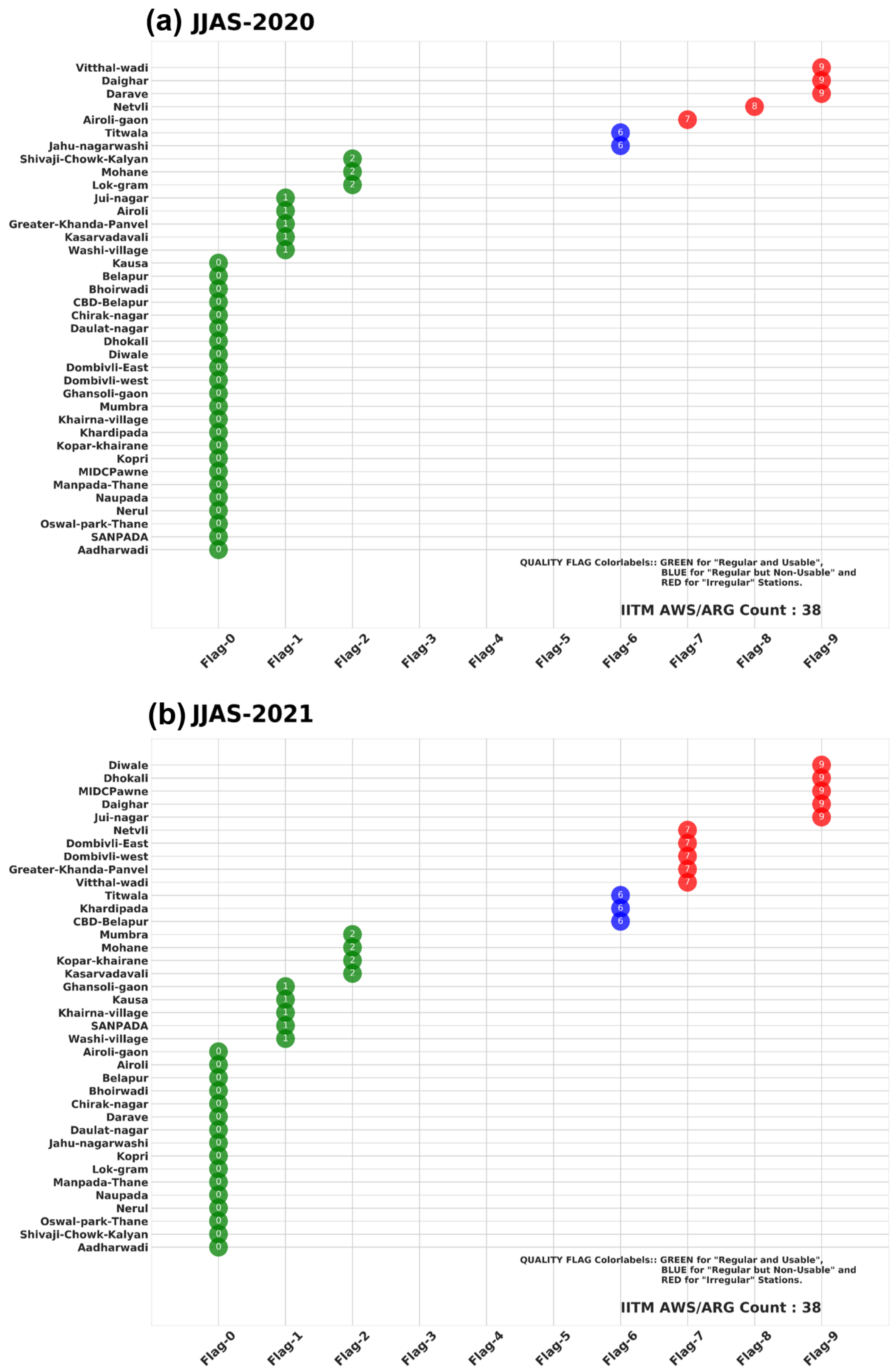


Fig. 10B. Status of each IITM-maintained ARG stations based on the Quality Flags assigned to those stations reporting rainfall observations during monsoon (JJAS) months of (a) 2020 and (b) 2021.

The stations that reported rainfall observations less than 50% of the days or have been missing the entire season were flagged from "Flag-7 to Flag-9" and were designated as "Irregular" stations (Figure 10Ba). Alike Figure 10Ba, Figure 10Bb can also be easily interpreted for JJAS-2021 from the figure itself. The stations, "Titwala" and "CBD-Belapur" also have reported 90-100% of the days of rainfall observations, as can be found from Figure 10Ab, but these stations were flagged with "Flag-6" and were designated in "Regular but Non-Usable" station categories during JJAS-2021 (Figure 10Bb). Similarly, other flagged stations maintained by IITM have their own interpretation based on the reported days of rainfall and the computed statistics for Quality flagging.

5.2 MCGM-maintained stations

Similar to Figure 10A-B, Figure 11A-B depicts the actual status regarding the regularity and usability of the MCGM-maintained stations reporting rainfall observations. During JJAS-2020, all of the MCGM-maintained stations have shown very poor performance in reporting regular rainfall data and all of them have reported less than 61 days (more accurately, 44 in count) over an investigation period of 122 days of JJAS monsoon length in 2020, except two stations, namely, "BKC Fire Station" and "L-Ward Office" (Figure 11Aa). The former station has not reported a single day of rainfall observation while the latter has reported only 3 days of rainfall data. On the contrary, during JJAS-2021, these MCGM-maintained stations has improved significantly and most of them has reported between 90-93 days of rainfall observations, except "BKC Fire Station" (Figure 11Ab). Similar to JJAS-2020, "BKC Fire Station" has not even reported a single day of rainfall data in JJAS-2021. It is also to be noted that "L-Ward Office" station (that has reported only 3 days of rainfall data in JJAS-2020) has improved in reporting more than 90 days of rainfall observations.

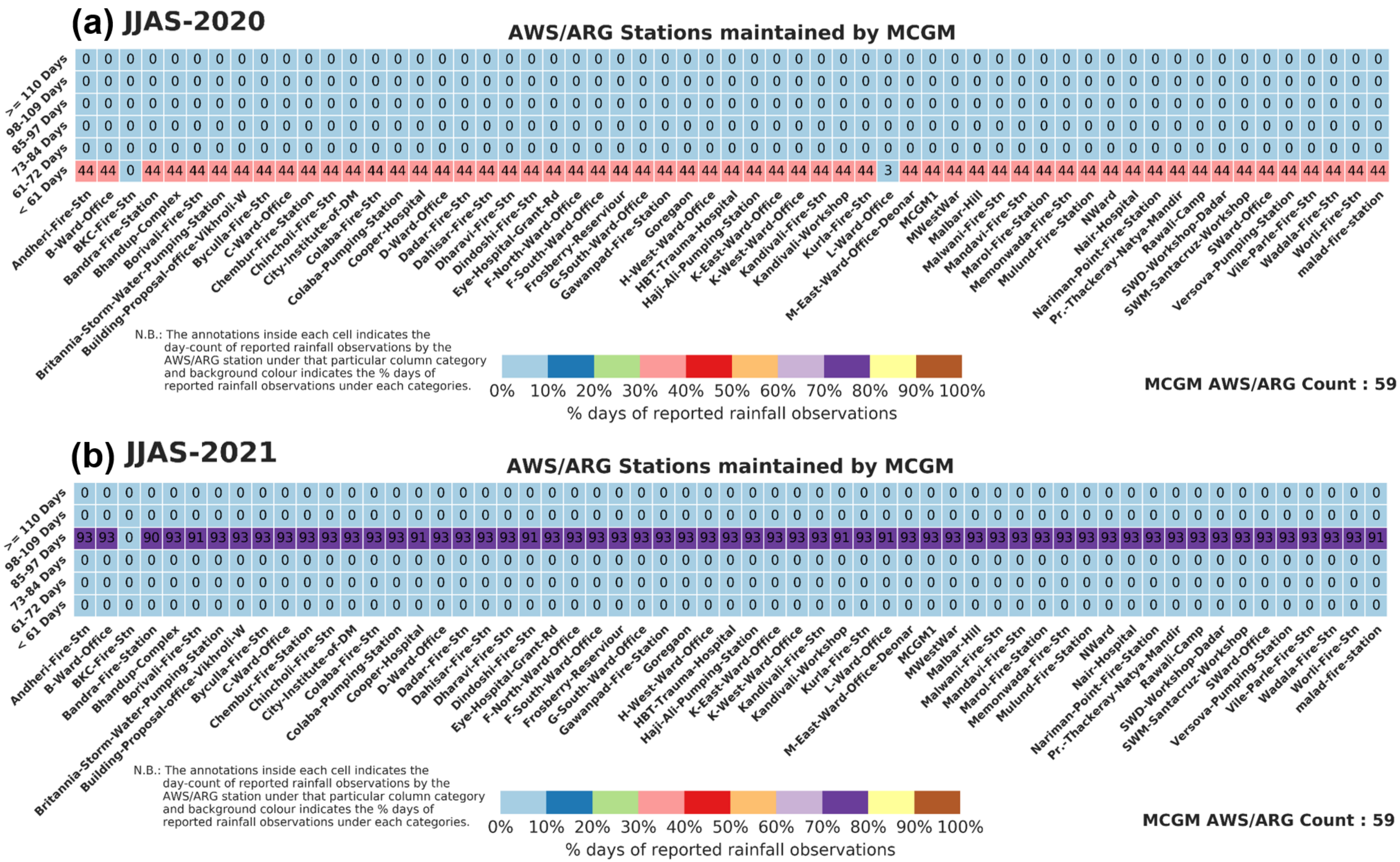


Fig. 11A. Heatmap statistics, for each ARG sites, based on the percentage days as well as the reported day-count of rainfall observations by ARG stations as maintained by MCGM during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

