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Analysis of long-term trends of rainfall and extreme rainfall events over Andaman & Nicobar and Lakshadweep Islands of India

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सार – भारत के दो प्रमुख द्वीपसमूह, अंडमान और निकोबार द्वीप समूह और लक्षद्वीप क्रमशः बंगाल की खाड़ी और अरब सागर के जलवायु-जनित खतरों के क्षेत्रों में स्थित हैं, जो समुद्र के ऊपर विकसित होने वाली मौसम प्रणालियों और भारी वर्षा गतिविधियों से काफी हद तक प्रभावित होते हैं। आईएमडी द्वारा हाल ही में प्रकाशित दो दैनिक ग्रिडयुक्त वर्षा डेटा सेट; राजीवन एट अल. (2010) 1° × 1° स्थानिक विभेदन पर और पै एट अल. (2014) 0.25° × 0.25° पर 100 वर्षों से अधिक की अवधि तक विस्तारित स्थानिक विभेदन का उपयोग शोधकर्ताओं द्वारा भारतीय मुख्य भूमि पर विभिन्न स्थानिक-अस्थायी पैमानों पर वर्षा की विशेषताओं का अध्ययन करने के लिए बड़े पैमाने पर किया गया है। हालाँकि, इन डेटा सेटों में भारत के इन दो द्वीपों के मौसम उपखंडों के ग्रिड शामिल नहीं हैं, इसका मुख्य कारण इतनी लंबी अवधि के लिए दैनिक वर्षा प्रेक्षण नहीं लिया जाना है। इस अध्ययन में, हाल के 70 वर्षों (1951 से 2020) के लिए अवधि के दौरान सभी उपलब्ध द्वीप स्टेशन डेटा का उपयोग करके इन द्वीप उपखंडों पर दैनिक ग्रिडयुक्त वर्षा डेटा को दो स्थानिक विभेदनों यथा 1° × 1° और 0.25° × 0.25° में विकसित करने का प्रयास किया गया और इन द्वीपों पर वर्षा की विभिन्न विशेषताओं का सांख्यिकीय विश्लेषण किया गया। इन दोनों द्वीप उपखंडों के लिए 0.25° × 0.25° डेटा सेट को आईएमडी की आधिकारिक वर्षा समय श्रृंखला के साथ अधिक तुलनीय पाया गयाऔर इसलिए इन दो द्वीप उपखंडों के लिए 1951-2020 की संपूर्ण डेटा अवधि और 1971-2020 की जलवायु काल परिवर्तन अवधि के लिए इस डेटा सेट का उपयोग वर्षा की दैनिक घटनाओं (>=5 मिमी) की प्रवृत्तियों का विश्लेषण करने के लिए किया गया। डीईआर को दो श्रेणियों डीएमआर (5-100 मिमी), दैनिक मध्यम वर्षा की घटनाओं और डीएचआर (100 मिमी और अधिक) दैनिक भारी वर्षा की घटनाओं में वर्गीकृत किया गया। डीईआर (डीएमआर और डीएचआर के साथ) की आवृत्ति में दीर्घकालिक प्रवृत्तियों के संकेत और परिमाण ने हाल की अवधि 1971-2020 के दौरान महत्वपूर्ण परिवर्तन दर्शाए।

ABSTRACT. The two major archipelagos of India, the Andaman & Nicobar Islands and the Lakshadweep situated in the climate-hazardous areas of the Bay of Bengal and Arabian Sea respectively are largely affected by weather systems developing over the sea and heavy rainfall activities. The recent two daily gridded rainfall data sets published by IMD; Rajeevan *et al*. (2010) at 1° × 1° spatial resolution and Pai *et al*. (2014) at 0.25° × 0.25° spatial resolution extending for a period of more than 100 years have been extensively used by researchers to study the rainfall characteristics at various spatiotemporal scales over the Indian mainland. However, these data sets do not include the grids over these two island meteorological subdivisions of India mainly because of the absence of daily rainfall observation for this long period. In this study, an attempt has been made to develop daily gridded rainfall data over these island subdivisions for the recent 70 years (1951 to 2020) in two spatial resolutions, *viz*., 1° × 1° and 0.25° × 0.25° using all the available islands station data during the period and carry out statistical analyses of various rainfall characteristics over these islands. The 0.25° × 0.25° data set was observed to be more comparable with the official rainfall time series of IMD for both these two Island subdivisions, and hence this data set has been used to carry out the trend analysis of Daily events of rainfall DER (> = 5 mm) for these two island subdivisions for the whole data period of 1951-2020 and the climate regime shift period of 1971-2020. DER was classified into two categories DMR (5-100 mm), daily moderate rainfall events and DHR (100 mm and above) daily heavy rainfall events. Signs and magnitude of the long-term trends in the frequency of DER (with DMR & DHR) showed significant changes during the recent period 1971-2020.

Key words – Islands, Rainfall, Frequency, Variability, Trend.

1. Introduction

The two daily gridded rainfall data sets over India; at 1° × 1° spatial resolution based on a fixed network of 2140 rainguage station data (Rajeevan *et al*., 2010) and at 0.25° × 0.25° spatial grid resolution based on a variable network of 6955 stations (Pai *et al*., 2014) have been extensively used worldwide by researchers to study

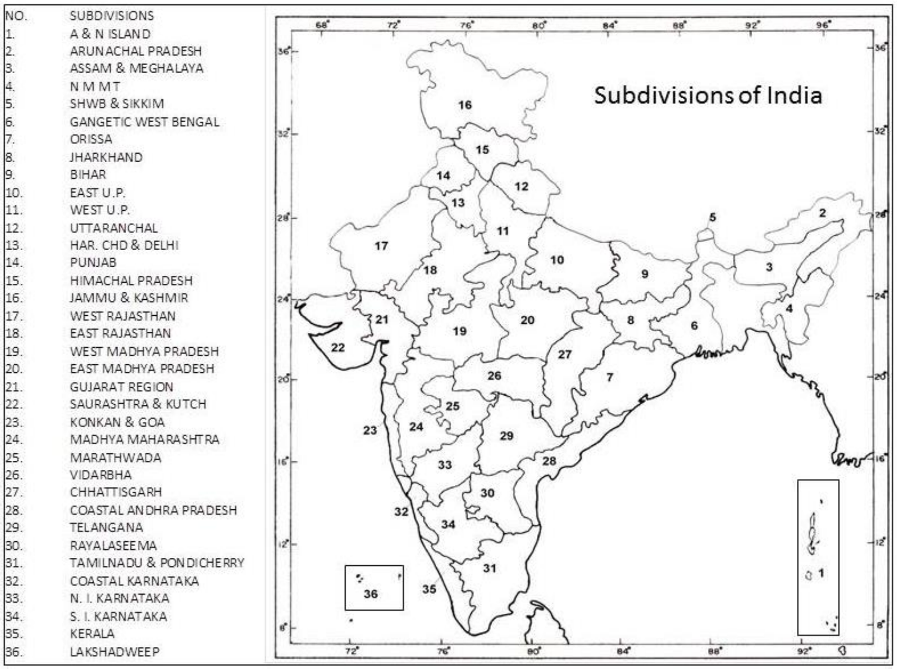


Fig. 1. The 36 meteorological subdivisions of India including Andaman & Nicobar and Lakshadweep Islands

rainfall characteristics at various spatial and temporal scales over the Indian Mainland and model verification. However, these two data sets or other daily gridded rainfall data sets over the Indian region (Rajeevan *et al*., 2006 & 2009, Yatagai *et al*., 2012) do not include grids over the island met subdivisions of Andaman & Nicobar Islands and the Lakshadweep (36 meteorological sub-divisions of India are shown in Fig. 1).

Andaman & Nicobar with an area of about 8249 Sq.km. comprises of 3 districts namely Nicobar Islands (headquarters at Carnicobar), North & Middle Andaman (headquarters at Mayabandar) and South Andaman (headquarters at Port Blair). About 572 islands are scattered across these 3 districts. Lakshadweep scattered over about 10 inhabited and 17 uninhabited islands is administratively considered as 1 district having an area of about 32.62 Sq km.

These two island subdivisions on either side of the Indian mainland are located in the climate-hazardous warm pool tropical region of the Bay of Bengal and Arabian Sea respectively over which the Inter Tropical Convergence Zone (ITCZ) crosses twice a year (May and October-November) and are largely affected by weather systems developing over the sea and heavy rainfall activities. Hence, analysing the rainfall characteristics is very important to understand long-term change and variability in the rainfall over these two island subdivisions.

A few earlier studies (Kumar *et al* 2012, Sreekesh 2016, Velmurugan *et al*., 2018, Adamala and Velmurugan (2020), Koutavarapu *et al*., 2021) have related to variability and trend of rainfall and its extremes over these two major Indian archipelago subdivisions, which lay in the warm pool tropical region. A statistically significant decreasing trend (95 %) for yearly rainfall averaged over the Andaman & Nicobar Islands was observed by Kumar *et al*., (2012) for the period 1961-2000. Insignificant positive trends of rainfall during JJAS and OND seasons for the period 1951-2004 over Amini and Minicoy stations of the Lakshadweep islands were observed by Sreekesh (2016). Velmuragan *et al*., (2018) analysed the rainfall frequencies of Andaman and Nicobar Islands for a limited period of 2013-2016 and indicated an increase in heavy to very heavy rainfall categories. Using the data of Port Blair for the period 1949-2019 and representing it as Andaman and Nicobar Islands, Adamala and Velmurugan (2020) studied the trend of rainfall and found a non-significant decrease at the rate of 0.195 mm per year in the total annual rainfall. However, they have not considered any other station from this island subdivision for the entire period for this study. Using the ERA5 data (Hersbach and Dee 2016), Koutavarapu *et al*., (2021), in order to study the convective activities over these two islands, computed seasonal rainfall averages over them (Andaman and Nicobar islands as one box which extends between 6° N and 14° N latitudes and 92° E and 94° E longitudes and Lakshadweep islands are taken as another box which extends between 8° N and 12.30° N latitudes and 71° E

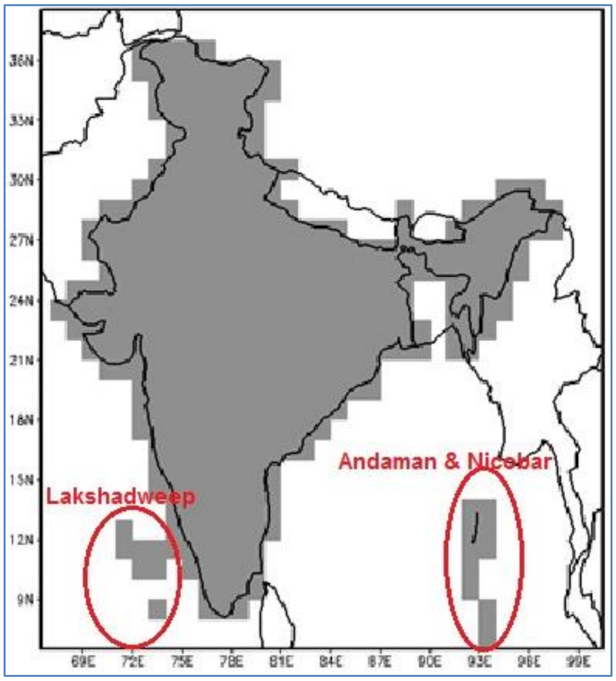


Fig. 2(a). Number of grids of 1° × 1° taken into account for Andaman & Nicobar and Lakshadweep Islands

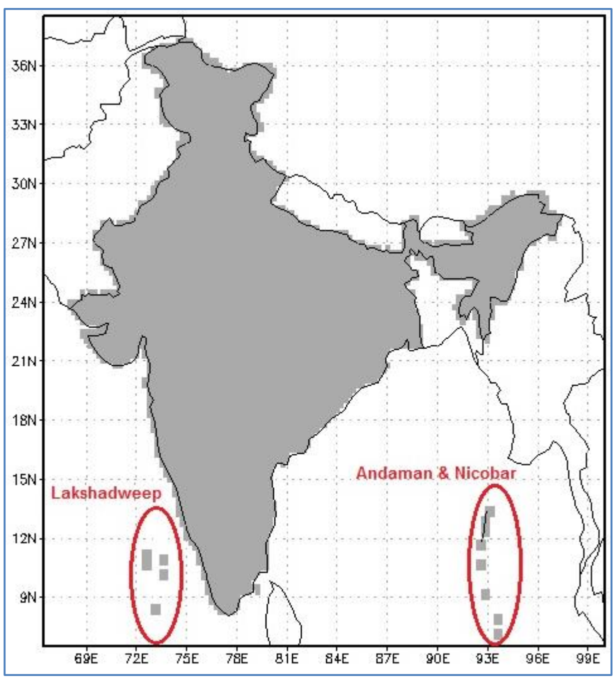


Fig. 2(b). Number of grids of 0.25° × 0.25° taken into account for Andaman & Nicobar and Lakshadweep Islands

and 74° E longitudes), the values computed by them over these islands very much underestimating when compared for each season with IMD operational rainfall time series as well as with the 1° × 1° and 0.25° × 0.25° data sets for the Indian islands developed and discussed in this study. This underestimation in values may be due to the area considered for computing rainfall for these islands as a whole individually, comprising much of the ocean portion. Aiming to overcome the limitations of the earlier studies in terms of data continuity and land-specific data availability to the maximum possible extent over these island sub-divisions (excluding the ocean portion enveloping these islands as far as possible), the main objectives of the present study are to develop daily gridded rainfall data set over the two island subdivisions for the recent 70 years (1951 to 2020) in two spatial resolutions, *viz*., 1° × 1° and 0.25° × 0.25°, and to use the data to examine various characteristics of rainfall such as climatology, variability at different temporal scales, trends, extreme rainfall events *etc*. over these two subdivisions.

2. Data and methodology

This study used daily station rainfall data for a fixed network of 15 stations (9 over Andaman & Nicobar and 6 over Lakshadweep) archived at the National Data Centre, IMD Pune for the period 1951-2020. The observed rainfall data was subject to multi-stage quality control before interpolating them into regular grids of 1° × 1° and 0.25° × 0.25° resolutions. As in the case of Rajeevan *et al*., (2006) and Pai *et al*., (2014), this study also used the interpolation method proposed by Shepard (1968) for interpolating station rainfall data into regular grids including the directional effects and barriers.

Figs. 2(a&b) show the number of grids of 1° × 1° and 0.25° × 0.25° resolutions over the Indian Islands taken for developing daily gridded rainfall data series. The Andaman and Nicobar & Lakshadweep Islands comprise of a total of 11 and 7 grid points respectively for the 1° × 1° resolution & a total of 8 and 6 grid points respectively for the 0.25° × 0.25° resolution data sets. The station data for each of these subdivisions was at least 70% on a daily basis, *i.e*. at least 6 stations over Andaman and Nicobar Islands and 4 stations over Lakshadweep during the whole period of 1951-2020). However, for the computation of rainfall time series, the fractional area of land falling in the respective grids has been considered avoiding the ocean part.

The IMD operational Rainfall time series over these two island subdivisions have been used for comparison with 1° × 1° and 0.25° × 0.25° data sets for the Indian islands. IMD's operational rainfall series contains monthly rainfall data for the period 1901-2012 from delayed mode computation using all available stations and 2013-2020 from real-time data series of DRMS (District Rainfall Monitoring Scheme). In this data series the monthly data

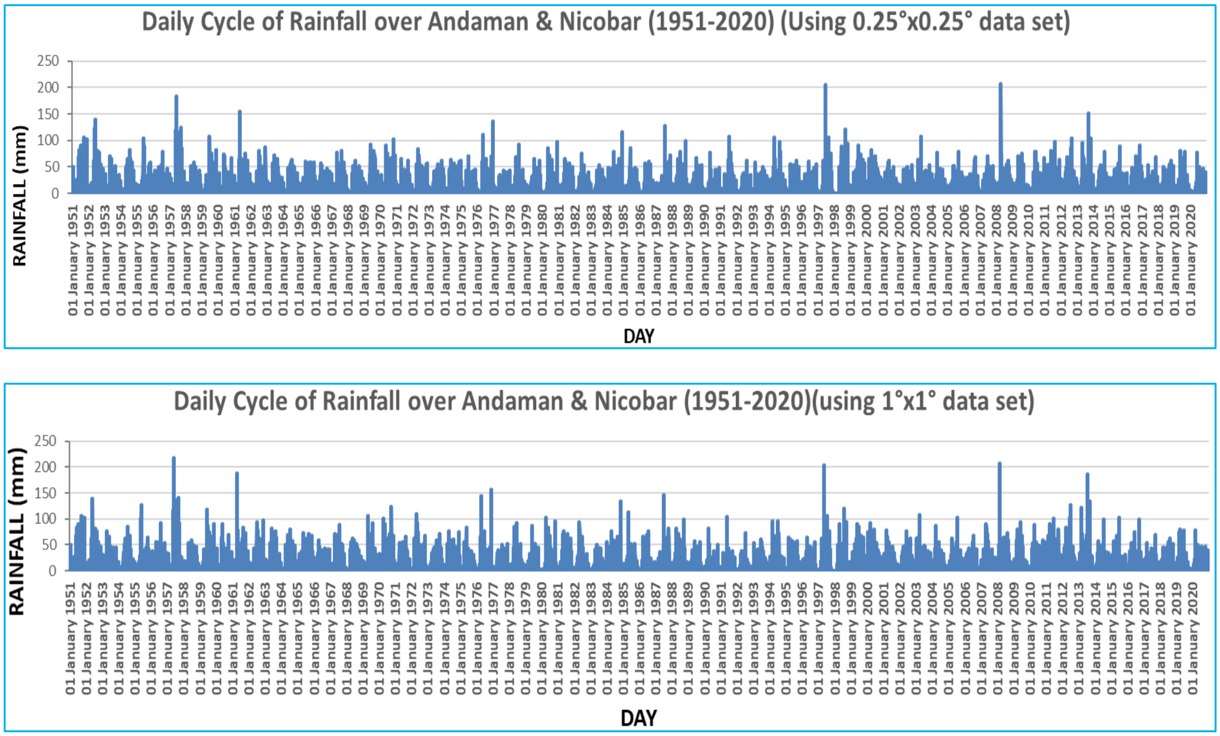


Fig. 3. Daily Mean of Area-Weighted Rainfall over Andaman & Nicobar (1951-2020)

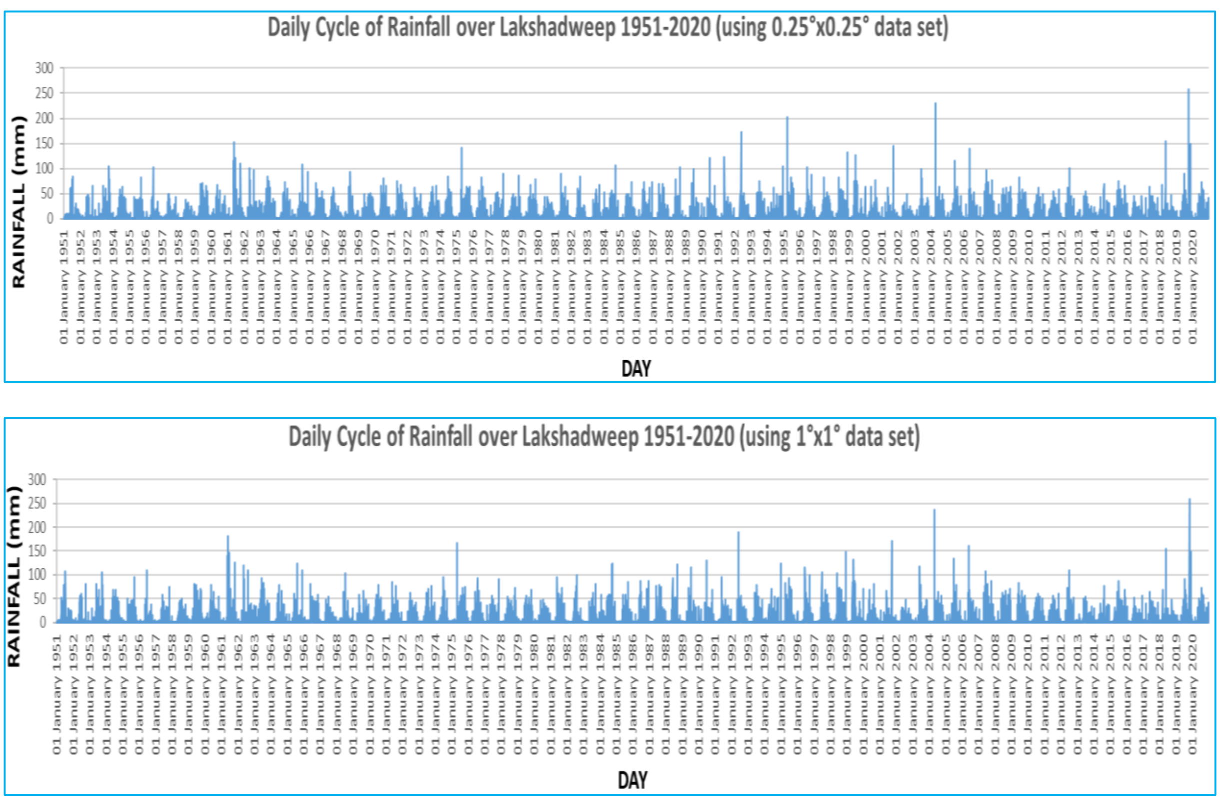


Fig. 4. Daily Mean of Area-Weighted Rainfall over Lakshadweep (1951-2020)

TABLE 1

Rainfall climatology (in mm) (1971-2020) for various months and seasons over Andaman & Nicobar Islands