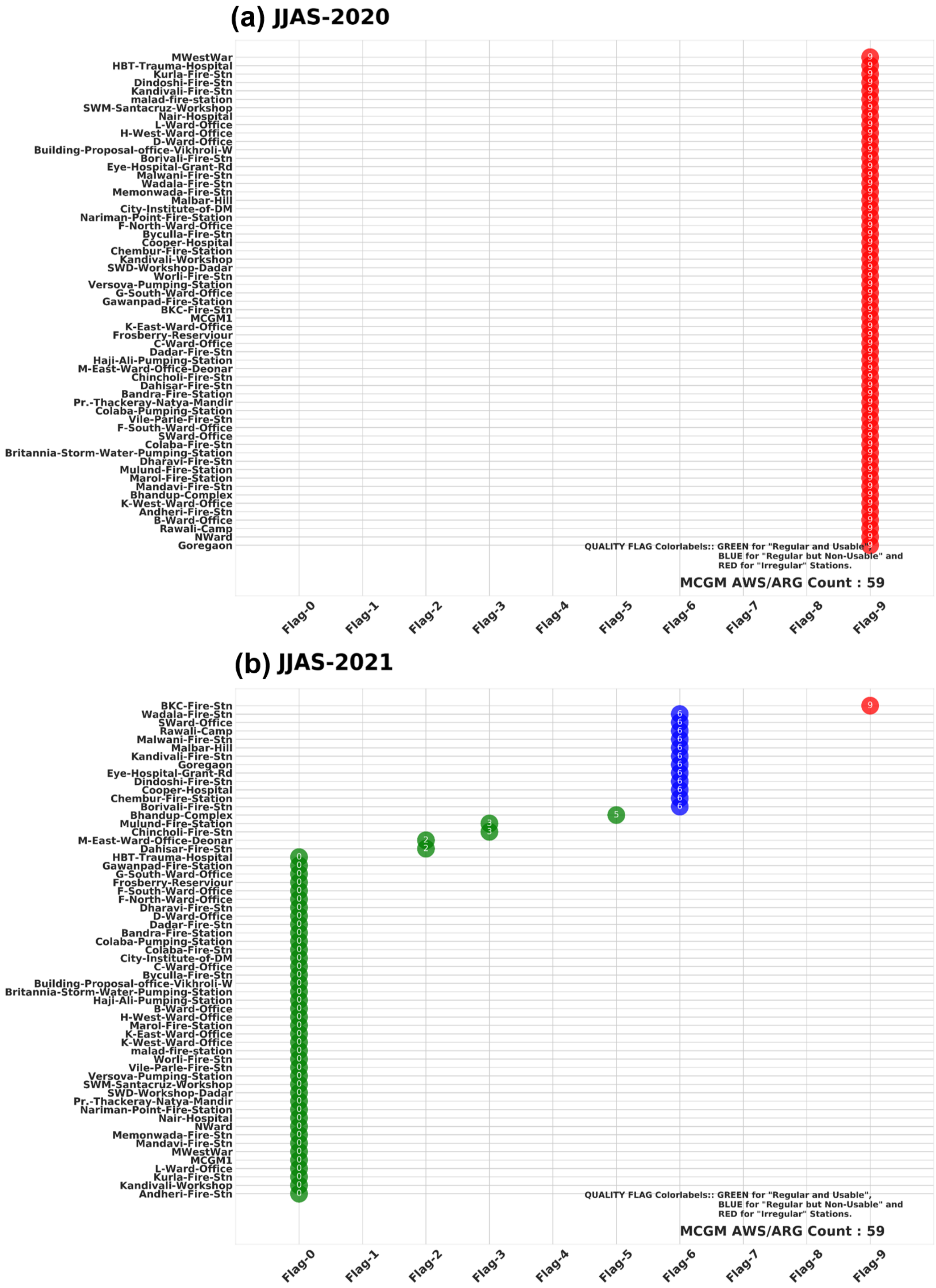


Fig. 11B. Status of each MCGM-maintained ARG stations based on the Quality Flags assigned to those stations reporting rainfall observations during monsoon (JJAS) months of (a) 2020 and (b) 2021.

Now, similar to Figure 10B, Figure 11B indicates the regularity and usability of MCGM-maintained stations as per the assigned Quality Flags to each of the stations on the basis of computed statistics between rainfall observations from the ground-based in-situ (ARG) stations with the neighboring ground-based stations (within 3 km radius), satellite-based rainfall from GPM, gridded rainfall observations from IMD and merged satellite-gauge NMSG rainfall respectively. During JJAS-2020, it can be depicted from Figure 11Ba that all the stations maintained by MCGM have been assigned to “Flag-9” and all these stations are actually “Irregular” in nature, since these stations have reported less than 50% of the days (i.e. 61 of 122 days) in monsoon 2020. As can be depicted from Figure 11Ab, during JJAS-2021, improvement in the regularity of the MCGM-maintained ARG stations were also supported by the usability of those station rainfall data, as indicated from Figure 11Bb. It can be found that, most of the stations have been assigned to “Flag-0” and were designated as “Regular and Usable” stations while 12 other stations were assigned to “Flag-6” and one station to “Flag-9” category (Figure 11Bb). “BKC Fire Station” was assigned to “Flag-9” since this station has not reported a single day of rainfall observation in JJAS-2020 as well as JJAS-2021 as can be depicted from Figure 11A. It is noteworthy, that “L-Ward Office” station has been assigned to “Flag-0” in JJAS-2021 since this station has shown a significant improvement in reporting rainfall observations in a regular basis than JJAS-2020 and the rainfall data was found to be useful according to the computed statistics for Quality flagging criteria.

5.3 IMD-maintained stations

Figure 12A and Figure 12B indicates the regularity as well as the usability of the IMD-maintained ARG station rainfall observations during the monsoon months (JJAS) of 2020 and 2021 respectively. During JJAS-2020, out of 7 IMD rain gauge stations, 5 of them have reported 73-84 days of rainfall observations out of 122 days of monsoon length of the year.

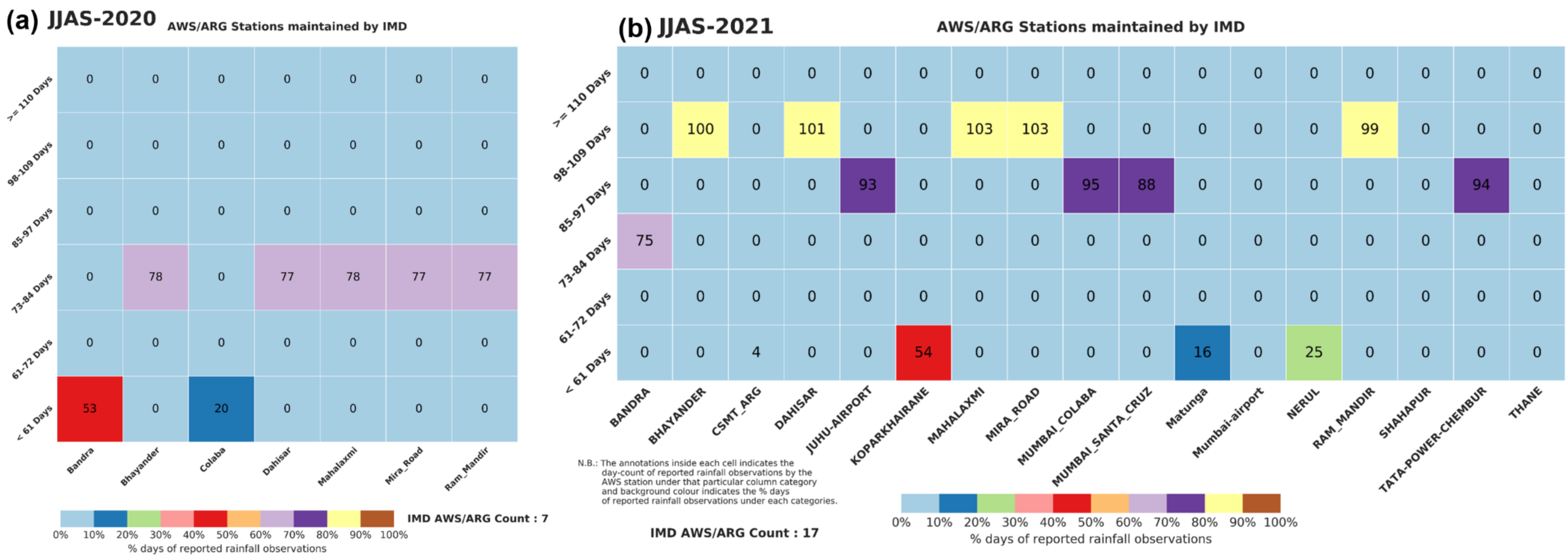


Fig. 12A. Heatmap statistics, for each ARG sites, based on the percentage count as well as the reported count of rainfall observations by ARG stations as maintained by IMD during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

Only the stations, namely, "Bandra" and "Colaba" have reported less than 61 days (more precisely, 53 and 20 days in count) of rainfall observations and were labelled as "Irregular" stations during JJAS-2020 (Figure 12Aa). On the contrary, during JJAS-2021, 10 more stations, namely, "CSMT ARG", "Juhu Airport", "Kopar Khairane", "Mumbai SantaCruz", "Matunga", "Mumbai Airport", "Nerul", "Shahapur", "Tata Power Chembur" and "Thane", were augmented by IMD within this network than the previous monsoon (Figure 12Ab). Out of these newly augmented stations in JJAS-2021, only 3 stations namely, "Juhu Airport", "Mumbai SantaCruz" and "Tata Power Chembur" has reported 85-97 days of rainfall observations within 122 days of monsoon while the other stations have reported less than 61 days of rainfall data. It is noteworthy to mention that out of these new stations, namely "Mumbai Airport", "Shahapur" and "Thane", have not reported a single day of rainfall observation. Thus, the regularity of the IMD-maintained stations were average in count during both JJAS-2020 and JJAS-2021.

Similar to Figure 11B, Figure 12B indicates the regularity and usability of IMD-maintained ARG stations over Mumbai region as per the assigned Quality Flags. As depicted from Figure 12Ba, the stations namely "Bhayander", "Dahisar", "Mahalaxmi", "Mira Road" and "Ram Mandir" were found to be assigned to "Flag-6" which indicates that these stations may be regular but the reported rainfall data by these stations were not useful for future particular applications by end-users during JJAS-2020. The other two stations namely, "Bandra" and "Colaba" were assigned to "Flag-7" and "Flag-9" respectively, which indicates that these stations were "Irregular" in JJAS-2020 (Figure 12Ba). During JJAS-2021, the name of the station "Colaba" changed to "Mumbai Colaba" and it is worth-mentioning that it has shown a significant improvement in the regularity as well as usability of rainfall observations from this particular station. This station was in the "Irregular" category (assigned to Flag-9) in JJAS-2020 and it has been assigned to "Flag-0" in JJAS-2021 as can be seen from Figure 12Bb. In JJAS-2021, there has been an increase in "Irregular" category stations than JJAS-2020. It is important to mention that the newly augmented stations, namely, "Kopar Khairane", "Mumbai Airport", "CSMT ARG", "Nerul", "Thane", "Matunga" and "Shahapur" have been assigned to "Flag-9" and were designated as "Irregular" stations. Thus, there has been no such significant improvement in reporting rainfall observations by the newly augmented ARG stations by IMD over Mumbai (Figure 12Bb). Thus, a serious assessment of IMD-maintained stations needs to be done for further applications of rainfall observations by end-user.

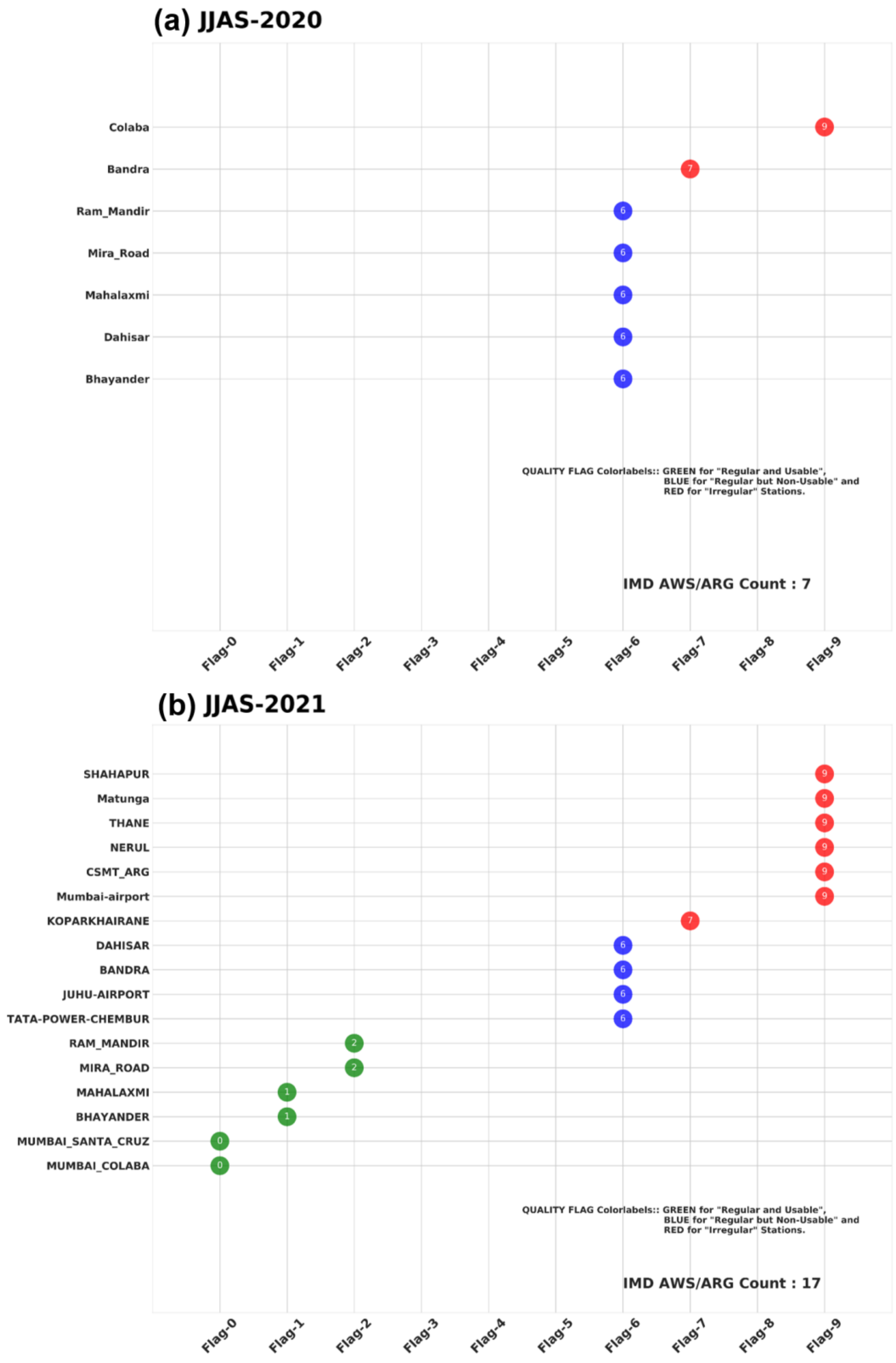


Fig. 12B. Status of each IMD-maintained ARG stations based on the Quality Flags assigned to those stations reporting rainfall observations during monsoon (JJAS) months of (a) 2020 and (b) 2021.

5.4 SAFAR-maintained stations

Figure 13Aa indicates that all of the ARG stations maintained by SAFAR have reported rainfall observations between 61-72 days within 122 days of JJAS-2020 (~ 50-60% of the days) except one station, namely "Silvasa", which did not report a single day of rainfall observation in JJAS-2020. During JJAS-2021, all of these stations have improved a lot in reporting more number of days (~ 75-80% of days, i.e. 85-97 days out of 122 days) than the previous monsoon, except the station "Silvasa" (Figure 13Ab).

As we know, the regularity of the stations reporting rainfall observations does not always imply the usability of the provided rainfall data by those stations. As a result, Figure 13B indicates the regularity with usability of station rainfall data during monsoon 2020 and 2021 respectively. Figure 13Ba depicts that except "Silvasa" which was assigned to "Flag-9", all other station observations are regular but all of them are not usable during monsoon 2020. 11 out of 28 SAFAR-maintained stations were assigned to "Flag-6" category, which indicates that these stations may report regular observations but were not usable and rest of the other stations were distributed among "Flag-0" to "Flag-5" during JJAS-2020. During JJAS-2021, Figure 13Bb indicates a significant reduction in the usability of station rainfall observations. The station "Silvasa" did not report a single day of observation in JJAS-2021 also similar to previous year monsoon period. Only 5 SAFAR-maintained stations, namely, "BKC", "Chembur", "LGPWORLI", "Mazgaon" and "Navi Mumbai", which were assigned to "Flag-5" category, all the other ARG stations were assigned to "Flag-6" quality flagging (Figure 13Bb). Most of the stations which were assigned to "Flag-0" to "Flag-5" during JJAS-2020 were assigned with "Flag-6" during JJAS-2021, e.g. the station "BANDRA" was assigned to "Flag-0" in JJAS-2020 has been assigned with "Flag-6" in JJAS-2021. This basically indicates a significant deterioration of the usability of SAFAR-maintained stations during JJAS-2021 than JJAS-2020.