Month/ Season	IMD Official RF (mm)	1 × 1 Degree RF (mm)	0.25×0.25 Degree RF (mm)	Difference (mm)	Difference (mm)	Correlation Coefficient	
				(IMD Official – 1 × 1 Degree)	(IMD Official – 0.25 × 0.25 Degree)	(IMD Official & 1 × 1 Degree)	(IMD Official & 0.25 × 0.25 Degree)
January	60.3	53.6	62.5	6.7	-2.2	0.94	0.94
February	31.1	25.0	28.1	6.1	2.9	0.84	0.87
March	41.6	43.5	45.8	-1.8	-4.1	0.90	0.88
April	83.2	80.9	84.5	2.3	-1.3	0.81	0.82
May	336.4	354.9	336.7	-18.5	-0.4	0.91	0.96
June	385.9	421.3	402.5	-35.4	-16.7	0.77	0.75
July	365.6	407.0	373.5	-41.4	-7.9	0.83	0.86
August	359.0	395.9	372.2	-36.9	-13.2	0.78	0.80
September	410.1	425.3	410.4	-15.2	-0.3	0.77	0.80
October	286.7	276.9	287.2	9.8	-0.5	0.81	0.83
November	250.9	233.7	248.7	17.1	2.1	0.89	0.92
December	157.0	137.9	160.1	19.2	-3.0	0.97	0.97
JF	91.4	78.5	96.6	12.8	-5.3	0.92	0.92
MAM	461.2	479.2	467.0	-18.1	-5.8	0.91	0.95
JJAS	1520.6	1649.5	1558.6	-128.9	-38.0	0.58	0.58
OND	694.6	648.5	696.0	46.1	-1.4	0.86	0.86
Annual	2767.8	2855.8	2818.2	-88.1	-50.5	0.59	0.59

has been computed by calculating the daily district rainfall values taking the simple arithmetic mean of values of all available stations in the district on that particular day first, and then adding up these daily values to obtain values of each month of that district. Subdivision-wise monthly rainfall values have been calculated based on the district area weighted method.

The daily rainfall data computed from each of the 1° × 1° and 0.25° × 0.25° data sets were used to calculate the monthly and seasonal values. The mean rainfall of each month and season obtained from the IMD operational data set was compared with the corresponding monthly and seasonal area-weighted rainfall computed from 1° × 1° and 0.25° × 0.25° data sets. Long-term statistical features such as climatology, variability and linear trends of the area-weighted rainfall as well as DER and its two categories DMR and DHR for the whole data period of 1951-2020 as well as for the recent 50-year period of 1971-2020 were examined. The linear trends were computed using the simple linear regression method and the student's *t*-test was used to test the linear trends' significance.

The annual cycle time series of daily rainfall over Andaman & Nicobar and Lakshadweep are shown in Figs. 3&4 respectively computed using 1° × 1° and 0.25° × 0.25° data sets. The area-weighted daily rainfall over all the grid points over the respective islands was computed as the daily rainfall over them. Both the inter-annual and intra-seasonal variability can be seen along with extreme rainfall events embedded in the 70 years of the study period of 1951-2020 in Figs. 3&4. These islands are prone to heavy rainfall events associated with low-pressure weather systems originating in the sea like depressions and cyclonic storms. Over the Andaman & Nicobar Islands, Cyclone Nargis was predominantly the reason behind the highest rainfall observed at the end of April 2008 as seen in Fig. 3. The highest rainfall over Lakshadweep was observed during the end of October 2019 as seen in Fig. 4 with Cyclone Maha being the reason behind it. As seen in Fig. 3, over Andaman &

TABLE 2

Rainfall climatology (in mm) (1971-2020) for various months and seasons over Lakshadweep Islands

Month/ Season	IMD Official RF (mm)	1 × 1 Degree RF (mm)	0.25 × 0.25 Degree RF (mm)	Difference (mm)	Difference (mm)	Correlation Coefficient	
				(IMD Official – 1 × 1 Degree)	(IMD Official – 0.25 × 0.25 Degree)	(IMD Official & 1 × 1 Degree)	(IMD Official & 0.25 × 0.25 Degree)
January	18.6	15.7	16.4	3.0	2.2	0.90	0.95
February	9.8	4.8	7.1	5.0	2.7	0.82	0.95
March	16.7	7.0	13.6	9.7	3.1	0.90	0.98
April	32.6	22.7	28.9	9.9	3.7	0.82	0.89
May	160.4	145.9	147.3	14.4	13.1	0.92	0.94
June	331.0	349.6	339.7	-18.5	-8.7	0.93	0.96
July	276.9	301.5	297.8	-24.6	-20.9	0.95	0.97
August	228.0	231.4	232.1	-3.4	-4.1	0.95	0.97
September	164.0	162.6	165.9	1.4	-1.9	0.92	0.96
October	144.7	144.2	150.2	0.5	-5.5	0.86	0.92
November	122.4	105.2	113.3	17.1	9.1	0.92	0.96
December	55.8	43.4	55.6	12.5	0.3	0.88	0.93
JF	28.4	20.5	23.5	7.9	4.9	0.90	0.96
MAM	209.6	175.6	187.8	34.1	21.8	0.91	0.93
JJAS	1000.0	1045.1	1035.5	-45.1	-35.5	0.93	0.96
OND	322.9	292.8	322.6	30.0	0.3	0.92	0.94
ANNUAL	1560.9	1534.0	1569.3	26.9	-8.4	0.92	0.93

Nicobar Islands the peak rainfall activity during July 1997 can be attributed to the active MJO phase over the Indian Ocean.

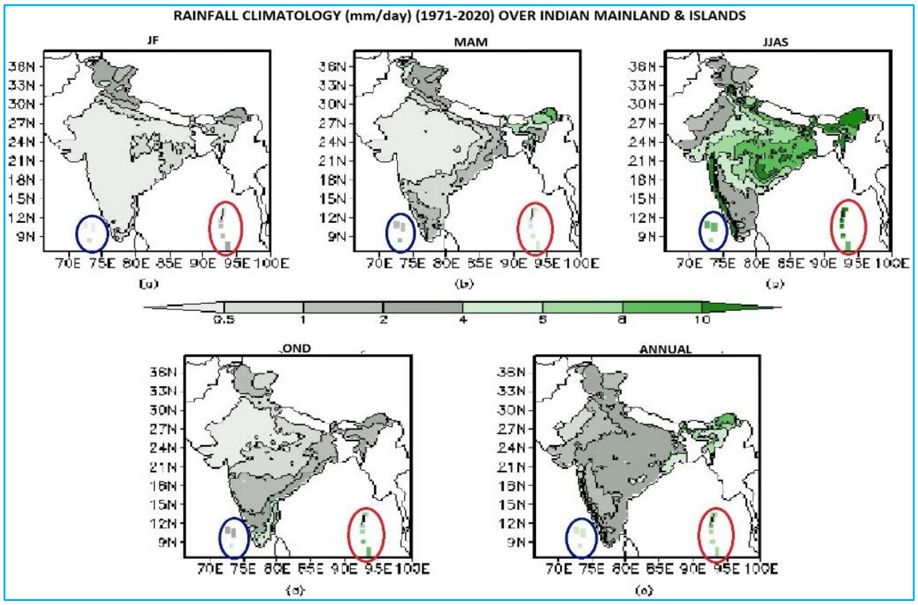
The mean rainfall of each month and season obtained from the IMD operational data set was compared with the corresponding monthly and seasonal area-weighted rainfall computed from 1° × 1° and 0.25° × 0.25° data sets.

3. Results and discussions

3.1. *Climatology, inter-annual variability and trend of area-weighted seasonal and annual rainfall*

Tables 1&2 show the comparison of mean rainfall (mm) for the period 1971-2020 and also the Coefficient of Correlation (CC) between the IMD official rainfall data set and the present gridded data sets for Andaman & Nicobar Islands and Lakshadweep respectively. Monthly and seasonal rainfall climatology computed using the 0.25° × 0.25° resolution data set was more comparable with IMD operational rainfall time series than the 1° × 1° resolution data set. Also, the CC of the IMD operational data set with the 0.25° × 0.25° resolution data set was observed to be better than those with the 1° × 1° resolution data set. Hence, further analysis carried out using the 0.25° × 0.25° data set has been discussed in the present study. The seasonal and annual climatology of rainfall over the islands have been shown along with those over the Indian mainland in Fig. 5 using the 0.25° × 0.25° resolution data set.

It can be seen from Fig. 5 that during the JF season, the rainfall over most parts of Andaman & Nicobar Islands was less than 4 mm/day and that over Lakshadweep was about 0.5 mm/day. During the MAM season, the rainfall over most parts of Andaman & Nicobar Islands was between 4-6 mm/day and that over Lakshadweep was about 2 mm/day. During the JJAS season, the rainfall over most parts of Andaman & Nicobar Islands was 8 to >10 mm/day and that over Lakshadweep was about 6-10 mm/day. During the OND season, the rainfall over most parts of Andaman &



Figs. 5(a-e). Seasonal and Annual Rainfall climatology (mm/day) over Indian Mainland & Islands (The islands Andaman & Nicobar and Lakshadweep are circled in RED and BLUE respectively)

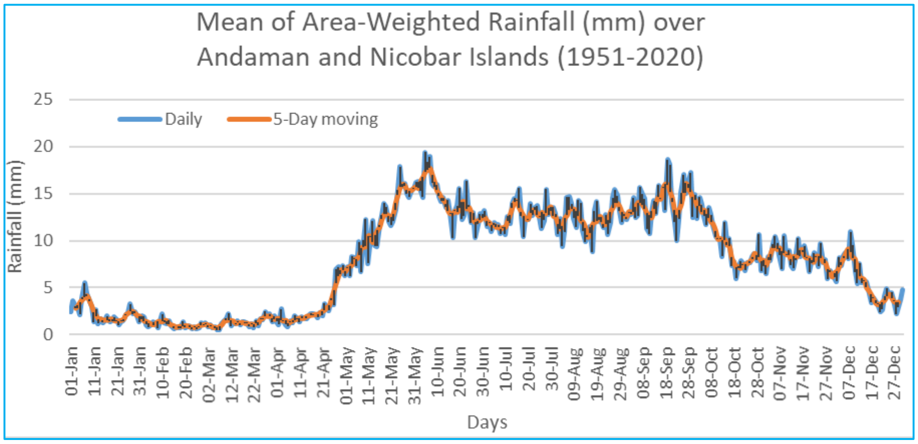


Fig. 6(a). Daily and 5-Day moving Mean of Area-Weighted Rainfall over Andaman &Nicobar Islands (1951-2020)