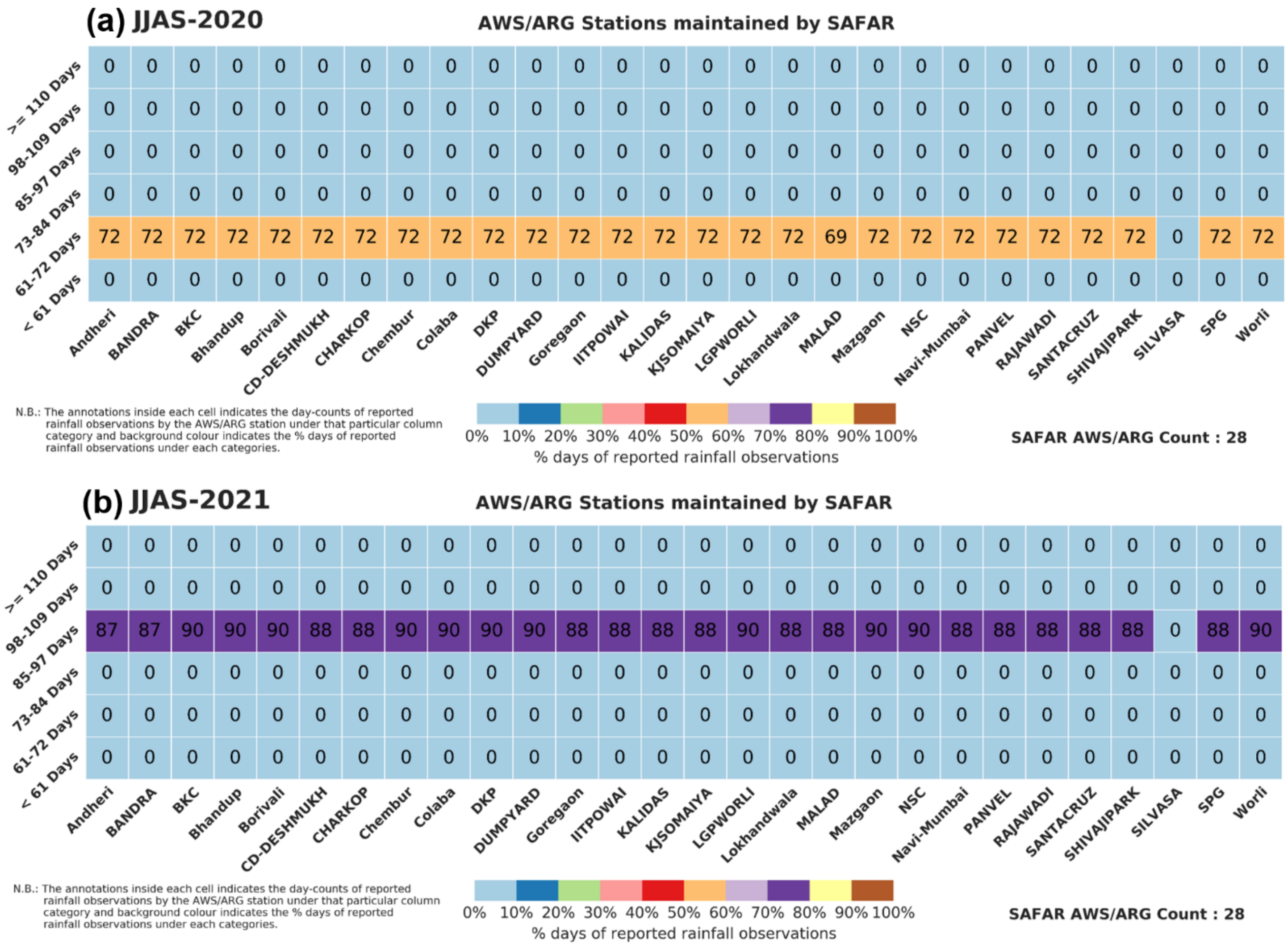


Fig. 13A. Heatmap statistics, for each ARG sites, based on the percentage count as well as the reported count of rainfall observations by ARG stations as maintained by SAFAR during monsoon (June-September, JJAS) months of (a) 2020 and (b) 2021.

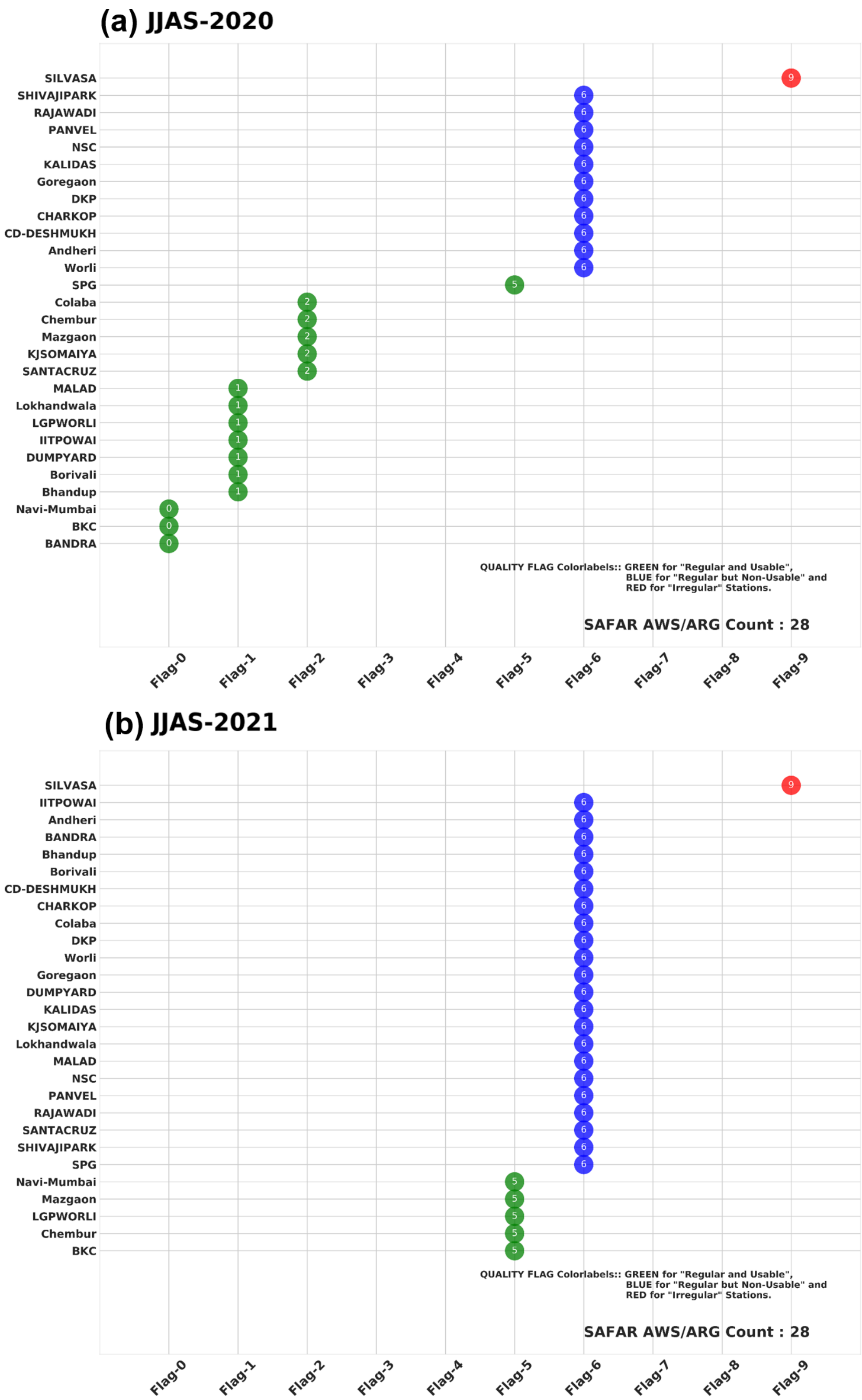


Fig. 13B. Status of each SAFAR-maintained ARG stations based on the Quality Flags assigned to those stations reporting rainfall observations during monsoon (JJAS) months of (a) 2020 and (b) 2021.

6. Extreme Rainfall Cases: Time Series plots

Based on the amount of accumulated rainfall in a day for extreme event studies, India Meteorological Department (IMD) has classified rainfall intensities into different categories, viz. i) Heavy Rainfall (HR, 64.5 mm $< R \leq$ 115.4 mm), ii) Very Heavy Rainfall (VHR, 115.5 mm $< R \leq$ 204.4 mm) and iii) Extremely Heavy Rainfall (EHR, $R \geq$ 204.5 mm), where R indicates Rainfall. An attempt has been made to verify the cases where MESONET ARG stations over Mumbai could capture this extreme rainfall events during JJAS 2020 and 2021.

6.1 ARG stations capturing Extreme Rainfall observations

Figure 14A (a-d) represents the time-series plots for the ARG rainfall observations from this Mumbai-MESONET that could capture the extreme rainfall events and matching well with the collocated neighbouring ARG (within 3 km radius of the base station) rainfall mean (NHBR_MEAN) or gridded rainfall observations (IMD/NMSG) or the satellite-retrieved rainfall (GPM) during JJAS-2020 and JJAS-2021 respectively. Since, most of the MESONET ARG stations are located within 10–25 km and inter-gauge distances are comparatively less between each stations, hence, mean rainfall from the neighbouring stations may help us to determine the efficiency of the particular base station. Rainfall from IMD/NMSG/GPM may underestimate or overestimate the extreme rainfall event, while the neighbouring stations must capture the extreme event, if properly functioning. It is to be noted that if a station is found to be not functioning, then the collocated station (within 3 km radius) may be useful for validation of the base station rainfall data. Hence, mean of all the neighbouring station rainfall are considered in computing statistical verification metrics. Now, Figure 14Aa indicates the validation of the reported rainfall observations by the station, namely, “Aadharwadi (IITM)” with NHBR_MEAN, GPM, IMD or NMSG rainfall data during JJAS-2020.

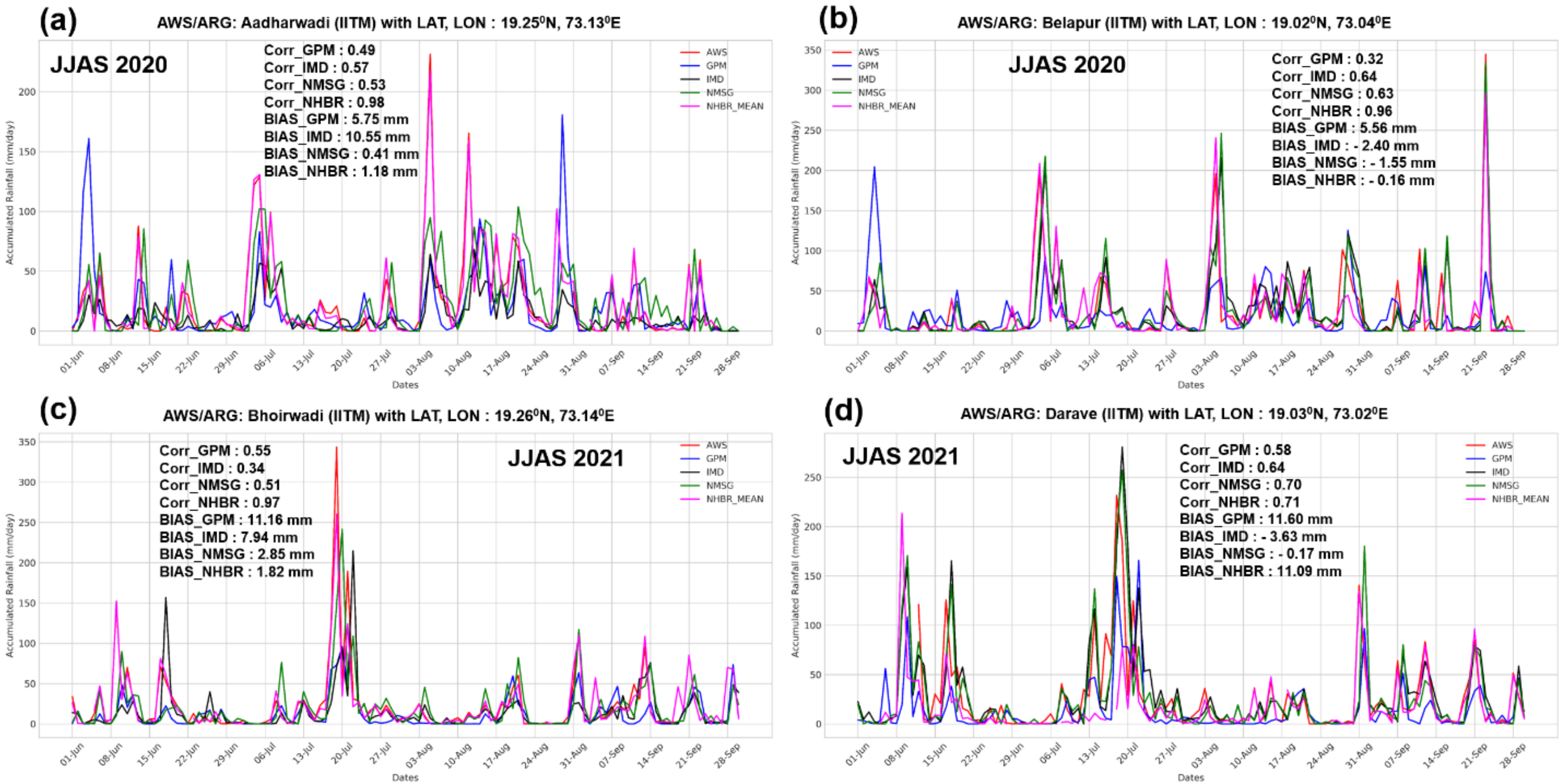


Fig. 14A. ARG rainfall observations that captured extreme rainfall events during (a)-(b) JJAS-2020 and (c)-(d) JJAS-2021.

There were a number of HR, VHR and EHR events during JJAS-2020, e.g. HR on 13 June, 2020, VHR on 4 July, 2020 and EHR on 5 August, 2020, etc. The rainfall time-series for the station "Aadharwadi (IITM)" has mostly captured the extreme rainfall events during JJAS-2020.

The statistical metrics were given within the figure itself. Similarly, Figure 14Ab indicates the validation of the reported rainfall observations by the station, namely, “Belapur (IITM)” during JJAS-2020. It shows that the reported rainfall from this station very nicely captured the HR event on 27 July, 2020, VHR event on 4 July, 2020 and EHR events on 5 August and 23 September, 2020 respectively. The statistical metrics were given within the figure itself. On the other hand, during JJAS-2021, the rainfall observations from the stations, namely, “Bhoirwadi (IITM)” and “Darave (IITM)” were found to be regular as well as these stations have captured extreme rainfall events during 18-21 July, 2021 very nicely and statistical metrics with the other sources of rainfall indicates the efficiency of these stations in capturing extreme rainfall occurrences over Mumbai (Figure 14A c-d).

6.2 ARG stations not capturing the Extreme Rainfall observations

Figure 14B (a-d) represents the time-series plots for the ARG rainfall observations within the network that failed to capture the extreme rainfall events reported by the collocated neighbouring ARG (within 3 km radius of the base station) or gridded rainfall observations (IMD/NMSG) or the satellite-retrieved rainfall (GPM) during JJAS-2020 and JJAS-2021 respectively. Both during JJAS-2020 and JJAS-2021, the ARG stations, namely, “Jahunagarwashi (IITM)”, “Worli (SAFAR)”, “Jui-nagar (IITM)” and “Thane (IMD)” has completely failed to capture the extreme rainfall events and not even they have captured any rainfall occurrences as indicated by NHBR_MEAN/GPM/IMD/NMSG observations. Statistical details are given within each of the figure itself and were self-explanatory. In the first two cases during JJAS-2020, ARG stations have provided zero rainfall data which indicates that either mechanical errors occurred during any extreme events or sensors were non-functional due to non-calibration or non-maintenance of the ARG site (Figure 14B a-b). Similarly, Figure 14B (c-d) indicates missing or no-rainfall observation by the base stations during JJAS-2021.

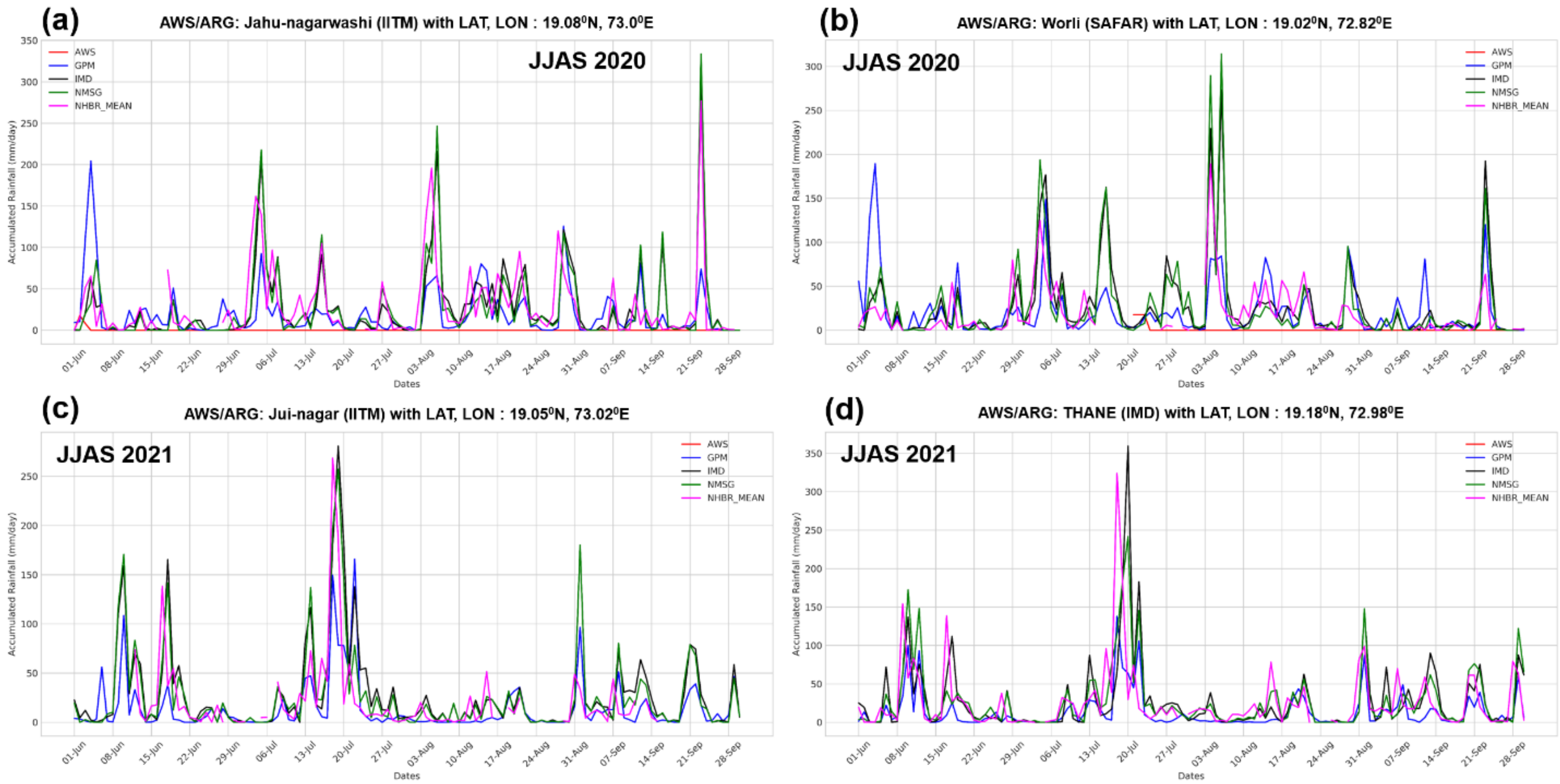


Fig. 14B. ARG rainfall observations that failed to capture extreme rainfall events during (a)-(b) JJAS-2020 and (c)-(d) JJAS-2021.