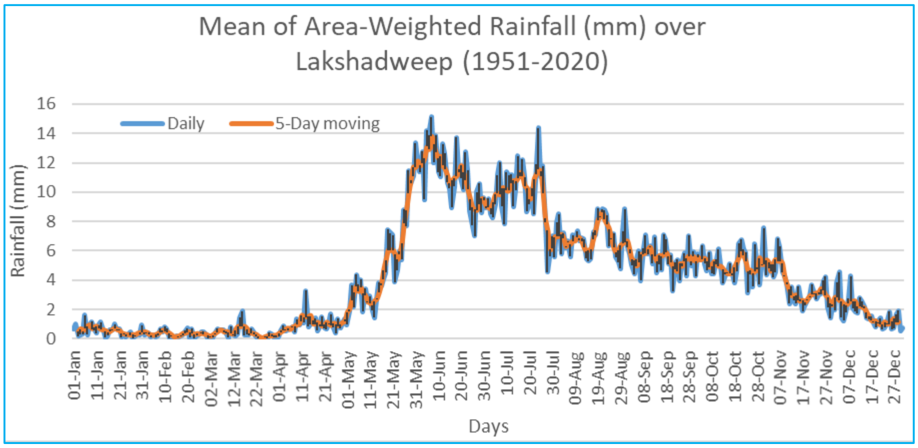


Fig. 6(b). Daily and 5-Day moving Mean of Area-Weighted Rainfall over Lakshadweep (1951-2020)

TABLE 3

Statistical properties of area-weighted rainfall averaged over Andaman & Nicobar Islands

Season	Property	1951-2020	1971-2020
JF	Mean (mm/day)	1.8	1.6
	Standard Deviation (SD) (mm/day)	1	1.1
	Median (mm/day)	1.4	1.3
	trend/decade (mm/day/decade)	2.6	17.32*
MAM	Mean (mm/day)	5.2	5.1
	Standard Deviation (SD) (mm/day)	5.1	4.7
	Median (mm/day)	2.2	2.5
	trend/decade (mm/day/decade)	-6.6	-0.7
JJAS	Mean (mm/day)	13.4	12.8
	Standard Deviation (SD) (mm/day)	2.1	2.1
	Median (mm/day)	12.9	12.6
	trend/decade (mm/day/decade)	-15.3	25.2
OND	Mean (mm/day)	7.8	7.6
	Standard Deviation (SD) (mm/day)	2.8	2.7
	Median (mm/day)	7.8	7.3
	trend/decade (mm/day/decade)	-13.12	-14.1
ANNUAL	Mean (mm/day)	8	7.7
	Standard Deviation (SD) (mm/day)	5.3	5
	Median (mm/day)	8.3	7.9
	trend/decade (mm/day/decade)	-32.4	25.6

The level of significance is marked by (*) for 95% for the trends in area-weighted rainfall

TABLE 4

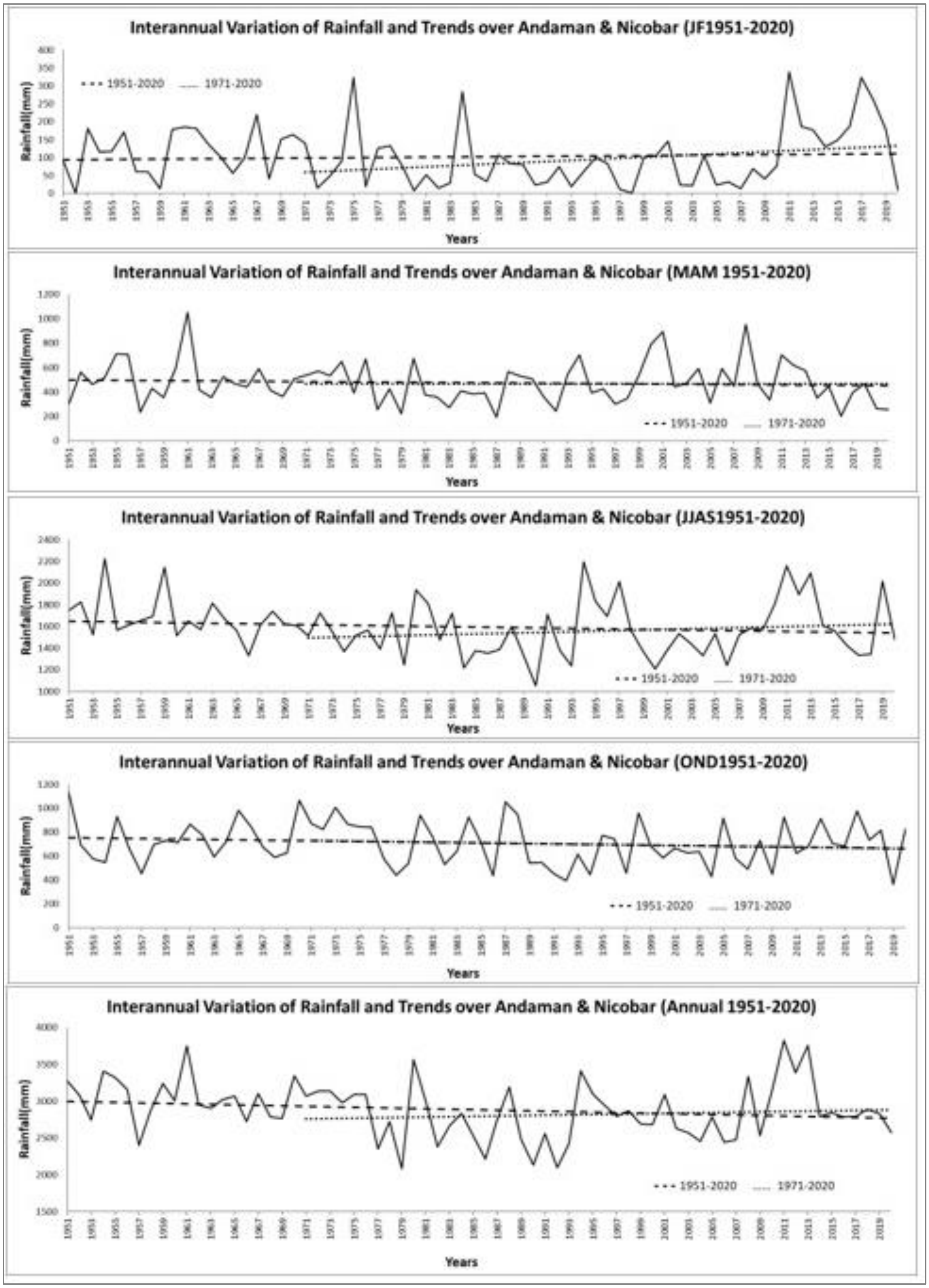
Statistical properties of area-weighted rainfall averaged over Lakshadweep

Season	Property	1951-2020	1971-2020
JF	Mean (mm/day)	0.4	0.4
	Standard Deviation (SD) (mm/day)	0.3	0.4
	Median (mm/day)	0.3	0.3
	trend/decade (mm/day/decade)	-0.3	3.96
MAM	Mean (mm/day)	2.2	2
	Standard Deviation (SD) (mm/day)	2.8	2.7
	Median (mm/day)	1	0.9
	trend/decade (mm/day/decade)	-2.1	14.2
JJAS	Mean (mm/day)	8.3	8.5
	Standard Deviation (SD) (mm/day)	2.8	2.8
	Median (mm/day)	7.9	8.2
	trend/decade (mm/day/decade)	0.43	-35.7+
OND	Mean (mm/day)	3.4	3.5
	Standard Deviation (SD) (mm/day)	1.8	1.9
	Median (mm/day)	3.6	3.5
	trend/decade (mm/day/decade)	4.1	5.77
ANNUAL	Mean (mm/day)	4.3	4.3
	Standard Deviation (SD) (mm/day)	3.8	3.9
	Median (mm/day)	3.7	3.6
	trend/decade (mm/day/decade)	2.2	-11.8

The level of significance is marked by (*) for 95% for the trends in area-weighted rainfall

Nicobar Islands was 4-8 mm/day and that over Lakshadweep was less than 4 mm/day. The annual rainfall over most parts of Andaman & Nicobar Islands was less than 8 mm/day and that over Lakshadweep was less than 2 mm/day.

The daily and 5-Day moving mean of area-weighted rainfall over Andaman & Nicobar and Lakshadweep Islands for a long period of 70 years (1951-2020) are shown in Figs. 6(a&b) respectively computed using the 0.25° × 0.25° data set. From Fig. 6(a), it can be seen that over Andaman & Nicobar Islands, the daily rainfall on an average is about 4-6 mm/day till mid-January, thereafter decreasing to about less than 4 mm/day, remaining so till mid-May. Thereafter, a steady rise in the mean daily rainfall is seen between the second week of May (coinciding with the normal onset date of Southwest Monsoon over the region) to the first week of June, peaking at about 19 mm/day during the end of the first week of June. The mean daily rainfall was observed to be between 10-18 mm/day from mid-June to mid-October, thereafter becoming about 6-10 mm/day till mid-December and further decreasing to 2-4 mm/day till the end of the year. From Fig. 6(a), it can be seen from the 5-day moving average that the mean daily rainfall over Andaman & Nicobar Islands began to steadily increase from 21st April onwards from about 2.5 mm, peaking around 10th June to about 17.5 mm. A slight decline thereafter till 20th June to about 13.5 mm, thereafter steady till the end of September. A gradual decline is observed



Figs. 7(a-e). Inter-annual variation of rainfall and Trend over Andaman & Nicobar Islands thereafter till mid-October ranging from about 7.5 mm to 10 mm till the first week of December. The mean daily rainfall is seen to be less than 5 mm from the second week of December till the third week of April.

It can be seen from Fig. 6(b) that over Lakshadweep Islands, the mean daily rainfall is less than 2 mm/day from the start of the year to the end of April. A steady increase in rainfall is observed from the first week of May to the first week of June, ranging between 2-15 mm/day, peaking at about 15 mm/day during the end of the first week of June. A little decrease in the mean daily rainfall (ranging between 7-14 mm/day) is observed from the second week of June to the end of July. From August to mid-November, there was a further decrease in the mean daily rainfall, ranging between 4-7 mm/day, thereafter becoming less than 4 mm/day till the end of the year. From Fig. 6(b), it can be seen from the 5-day moving average that the mean daily rainfall over Lakshadweep began to steadily increase from the first week of May onwards from about 2.0 mm, peaking around 7th June to about 14 mm, thereafter up to the end of July ranging between 8-12 mm. Rainfall is observed to be more or less steady ranging between 4-8 mm until the first week of November. The mean daily rainfall is seen to be between 2-4 mm from the second week of November to the first week of December and thereafter less than 2 mm till the end of April.

Statistical properties including the trends of the area-weighted rainfall during all the seasons aggregated over Andaman and Nicobar Islands & Lakshadweep computed using 0.25° × 0.25° data set are given in Tables 3&4 respectively. To see if any climate shift is visible in the recent 50 years, these statistics were computed for the two periods 1951-2020 and 1971-2020 and are also given in these tables. The level of significance is marked by (*) for 95% and (+) for 90% for the trends in area-weighted rainfall.