Thus, a periodic maintenance of all such stations, including sensor checks and calibrations, as well as validation of the rainfall data collected are need to be properly assessed, monitored and quality checked before the data to be used for any further hydrological applications.

7. Real-time Monitoring of ARG rainfall over Mumbai

It is very much important to monitor the quality or performance of ARG rainfall data over this high-density network over Mumbai in both real time and archived historical period. As discussed in the previous sections of validation, there were a huge number of ARG stations that were either not reporting a single day of rainfall observation or irregular or reporting erroneous data. It is of utmost necessary to identify those stations through proper real-time monitoring of ARG rainfall network (Mumbai-MESONET) in order to calibrate the bad sensors or repair those to utilizable condition. As we are aware of the fact that extreme rainfall over the globe is increasing since past two decades, particularly Indian region (Roxy et al., 2017; Saha et al., 2020, 2022; Singh et al., 2021) where almost every year, Mumbai receives high intensity of rainfall that leads to flood. Hence, it is required to monitor the performance of the Mumbai-MESONET high-density network stations reporting rainfall observations in real time in order for the usability and applicability of the rainfall data from these stations in particular applications by end-users. Also, the monitoring of these ARG stations are also very much important for the agro-meteorology to aviation sectors, since they also use these ground-based in-situ rainfall observations for their applications. For this purpose, a real-time quality monitoring of ARG stations over Mumbai has been developed in NCMRWF, based on the validation results for flagging of each individual observations centred on computed verification scores over previous 15-day span. As discussed in Section 4, rainfall reported by each ARG stations are assigned to Quality Flags ranging from Flag-0 to Flag-9, with Flag-0 as the best. Quality Flags 7-9 are assigned to irregular stations. And, Quality Flags 1-6 indicates different qualities and the rainfall data with these flags can be chosen by end-user for particular applications. During the validation of rainfall data of individual rain gauge stations with neighbouring in-situ/gridded/satellite/merged-satellite data, it has been obtained that many of the stations have large biases in rainfall.

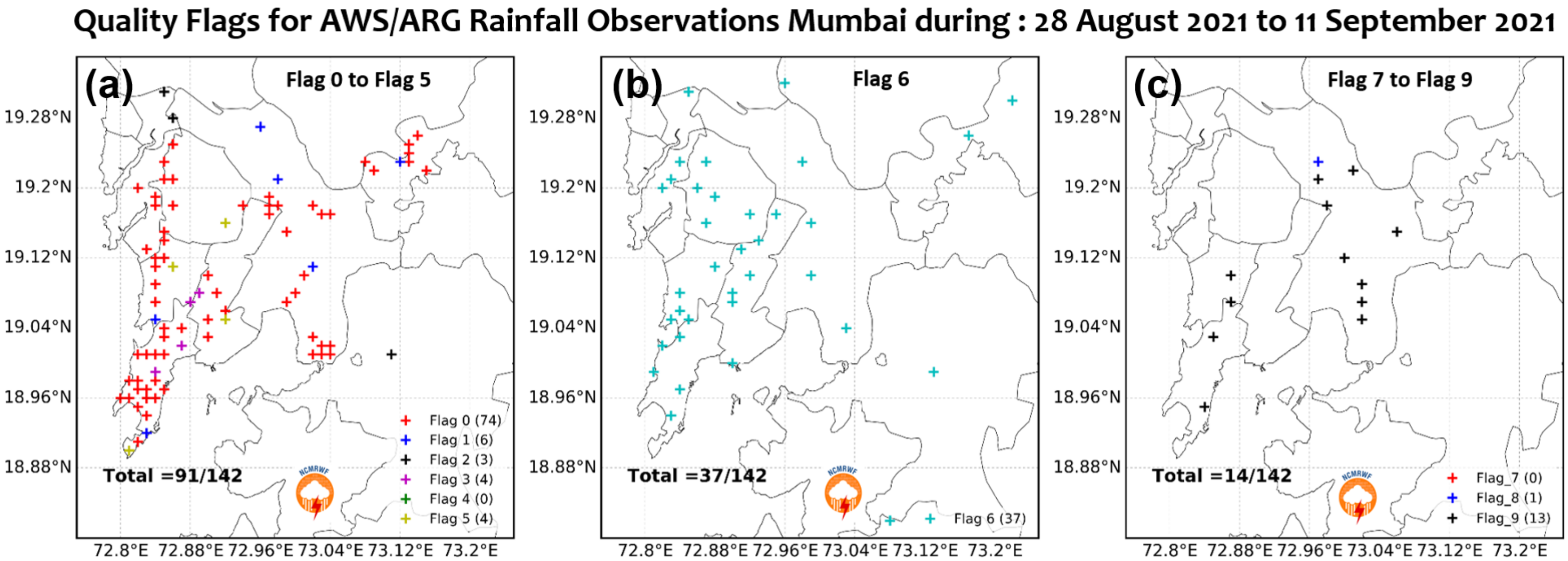


Fig. 15A. Coverage of ARG stations assigned with Quality Flags with (a) "Flag 0" to "Flag 5", (b) "Flag 6", and (c) "Flag 7" to "Flag 9" on 11 September 2021 over Mumbai.

Hence, it is decided to proceed the quality flagging of individual stations which have minimum biases and maximum correlation among them.

The detailed methodology adopted for assigning Quality Flags to individual stations in Real-time is described in the Appendix section.

For real-time monitoring purpose, figures with assignment of flags from Flag-0 to Flag-9 are plotted daily based on the locus of each ARG stations of Mumbai-MESONET as shown in Figure 15A. The figure represents the spatial distribution of stations assigned with Quality Flags on 11 September 2021 (i.e. previous 15 days span of 28 August 2021 to 11 September 2021) over Mumbai. Stations assigned with "Flag 0" to "Flag 5" were treated as "Regular and Usable" and to be taken for research as well as operational purpose since these stations are sorted based on high correlation and minimum bias criteria. It can be depicted from Figure 15A, on 11 September 2021, out of 142 stations, a totality of 91 stations were flagged as "Flag 0" to "Flag 5", while 37 stations were flagged as "Flag 6" following the corollaries of STEP-1 and STEP-2 of Quality Flagging Determination method and these latter stations were designated as "Regular but Not-Usable" stations (Figure 15A a-b). 14 stations out of total 142 ARG stations have reported irregular rainfall observations and were flagged as "Flag 7" to "Flag 9" following the STEP-3 criteria of Quality Flagging (Figure 15Ac). Figure 15B shows the statistical details for the category-wise count of ARG stations reported and also the percentage distribution of Quality Flags assigned to those stations. On 11 September, 2021, 85.92% of the total ARG stations (122 of 142 stations in total count) have reported 15 out of 15 days of rainfall observations and were designated as "Regular" stations, while the other categories were almost negligible. Almost ~ 9.9 % of the total stations (14 of 142) have reported less than 7 days of rainfall data and were designated as "Irregular" stations (Figure 15B a-b). The Quality Flags assigned to each of these stations may elucidate the usability of the rainfall observations from them. Almost ~ 71.05% of the IITM-maintained stations, ~ 88.14% of the MCGM-maintained stations, ~ 58.82% of the IMD-maintained stations and ~ 7.14% of the SAFAR-maintained stations were found to be "Regular and Usable" ("Flag-0 to Flag-5") during the last 15 days span (Figure 15Bc). Moreover, ~ 89.29 of the SAFAR stations were found to be regular but reported rainfall data were not useful ("Flag-6") and needs to be supervised.

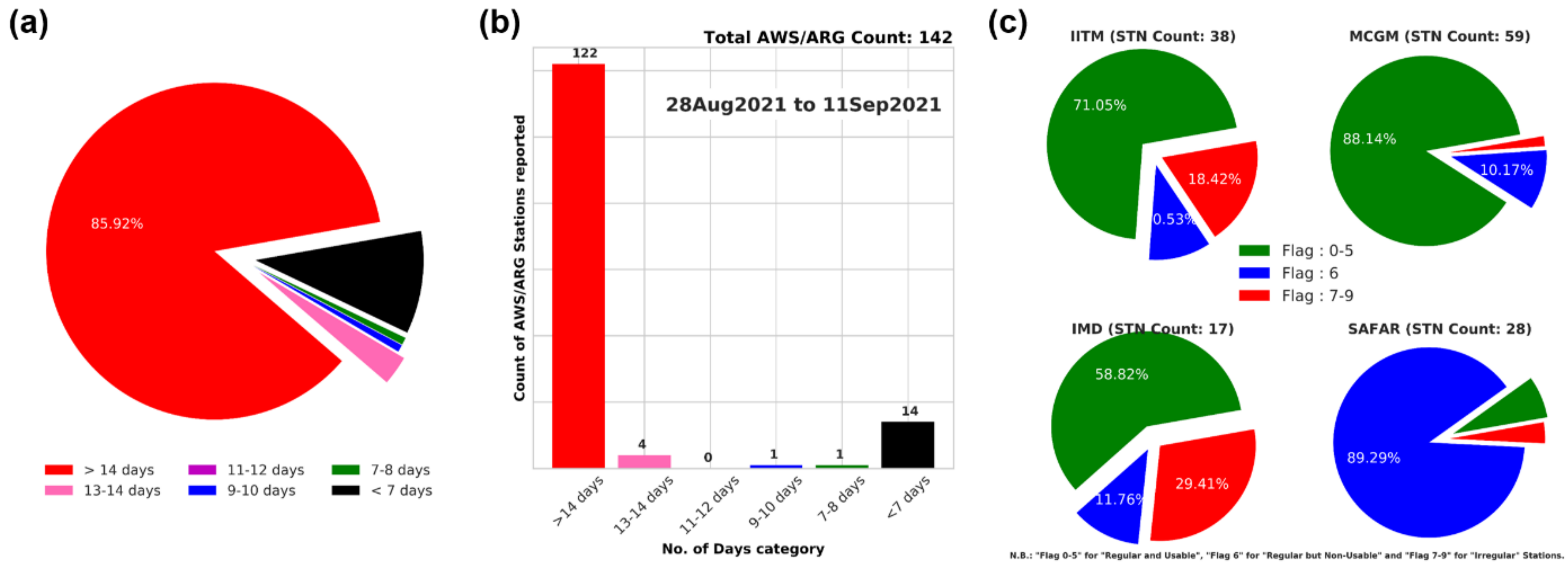


Fig. 15B. Statistics for the ARG station coverage based on the reported days of rainfall observation as well as assigned quality flags on 11 September 2021.

The stations from IITM, MCGM and IMD assigned to “Flag-6” were not so huge in count (~ 0.53% for IITM, ~ 10.17% for MCGM and ~ 11.76% for IMD). During this 15-day period, ~29.41% of the IMD-maintained stations reported either no rainfall observations or have reported less than 7 days and were designated as “Irregular” stations, while ~18.42% of the IITM-maintained stations lie in this category. For MCGM and SAFAR, less than 10% of the stations were found to be irregular (Figure 15Bc). Thus, these statistics gives a clear overview of the real-time activity in terms of regularity of the station and usability of the reported rainfall observations to be assessed and informed.

8. Summary and Conclusions

This study presents the preliminary results for the validation and quality checking of high-density ARG network of Mumbai-MESONET during monsoon months (June-September, JJAS) of 2020 and 2021 respectively. The MESONET consists of ~142 rain gauges from various agencies (IITM, MCGM, IMD and SAFAR) that were deployed over different locations in the Mumbai metropolitan (18.8^{0}N-19.35^{0}N, 72.8^{0}E-73.25^{0}E) region. During the southwest monsoon (June–September), Mumbai and surrounding regions receives copious amount of rainfall and drains overflowed causing local flooding. High-quality data along with real-time information are thus of great importance for the data end users, for example, in crisis management during flood emergencies or in the issuing of dangerous weather warnings. Thus, it is very much necessary to daily monitor and check the quality of rainfall data from the high-density Mumbai-MESONET.

An attempt has been made to validate high-density 24-hourly (08:30AM of previous day to 08:30 AM of next day) daily ARG accumulated rainfall observations of Mumbai-MESONET against the high-resolution satellite-retrieved rainfall product from GPM-IMERG, gridded observations from IMD, IMD-NCMRWF merged satellite-gauge rainfall product as well as rainfall data from the collocated neighbouring ARG sites. Since, there are a good number of stations with irregular rainfall data, those stations are considered to be “Regular” which are actually reporting rainfall data at least 61 days (50%) in a monsoon (JJAS, comprising 122 days) season and the rest stations are termed as “Irregular” stations. Based on the validation results, a methodology has been devised to delineate good quality ARG rainfall observations from Mumbai-MESONET and judicially using these high-density rainfall observations for its further utilisation in real time operation, weather monitoring as well as for verification of numerical weather prediction (NWP) model outputs. Finally, the study also attempts a real-time daily monitoring and quality checking for the Mumbai-MESONET rainfall observations. Apart from the standard public utility on real-time rainfall information, Integrated Flood Warning System for Mumbai (iFLOWS-MUMBAI), which is a recently launched flood warning system developed by MoES, India for Mumbai, also utilizes the MESONET data as one of the primary input in the data assimilation module in the system (https://www.nccr.gov.in/sites/default/files/IFLOWS_0.pdf). The main conclusions are listed below as:

1. There are total of 132 stations (38 IITM, 59 MCGM, 7 IMD and 28 SAFAR-maintained) during JJAS-2020, while the same has increased to 142 stations with 10 newly deployed stations by IMD in JJAS-2021.

2. During JJAS-2021, there has been a decrease in the counts of irregular stations than the previous year monsoon (67 in 2020 while 19 in JJAS-2021). During JJAS-2020, almost 50.76% of the stations were irregular while this percentage is only 13.38% in JJAS-2021. However, the stations reporting greater than 90% (i.e. > 110 days) of the days has decreased in JJAS-2021 (12 in count) than in JJAS-2020 (28 in count).

3. There has been a decrease in the count of regularly reporting (i.e. more than 110 days or > 90% of the days in the season) IITM-maintained stations in JJAS-2021 (12 reported out of 38 stations) than in JJAS-2020 (28 reported out of 38 stations). The stations maintained by MCGM has improved significantly in JJAS-2021 (58 stations reported within 85-97 days in a season) than in JJAS-2020 where all the stations were found to be “Irregular”. SAFAR-maintained stations have shown some improvement in JJAS-2021 based on the regularity of reporting rainfall observations.

4. Unlike JJAS-2020, irregular stations are increased for IMD in JJAS-2021, i.e. ~ 40-50% of the total count of stations are found to be irregular in 2021, and are reporting rainfall observations less than 61 days out of 122 JJAS days.

5. There has been a significant improvement in the regularity and usability of the station rainfall observations in JJAS-2021 than in JJAS-2020. 82 stations out of 142 total stations are found to be

"Regular and Usable" in JJAS-2021, whereas 47 out of 132 total stations lie in this category in JJAS-2020. Also there has been a significant reduction in "Irregular" stations in JJAS-2021 than the previous monsoon.

6. In continuation to point 5, all the agencies have shown significant improvement in the regularity and usability of rainfall observations, which is also supported by the quality flag assigned through the procedure described in the study. For example, almost 78% of the MCGM-maintained stations were assigned to Quality Flag 0-5 in JJAS-2021, which were basically assigned to Quality Flag 7-9 in JJAS-2020.

7. Most of the "Regular and Usable" stations captured extreme rainfall events over Mumbai during both the monsoons of JJAS-2020 and JJAS-2021 respectively.

8. Real-time daily monitoring and quality checking of ARG stations reporting rainfall observations along with the computed statistics actually indicate the regularity and usability of that particular station to be used by end-user for validation purpose in real-time.

Thus, the present quality-checked Mumbai-MESONET rainfall data from the good quality regularly reporting stations can improve hydro-meteorological monitoring and these information will be very crucial for all the stake holders, mainly, Weather forecasters, Disaster Management Department, Municipal Corporation, Western and Central Railways, Road transport, media and many others.

Acknowledgments

Authors are thankful to IMD, Pune for providing IMD gridded rainfall data as well as satellite-gauge merged rainfall product. The GPM-IMERG rainfall data were provided by the NASA Goddard Space Flight Centre's Precipitation Processing System (PPS) through the website: https://jsimpsonhttps.pps.eosdis.nasa.gov/imerg. Last but not the least, the authors highly acknowledge the entire team of IITM and Mumbai-MESONET for the development of a real-

time web-based platform and providing opportunity for the usage rainfall dataset through dedicated FTP-server.

References

Borga, M., Degli Esposti, S. and Norbiato, D., 2006. Influence of errors in radar rainfall estimates on hydrological modeling prediction uncertainty. Water Resources Research, 42 (8): W08409.

Huffman, G.J., E.F. Stocker, D.T. Bolvin, E.J. Nelkin, Jackson Tan (2019), GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: 25 March 2022, DOI: https://doi.org/10.5067/GPM/IMERG/3B-HH/06

Jena, P., Garg, S. and Azad, S., 2020. Performance analysis of IMD high-resolution gridded rainfall (0.25°× 0.25°) and satellite estimates for detecting cloudburst events over the northwest Himalayas. Journal of Hydrometeorology, 21(7), 1549-1569.

Jenamani, R.K., Bhan, S.C. and Kalsi, S.R., 2006. Observational/forecasting aspects of the meteorological event that caused a record highest rainfall in Mumbai. Current Science, 90, 1344-1362.

Mitra, A.K., Gupta, M.D., Singh, S.V. and Krishnamurti, T.N., 2003. Daily rainfall for the Indian monsoon region from merged satellite and rain gauge values: Large-scale analysis from real-time data. Journal of Hydrometeorology, 4 (5), 769-781.

Mitra, A.K., Bohra, A.K., Rajeevan, M.N. and Krishnamurti, T.N., 2009. Daily Indian precipitation analysis formed from a merge of rain-gauge data with the TRMM TMPA satellite-derived rainfall estimates. Journal of the Meteorological Society of Japan. Ser. II, 87, 265-279.

Mitra, A.K., Momin, I.M., Rajagopal, E.N., Basu, S., Rajeevan, M.N. and Krishnamurti, T.N., 2013. Gridded daily Indian monsoon rainfall for 14 seasons: Merged TRMM and IMD gauge analyzed values. Journal of Earth System Science, 122, 1173-1182.

Ośródka, K., Otop, I. and Szturc, J., 2022. Automatic quality control of telemetric rain gauge data providing quantitative quality information (RainGaugeQC). Atmospheric Measurement Techniques Discussions, pp. 1-22. DOI: https://doi.org/10.5194/amt-2022-83.