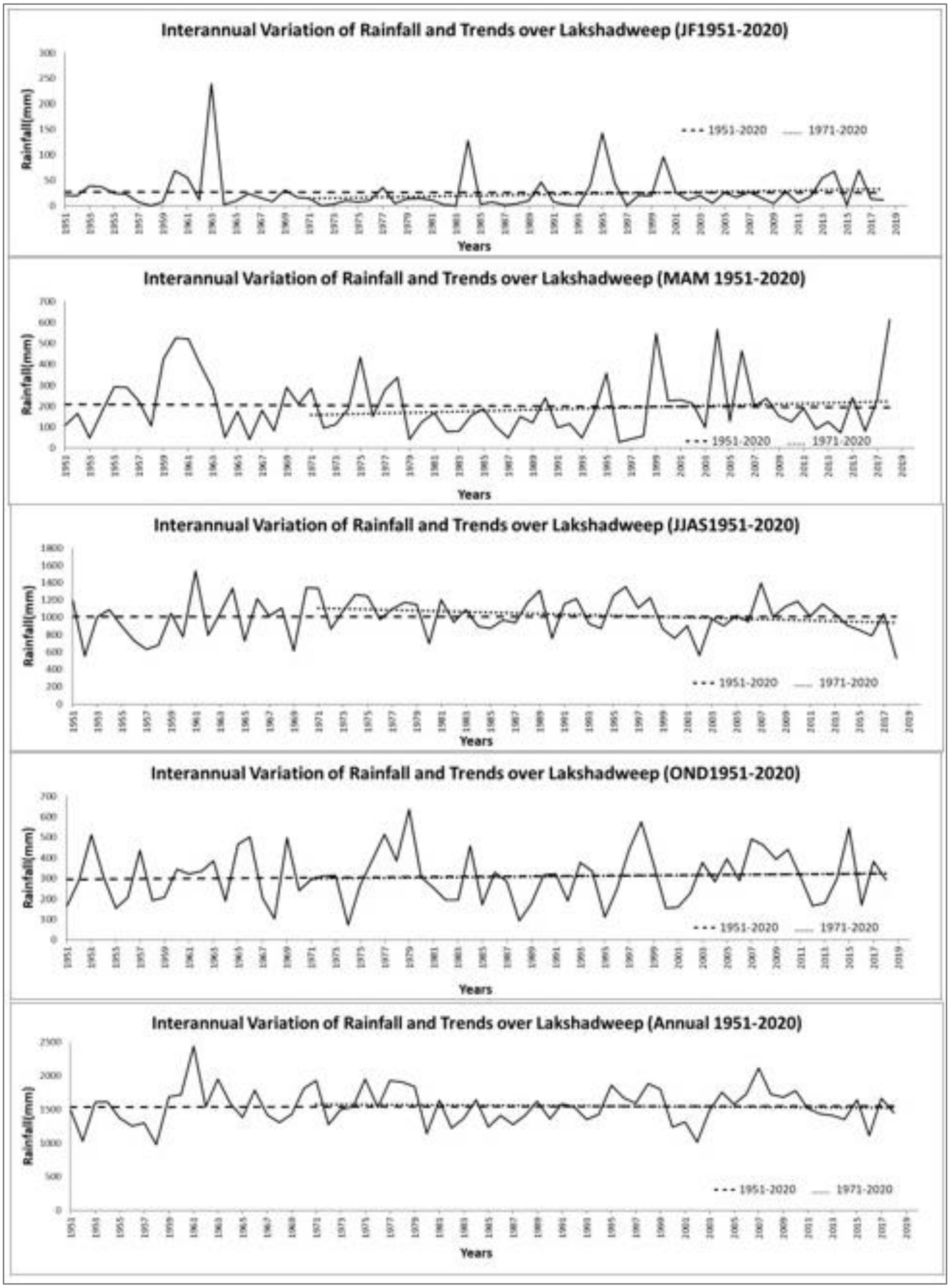
The inter-annual variation of rainfall over Andaman & Nicobar Islands showing trend lines fitted for the study period 1951-2020 and its recent 50-year sub-period 1971-2020 can be seen in Figs. 7(a-e). As seen in Table 3 and Figs. 7(a-e), for the JF season, Andaman & Nicobar Islands received mean area-weighted rainfall (averaged over 1951-2020) of 1.8 mm/day with a SD of 1 mm/day. An insignificant positive trend was also observed in the season rainfall over the whole data period. However, a positive linear trend of 17.32 mm/day/decade significant at 95% level was observed during 1971-2020. For the MAM season, Andaman & Nicobar Islands received mean area-weighted rainfall (averaged over 1951-2020) of 5.2 mm/day with a SD of 5.1 mm/day. An insignificant negative trend was observed in the MAM season rainfall over the whole data period as well as over 1971-2020. During the JJAS season, mean area-weighted rainfall of 13.4 mm/day averaged over 1951-2020 was received over Andaman & Nicobar Islands with a SD of 2.1 mm/day. However, the sign of linear trend changed from insignificantly negative during the whole data period of 1951-2020 to insignificantly positive during 1971-2020.

For the OND season, Andaman & Nicobar Islands received mean area-weighted rainfall (averaged over 1951-2020) of 7.8 mm/day with a SD of 2.8 mm/day. An insignificant negative trend was observed in the season rainfall over the whole data period as well as over 1971-2020. The annual mean area-weighted rainfall (averaged over 1951-2020) over the Andaman & Nicobar Islands was 8.0 mm/day with a SD of 5.3 mm/day. Similar to the JJAS season, the sign of linear trend changed from insignificantly negative during the whole data period of 1951-2020 to insignificantly positive during 1971-2020. However, no significant difference was observed between the rainfall means during the two periods 1951-2020 and 1971-2020 for all the seasons.

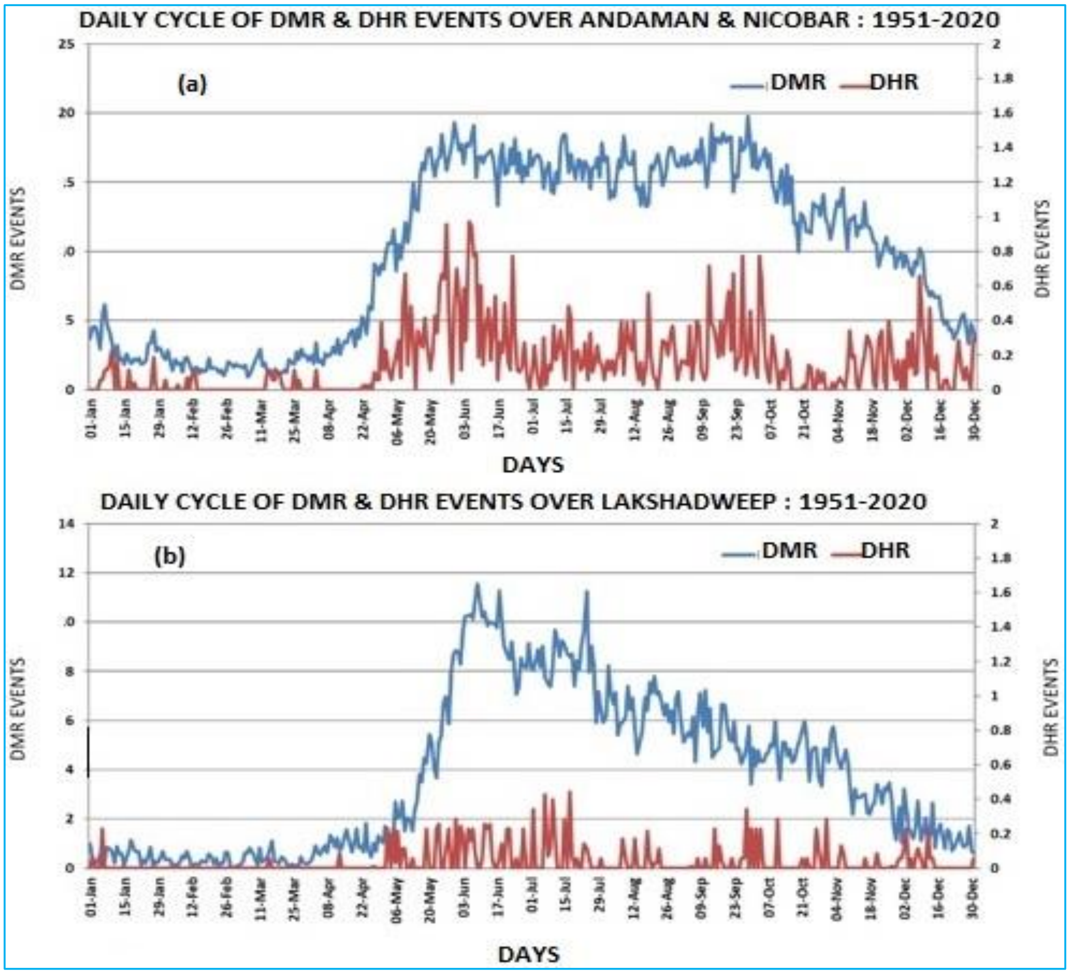
The inter-annual variation of rainfall over Lakshadweep showing trend lines fitted for the study period 1951-2020 and its recent 50-year sub-period 1971-2020 can be seen in Figs. 8(a-e). As seen in Table 4 and Figs. 8(a-e), for the JF season, Lakshadweep received mean area-weighted rainfall (averaged over 1951-2020) of 0.4 mm/day with a SD of 0.3 mm/day. However, the sign of linear trend changed from insignificantly negative during the whole data period of 1951-2020 to insignificantly positive during 1971-2020.

For the MAM season, Lakshadweep received mean area-weighted rainfall (averaged over 1951-2020) of 2.2 mm/day with a SD of 2.8 mm/day. However, similar to the JF season, the sign of linear trend changed from insignificantly negative during the whole data period of 1951-2020 to insignificantly positive during 1971-2020. During the JJAS season, mean area-weighted rainfall of 8.3 mm/day averaged over 1951-2020 was received over Lakshadweep with a SD of 2.8 mm/day.

The OND season's mean area-weighted rainfall of 3.4 mm/day with a SD of 1.8 mm/day was observed over Lakshadweep for the whole period of 1951-2020. During the JJAS and the OND seasons, an insignificant positive trend that was observed for the entire period of 1951-2020 is in line with Sreekesh (2016) who studied the rainfall trend over two stations of the Lakshadweep islands, namely, Amini and Minicoy for the period 1951-2004 and concluded with similar results. However, the sign of linear trend changed from insignificantly positive during the whole data period of 1951-2020 to significantly negative



Figs. 8(a-e). Inter-annual variation of rainfall and Trend over Lakshadweep Islands



Figs. 9(a&b). Daily cycle of DMR and DHR events over Andaman & Nicobar and Lakshadweep Islands for the period 1951-2020

(90%, at -35.7 mm/day/decade) during 1971-2020 for the JJAS season.

For the OND season, the insignificant positive trend continued for the period 1971-2020 also. The annual mean area-weighted rainfall (averaged over 1951-2020) over Lakshadweep was 4.3 mm/day with a SD of 3.8 mm/day. The sign of linear trend changed from insignificantly positive during the whole data period of 1951-2020 to insignificantly negative during 1971-2020. Similar to Andaman & Nicobar Islands, no significant difference was observed between the rainfall means during the two periods 1951-2020 and 1971-2020 for all the seasons.

As seen from Fig. 7(e) and Fig. 8(e), during the entire data period, the years 2011 and 1979 with 3824 mm and 2084 mm rainfall respectively were the wettest and driest year over Andaman & Nicobar Islands. The years 1961 and 1958 with 2435 mm and 979 mm of rainfall respectively were the wettest and driest year over Lakshadweep.

It was observed that the area-weighted rainfall and DER of these two island sub-divisions showed strong CC for all the seasons during the data period of 1951-2020. The CC between the area-weighted rainfall and number of DER during the data period 1951-2020 for Andaman and Nicobar Islands for JS, MAM, JJAS, OND & Annual were respectively 0.96, 0.85, 0.82, 0.84 and those for Lakshadweep were respectively 0.83 & 0.91, 0.84, 0.85, 0.85 and 0.80 (these values are not tabulated).

3.2. *Climatology and trends of daily extreme rainfall events*

Figs. 9(a&b) show the mean annual cycle of the number of DMR & DHR events over Andaman & Nicobar and Lakshadweep Islands respectively. From Fig. 9(a), it

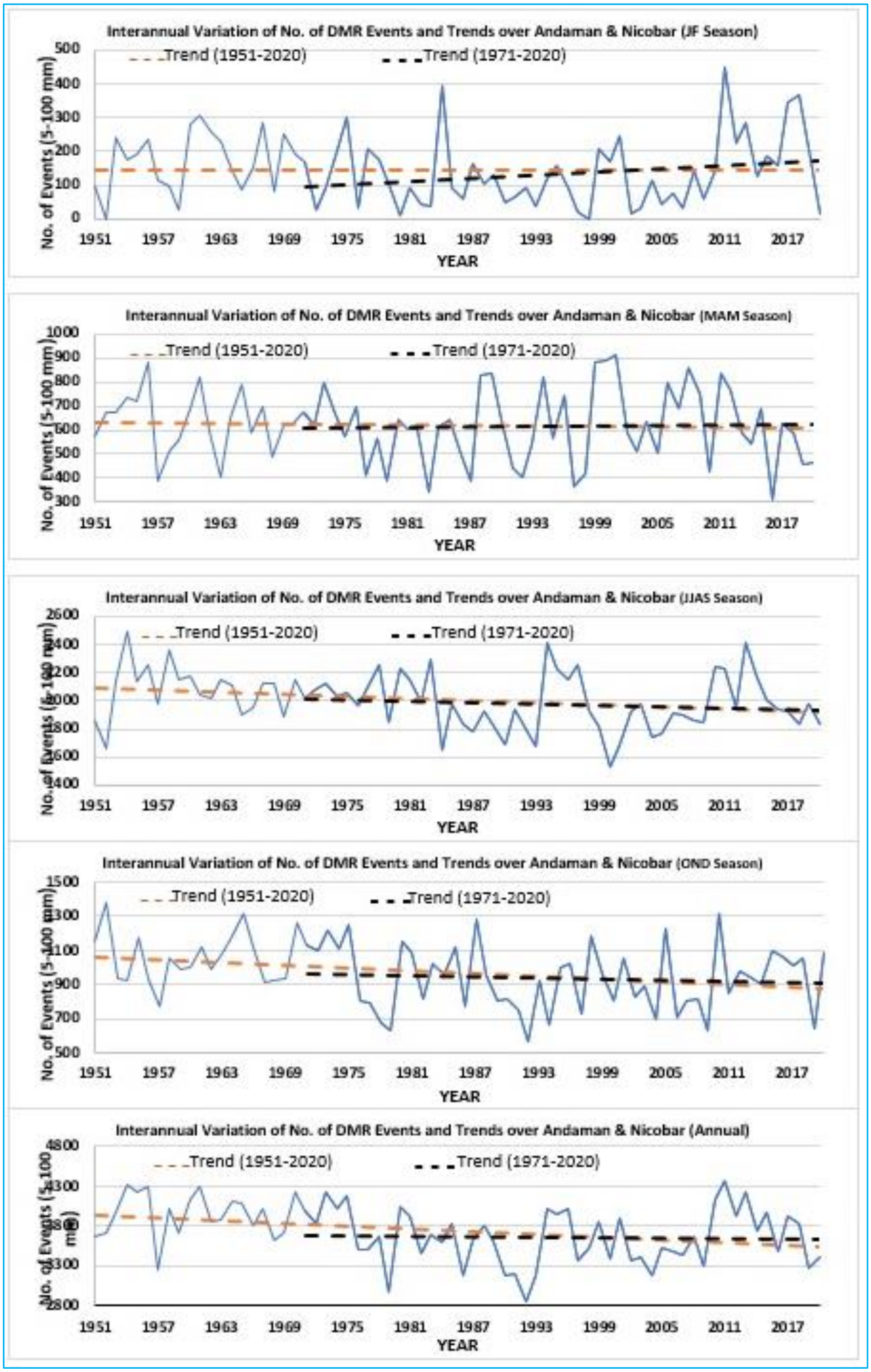


Fig. 10(a). Inter-annual variation of the number of DMR events and Trends for various seasons over Andaman & Nicobar Islands

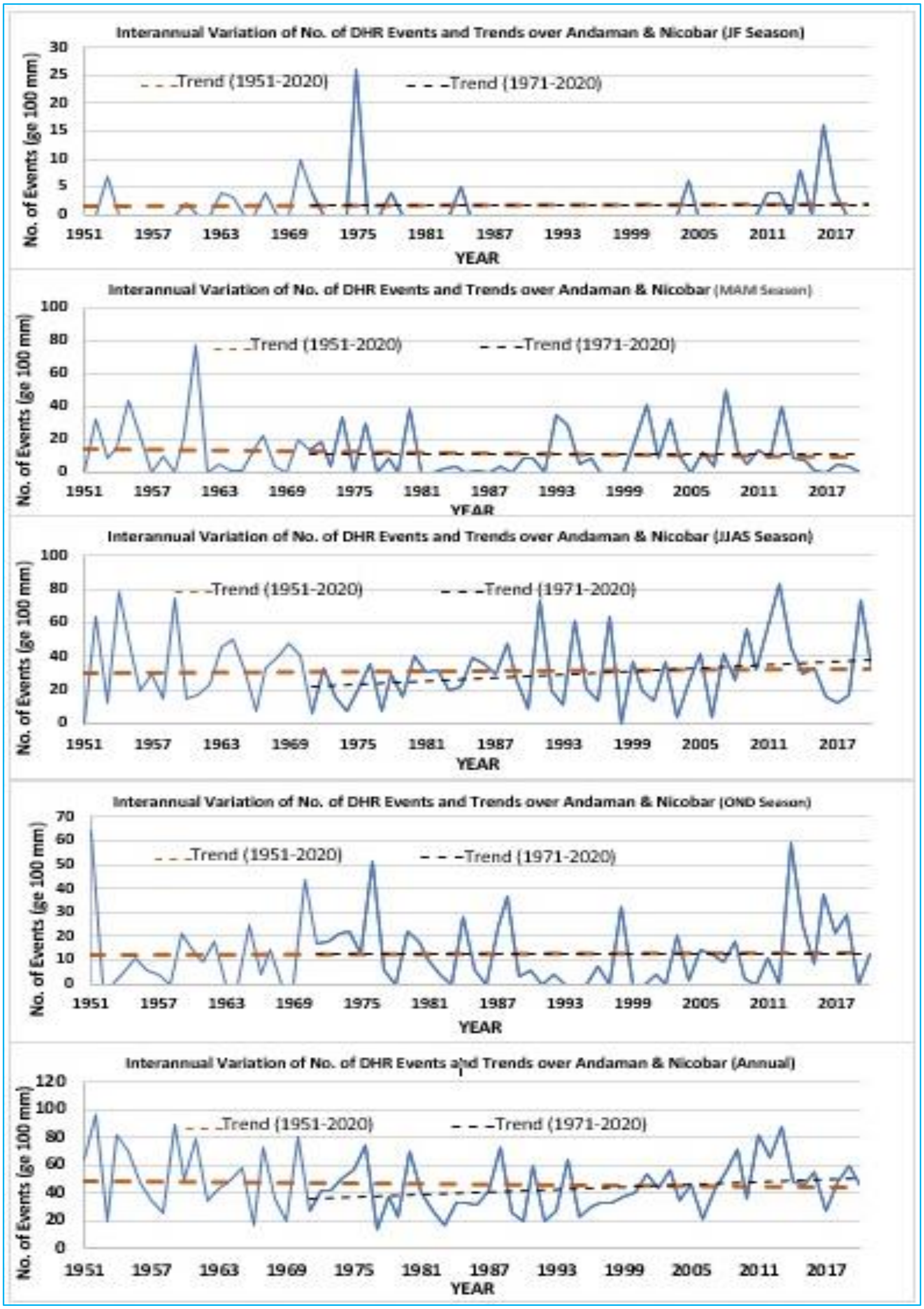


Fig. 10(b). Inter-annual variation of the number of DHR events and Trends for various seasons over Andaman & Nicobar Islands

TABLE 5

DER, DMR and DHR events Trend/decade for various seasons over Andaman & Nicobar Islands

Season	Events	1951-2020	1971-2020
JF	DER	1.83	20.03^{+}
	DMR	1.768	20.013^{+}
	DHR	0.068	0.023
MAM	DER	-2.252	7.183
	DMR	-1.529	6.89
	DHR	-0.723	0.245
JJAS	DER	-23.714	-10.15
	DMR	-24.23*	-13.71
	DHR	0.516	3.433*
OND	DER	-28.345*	-16.615
	DMR	-28.417*	-16.588
	DHR	0.072	-0.192
ANNUAL	DER	-52.47*	0.454
	DMR	-52.408*	-3.395
	DHR	-0.067	3.477^{+}

The level of significance is marked by (*) for 95% and by (+) for 90% for the trends in DER, DMR & DHR events

TABLE 6

DER, DMR and DHR events Trend/decade for various seasons over Lakshadweep Islands

Season	Events	1951-2020	1971-2020
JF	DER	-1.75	3.474+
	DMR	-1.83	3.474+
	DHR	0.073	4.802
MAM	DER	-3.24	2.637
	DMR	-3.283	2.149
	DHR	0.034	0.488
JJAS	DER	4.9	-10.439
	DMR	5.132	-10.158
	DHR	-0.223	-0.365
OND	DER	8.65	17.032+
	DMR	8.566	16.577+
	DHR	0.089	0.455
ANNUAL	DER	8.558	12.704
	DMR	8.585	12.042
	DHR	-0.027	0.662

The level of significance is marked by (*) for 95% and by (+) for 90% for the trends in DER, DMR & DHR events