Pai, D.S., Sridhar, L., Rajeevan, M., Sreejith, O.P., Satbhai, N.S. and Mukhopadhyay, B., 2014. Development of a new high spatial resolution (0.25× 0.25) long period (1901–2010) daily gridded rainfall data set over India and its comparison with existing data sets over the region. Mausam, 65 (1), 1-18.

Pattanaik, D.R. and Rajeevan, M., 2010. Variability of extreme rainfall events over India during southwest monsoon season. Meteorological Applications: A journal of forecasting, practical applications, training techniques and modelling, 17 (1), 88-104.

Prasad, V.S., Johny, C.J. and Sodhi, J.S., 2016. Impact of 3DVar GSI-ENKF hybrid data assimilation system. Journal of Earth System Science, 125 (8), 1509-1521.

Rajeevan, M., Bhate, J., Kale, J.D., Lal, B., 2006. High resolution daily gridded rainfall data for the Indian region: analysis of break and active monsoon spells. Current Science 296–306.

Rajeevan, M., Bhate, J., Jaswal, A.K., 2008. Correction to analysis of variability and trends of extreme rainfall events over India using 104 years of gridded daily rainfall data. Geophys. Res. Lett. 35, L23701.

Rana, A., Uvo, C.B., Bengtsson, L. and Parth Sarthi, P., 2012. Trend analysis for rainfall in Delhi and Mumbai, India. Climate Dynamics, 38 (1), pp. 45-56.

Rana, A., Foster, K., Bosshard, T., Olsson, J. and Bengtsson, L., 2014. Impact of climate change on rainfall over Mumbai using Distribution-based Scaling of Global Climate Model projections. Journal of Hydrology: Regional Studies, 1, 107-128.

Roxy, M.K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., Terray, P. and Rajeevan, M., 2017. A threefold rise in widespread extreme rain events over central India. Nature Communications, 8 (1), 1-11.

Saha, U., Singh, T., Sharma, P., Gupta, M.D. and Prasad, V.S., 2020. Deciphering the extreme rainfall scenario over Indian landmass using satellite observations, reanalysis and model forecast: Case studies. Atmospheric Research, 240, p.104943.

Saha, U., Das Gupta, M. and Mitra, A. K., 2021. Monitoring the Quality of AWS/ARG Rainfall Observations over India during Monsoon Season. *NCMRWF Research Report*

(NMRF/RR/01/2021), February 2021, pp. 1-48. Link of the report: https://www.ncmrwf.gov.in/Reports-php/Report_AWS_ARG_Feb_2021_Final_Upal_Saha_NCMRWF.php.

Saha, U. and Sateesh, M., 2022. Rainfall extremes on the rise: Observations during 1951–2020 and bias-corrected CMIP6 projections for near-and late 21st century over Indian landmass. Journal of Hydrology, 608, p.127682.

Setti, S., Maheswaran, R., Sridhar, V., Barik, K.K., Merz, B. and Agarwal, A., 2020. Inter-comparison of gauge-based gridded data, reanalysis and satellite precipitation product with an emphasis on hydrological modeling. Atmosphere, 11(11), 1252.

Singh, J., Sekharan, S., Karmakar, S., Ghosh, S., Zope, P.E. and Eldho, T.I., 2017. Spatio-temporal analysis of sub-hourly rainfall over Mumbai, India: Is statistical forecasting futile?. Journal of Earth System Science, 126 (3), 1-15.

Singh, T., Saha, U., Prasad, V.S. and Gupta, M.D., 2021. Assessment of newly-developed high resolution reanalyses (IMDAA, NGFS and ERA5) against rainfall observations for Indian region. Atmospheric Research, 259, p. 105679.

Sunilkumar, K., Narayana Rao, T., Saikranthi, K. and Purnachandra Rao, M., 2015. Comprehensive evaluation of multisatellite precipitation estimates over India using gridded rainfall data. Journal of Geophysical Research: Atmospheres, 120 (17), pp. 8987-9005.

Sunilkumar, K., Das, S.K., Kalekar, P., Kolte, Y., MuraliKrishna, U.V., Deshpande, S., Dani, K.K., Nitha, T.S., Hosalikar, K.S., Narvekar, M. and Mohan, K.N., 2022. A MESO-scale Rain gauge NETwork-MESONET over Mumbai: Preliminary results and applications. Urban Climate, 41, p.101029.

Szturc, J., Ośródka, K., Jurczyk, A., Otop, I., Linkowska, J., Bochenek, B. and Pasierb, M., 2022. Quality control and verification of precipitation observations, estimates, and forecasts. In *Precipitation Science* (pp. 91-133). Elsevier.

Reddy, M.V., Mitra, A.K., Momin, I.M., Mitra, A.K. and Pai, D.S., 2019. Evaluation and inter-comparison of high-resolution multi-satellite rainfall products over India for the southwest monsoon period. International Journal of Remote Sensing, 40 (12), 4577-4603.

Appendix

1. Quality-Flag Determination Method: Maximum Correlation with Minimum BIAS

For Quality Flag determination, the statistics has been computed over a period of 122 days of every monsoon 2020 and 2021 respectively. Based on 122 days of rainfall data, maximum correlation with minimum BIAS are considered to assign Quality Flags to individual stations.

Neighbouring Station Rainfall: NHBR,
Satellite-derived rainfall: GPM,
Gridded gauge rainfall: IMD,
Merged satellite-gauge rainfall: NMSG
Corr: Correlation, Flag: F
Let us consider,
Corr_NHBR = C1, Corr_GPM = C2, Corr_IMD = C3, Corr_NMSG = C4,
BIAS_NHBR = B1, BIAS_GPM = B2, BIAS_IMD = B3, BIAS_NMSG = B4,
Mean_AWS/ARG = M0, Mean_NHBR = M1, Mean_GPM = M2,
Mean_IMD = M3, Mean_NMSG = M4
R1 = 30% of the mean AWS rainfall
R2 = 150% of the mean AWS rainfall

STEP 1: When NHBR is PRESENT,

Corollary 1: If C1 ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 0
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 3
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

Corollary 2: If 0.5 ≤ C1 < 0.6:

(A) If max (C2, C3, C4) ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 1
- (b) If R1 < min(B1, B2, B3) ≤ R2, then F = 4
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

(B) If 0.5 ≤ max (C2, C3, C4) < 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 2
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 5
- (c) If min(B1, B2, B3, B4) > R2, then F = 6

(C) If 0.4 ≤ max (C2, C3, C4) < 0.5:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 3
- (b) If R1 < min(B1, B2, B3, B4), then F = 6

(D) If max (C2, C3, C4) < 0.4: then, F = 6 [NO OTHER CHECKS ARE DONE]

Corollary 3: If C1 < 0.5:

(A) If max (C2, C3, C4) ≥ 0.6:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 1
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 4
- (c) If min(B1, B2, B3, B4) > R2, then F = 5

(B) If 0.5 ≤ max (C2, C3, C4) < 0.6:
- (a) If min(B1, B2, B3) ≤ R1, then F = 2
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 5
- (c) If min(B1, B2, B3, B4) > R2, then F = 6

(C) If 0.4 ≤ max (C2, C3, C4) < 0.5:
- (a) If min(B1, B2, B3, B4) ≤ R1, then F = 3
- (b) If R1 < min(B1, B2, B3, B4) ≤ R2, then F = 6

(D) If max (C2, C3, C4) < 0.4: then, F = 6 [NO OTHER CHECKS ARE DONE]

STEP 2: When NHBR is NOT PRESENT,

Corollary 1: If C2 ≥ 0.6, C3 ≥ 0.6 and C4 ≥ 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 0
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 3
(c) If min(B2, B3, B4) > R2, then F = 5

Corollary 2: If max (C2, C3, C4) ≥ 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 1
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 4
(c) If min(B2, B3, B4) > R2, then F = 5

Corollary 3: If 0.4 ≤ max (C2, C3, C4) < 0.6:
(a) If min(B2, B3, B4) ≤ R1, then F = 2
(b) If R1 < min(B2, B3, B4) ≤ R2, then F = 5
(c) If min(B2, B3, B4) > R2, then F = 6

Corollary 4: If max (C2, C3, C4) < 0.4: then, F =6 [NO OTHER CHECKS ARE DONE]

STEP 3: For IRREGULAR STATIONS,

Corollary 1: If 53 ≤ Day_Count < 61: then F = 7, i.e. in between 43-50% out of 122 days

Corollary 2: If 34 ≤ Day_Count < 53: then F = 8, i.e. in between 27-43% out of 122 days

Corollary 3: If Day_Count < 34: then F = 9, i.e. less than 27% out of 122 days

2. Real-time Quality-Flag Determination Method:

For Real-time processing of Quality Flag determination, the statistics has been computed over a period of previous 15 days span. Now, based on last 15 days rainfall data, maximum correlation with minimum BIAS are considered to compute and assign Quality Flags to each individual stations. It is to be noted that, the method is exactly similar to Point No. 1 discussed above up to STEP-2, but for STEP-3, i.e. to determine irregular stations, the following Corollaries should be considered in case of real-time processing:

STEP 3: For IRREGULAR STATIONS (in case of real-time processing for previous 15 days),

Corollary 1: If 5 ≤ Day_Count ≤ 6: then F = 7

Corollary 2: If 3 ≤ Day_Count ≤ 4: then F = 8

Corollary 3: If Day_Count < 3: then F = 9