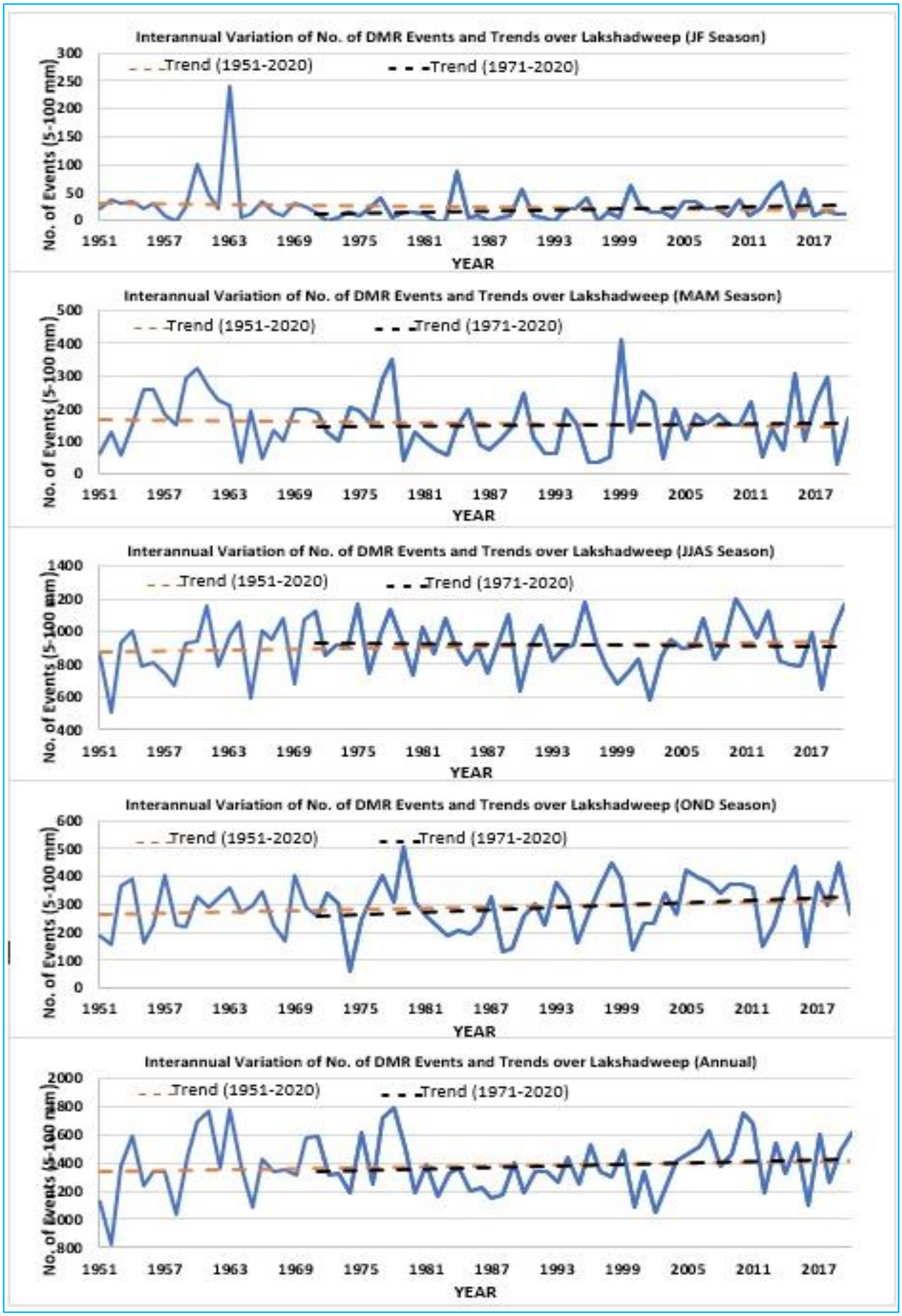


Fig. 11(a). Inter-annual variation of the number of DMR events and Trends for various seasons over Lakshadweep Islands

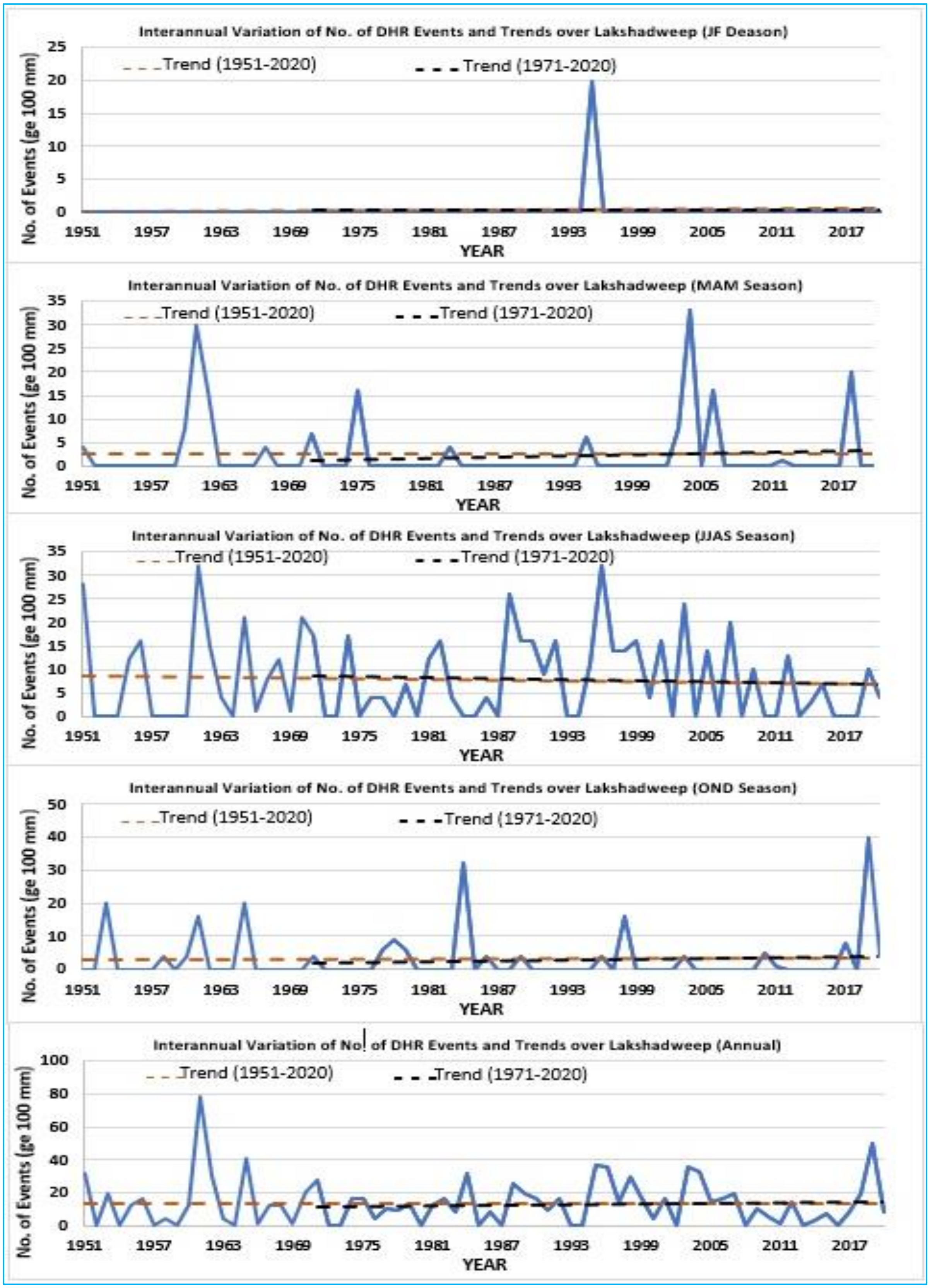


Fig. 11(b). Inter-annual variation of the number of DHR events and Trends for various seasons over Lakshadweep Islands can be seen that over Andaman & Nicobar Islands, on average 15-20 DMR events occurred between mid-May to mid-October. During mid-April to mid-May and Mid-October to mid-December, the range of average DMR events was between 5 and 15; during January to mid-April, they were less than 5. The mean DHR events were more than 1 during the few days of May & June, and for the other days, the mean HR events were less than 1. It can be seen from Fig. 9(b) that over Lakshadweep Islands, the mean DMR events ranged between 0-2 from January to April, increased progressively through May, ranging between 2-6, increasing steadily thereafter 6-12 during June and July. The mean DMR events showed a gradual decrease between 4-8 from August to October and between 0-4 in November and December. The mean HR events were seen to be less than 1 throughout the year.

About 98-99% of rainfall during seasonal and annual DER events over both these islands was observed to have been received in the form of DMR events.

The heaviest in 24 hours of grid-point rainfall of 374 mm was recorded on 31st December 1976 over Andaman & Nicobar Islands and over Lakshadweep of 297 mm on 15th October 1999.

The inter-annual variation of DMR and DHR events respectively over Andaman & Nicobar Islands respectively for the whole data period 1951-2020 and its sub-period 1971-2020 with trend lines fitted can be seen in Figs. 10(a&b) respectively. The DER events trend/ decade and also for its DMR & DHR categories over Andaman & Nicobar Islands for various seasons can be seen in Table 5. The level of significance is marked by (*) for 95% and (+) for 90%. Figs. 10(a&b) and Table 5 show that over Andaman & Nicobar Islands the significant (95%) negative trends for Annual, JJAS & OND seasons for the period 1951-2020 which were observed in the number of DMR events have become insignificant during the recent 50-year period 1971-2020. The insignificantly positive trend for DMR events during the JF season of the 1951-2020 period has become significant (90%) for the sub-period 1971-2020. The trend sign for DMR events for the MAM season has changed from insignificantly negative during 1951-2020 to insignificantly positive during 1971-2020.

The sign of trend for DHR events for the Annual and the MAM season over Andaman & Nicobar Islands has changed from insignificantly negative during 1951-2020 to significantly positive (90% significant) for the Annual and insignificantly positive for the MAM season during 1971-2020. The trends for DHR events for the JF season were observed to be insignificantly positive for both the 1951-2020 and 1971-2020 periods. For the JJAS season, the trends of DHR events were insignificantly positive for the 1951-2020 period but became 95% significantly positive for the recent 50-year period of 1971-2020. For the OND season, the sign of trend changed from positive during 1951-2020 to negative during 1971-2020, though statistically insignificant.

The inter-annual variation of DMR and DHR events respectively over Lakshadweep Islands respectively for the whole data period 1951-2020 and its sub-period 1971-2020 with trend lines fitted can be seen in Fig. 11(a) & Fig. 10(b) respectively. The DER events trend/decade and also for its DMR & DHR categories over Lakshadweep Islands for various seasons can be seen in Table 6. Levels of significance are marked by (*) for 95% and (+) for 90%. Figs. 11(a&b) and Table 6 show that insignificantly positive trends in the number of DMR events which were observed for Annual and OND seasons during the whole data period of 1951-2020 remained positive for Annual (insignificant) and OND (significant at 90%) during the sub-period 1971-2020. For the JF and MAM seasons, trends for DMR events which were insignificantly positive during 1951-2020 remained so during the MAM season of the period 1971-2020 but became significantly positive at 90% for the JF season of 1971-2020. The sign of trend for DMR events during 1951-2020 for the JJAS season changed from insignificantly positive during 1951-2020 to insignificantly negative during 1971-2020.

The DHR events over Lakshadweep Islands showed insignificant negative trends during 1951-2020 for the Annual and MAM seasons which became insignificantly positive for the sub-period 1971-2020. Insignificant negative (positive) trends for DHR events were observed for JJAS (OND) seasons during both periods and the JF season for both periods showed no trend in the number of DHR events.

4. Discussions

IMDs official gridded rainfall data sets (1° × 1° and 0.25° × 0.25°) do not include the grids over the two Island sub-divisions of India, the Andaman & Nicobar Islands and the Lakshadweep, mainly due to the unavailability of daily rainfall observations for a long period of over hundred years. However, from 1951 onwards, the daily rainfall data over these island sub-divisions are more or less consistently available for 9 stations over the Andaman & Nicobar Islands and 6 stations over Lakshadweep. Hence, in this study,

4.1. The gridded data sets in the two spatial resolutions of 1° × 1° and 0.25° × 0.25° have been developed for the two island subdivisions for the period 1951-2020.

4.2. The area-weighted rainfall computed using the data sets of these two resolutions over the Island subdivisions have been compared with the IMDs operational rainfall data series for all the months and seasons and it has been observed that:

(*i*) The rainfall data of both these spatial resolution data sets are comparable with their respective IMD operational rainfall series for all months and seasons over the two island sub-divisions.

(*ii*) Monthly and seasonal rainfall climatology computed using the 0.25° × 0.25° resolution data set for Andaman & Nicobar Islands was more comparable with IMD operational rainfall time series than the 1° × 1° resolution data set. When compared with IMD operational rainfall time series.

During the JF and OND seasons, the area-weighted rainfall computed using the 1° × 1° (0.25° × 0.25°) resolution data sets was overestimated by 12.8 mm and 46.1 mm (underestimated by 5.3 mm and 1.4 mm).

The annual area-weighted rainfall, as well as those of MAM and JJAS seasons, were underestimated; 18.1 mm for MAM, 128.9 mm for JJAS and 88.1 mm for Annual (5.8 mm for MAM, 38.0 mm for JJAS and 50.5 mm for Annual) using 1° × 1° (0.25° × 0.25°).

(*iii*) Monthly and seasonal rainfall climatology computed using the 0.25° × 0.25° resolution data set for Lakshadweep was more comparable with IMD operational rainfall time series than the 1° × 1° resolution data set. When compared with IMD operational rainfall time series.

The annual area-weighted rainfall computed using the 1° × 1° (0.25° × 0.25°) resolution data sets was overestimated by 26.9 mm (underestimated by 8.4 mm.

The area-weighted rainfall for the JJAS season was underestimated when computed using 1° × 1° (0.25° × 0.25°) resolution data sets, 45.1 mm (35.5 mm).

The area-weighted rainfall, for JF, MAM and JJAS seasons, was overestimated; 7.9 mm for JF, 34.1 mm for MAM and 30.0 mm for OND (4.9 mm for JF, 21.8 mm for MAM and 0.3 mm for OND) using 1° × 1° (0.25° × 0.25°).

(*iv*) The CC of the IMD operational data set with the 0.25° × 0.25° resolution data set was observed to be better than those with the 1° × 1° resolution data set.

4.3. The analyses of the daily mean of area-weighted rainfall over Andaman & Nicobar Islands using the 0.25° × 0.25° resolution data set revealed that:

(*i*) On average, the daily rainfall is about 4-6 mm/day till mid-January, thereafter decreasing to about less than 4 mm/day and remaining so till mid-May. A steady rise in the mean daily rainfall is between the second week of May to the first week of June, peaking at about 19 mm/day during the end of the first week of June. The mean daily rainfall is between 10-18 mm/day from mid-June to mid-October, thereafter becoming about 6-10 mm/day till mid-December and further decreasing to 2-4 mm/day till the end of the year.

(*ii*) An insignificant positive trend was observed in the JF season rainfall over the whole data period of 1951-2020. However, a positive linear trend of 17.32 mm/day/decade significant at a 95% level was observed during the period 1971-2020.

(*iii*) An insignificant negative trend was observed in the MAM as well as OND season rainfall over the whole data period as well as over 1971-2020.

(*iv*) The JJAS season as well as the annual area-weighted rainfall exhibited an insignificantly negative during the whole data period of 1951-2020. However, the sign of these linear trends changed to insignificantly positive during 1971-2020.

4.4. The analyses of the daily mean of area-weighted rainfall over Lakshadeep using the 0.25° × 0.25° resolution data set revealed that:

(*i*) On average the mean daily rainfall is less than 2 mm/day from the start of the year to the end of April. A steady increase in rainfall is observed from the first week of May to the first week of June, ranging between 2-15 mm/day, peaking at about 15 mm/day during the end of the first week of June. A little decrease in the mean daily rainfall (ranging between 7-14 mm/day) is from the second week of June to the end of July. From August to mid-November, there is a further decrease in the mean daily rainfall, ranging between 4-7 mm/day, thereafter becoming less than 4 mm/day till the end of the year.

(*ii*) The JF and MAM season area-weighted rainfall exhibited an insignificantly negative during the whole data period of 1951-2020. However, the sign of the linear trend changed to insignificantly positive during 1971-2020.

(*iii*) During the JJAS and the OND seasons, an insignificant positive trend was observed for the entire period of 1951-2020. However, the sign of linear trend changed from insignificantly positive during the whole data period of 1951-2020 to significantly negative (90%, at -35.7 mm/day/decade) during 1971-2020 for the JJAS season. For the OND season, the insignificant positive trend continued for 1971-2020 as well.

(*iv*) The sign of linear trend for the seasonal rainfall of OND season changed from insignificantly positive during the whole data period of 1951-2020 to insignificantly negative during 1971-2020.

4.5. No significant difference was observed between the rainfall means during the two periods 1951-2020 and 1971-2020 for all the seasons over the Andaman & Nicobar Islands as well as over Lakshadweep.

4.6. The area-weighted rainfall and DER of these two island sub-divisions showed strong CC for all the seasons during the data period of 1951-2020. The CC between the area-weighted rainfall and number of DER during the data period 1951-2020 for Andaman and Nicobar Islands for JS, MAM, JJAS, OND & Annual were respectively 0.96, 0.85, 0.82, 0.84 and those for Lakshadweep were respectively 0.83 & 0.91, 0.84, 0.85, 0.85 and 0.80.

4.7. During the recent 50-year period of 1971-2020, climate change can be attributed to significant changes that were observed in the trend for DMR and DHR events over both these major Indian archipelago subdivisions. The study of climatology and trends of daily extreme rainfall (DER) events over the Andaman & Nicobar Islands revealed that:

(*i*) On average 15-20 DMR events occurred between mid-May to mid-October. During mid-April to mid-May and Mid-October to mid-December, the range of average DMR events was between 5 and 15; during January to mid-April, they were less than 5. The mean DHR events were more than 1 during the few days of May & June; for the other days, the mean HR events were less than 1.

(*ii*) The significant (95%) negative trends for Annual, JJAS & OND seasons for the period 1951-2020 in the number of DMR events have become insignificant during the recent 50-year period 1971-2020.

(*iii*) The insignificantly positive trend for DMR events during the JF season of the 1951-2020 period has become significant (90%) for the sub-period 1971-2020.

(*iv*) The trend sign for DMR events for the MAM season has changed from insignificantly negative during 1951-2020 to insignificantly positive during 1971-2020.

(*v*) The sign of trend for DHR events for the Annual and the MAM season has changed from insignificantly negative during 1951-2020 to significantly positive (90% significant) for the Annual and insignificantly positive for the MAM season during 1971-2020.

(*vi*) The trends for DHR events for the JF season were insignificantly positive for both the 1951-2020 and 1971-2020 periods.

(*vii*) For the JJAS season, the trends of DHR events were insignificantly positive during 1951-2020 but became 95% significantly positive during 1971-2020.

(*viii*) For the OND season, the sign of trend changed from positive during 1951-2020 to negative during 1971-2020, though statistically insignificant.

4.8. The study of climatology and trends of daily extreme rainfall (DER) events over Lakshadweep revealed that:

(*i*) The insignificantly positive trends in the number of DMR events for the Annual and OND seasons during the whole data period of 1951-2020 remained positive for Annual (insignificant) and OND (significant at 90%) during the sub-period 1971-2020.

(*ii*) For the JF and MAM seasons, trends for DMR events which were insignificantly positive during 1951-2020 remained so during the MAM season of the period 1971-2020 but became significantly positive at 90% for the JF season of 1971-2020.

(*iii*) The sign of trend for DMR events during 1951-2020 for the JJAS season changed from insignificantly positive during 1951-2020 to insignificantly negative during 1971-2020.

(*iv*) The insignificant negative trends for DHR events during 1951-2020 for the Annual and MAM seasons which became insignificantly positive for the sub-period 1971-2020.

(*v*) Insignificant negative (positive) trends for DHR events were observed for JJAS (OND) seasons during both periods and the JF season for both periods showed no trend in the number of DHR events.

6. Conclusions

In this study, long-term trends of rainfall and daily extreme rainfall events over Andaman & Nicobar and Lakshadweep islands of India have been analysed and the daily gridded rainfall data set for the Indian islands for the period 1951 to 2020 in two spatial resolutions (1° × 1° and 0.25° × 0.25°) developed and used for these analyses has been discussed. A few statistical analyses of these gridded data sets for the two major Indian archipelagos have also been performed to demonstrate their use for various research purposes. The quality of the data for the two island subdivisions has been assessed by comparing it with the existing IMD official rainfall time series of these two independent island meteorological subdivisions. It is observed that the rainfall data of both these spatial resolution data sets are comparable with their respective IMD official rainfall series for all months and seasons. However, the 0.25° × 0.25° rainfall data over these islands are found to be closer to their respective IMD official rainfall time series and hence trend analysis has been carried out for daily extreme rainfall events for the Indian Islands in the climate change scenario for the periods 1951-2020 and 1971-2020 for all the seasons using this data set.

During the recent 50-year period of 1971-2020, climate change can be attributed to significant changes that were observed in the trend for DMR and DHR events over both these major Indian archipelago subdivisions. Over Andaman & Nicobar as well as Lakshadweep Islands the DMR and DHR events trends changed sign from insignificantly negative during 1951-2020 to insignificantly positive during 1971-2020 for the MAM season. The sign of trend for the Annual DHR events over Andaman & Nicobar Islands changed from insignificantly negative during 1951-2020 to significantly positive at 90% during 1971-2020. Over the Lakshadweep Islands, the sign of trend for Annual and OND HR events changed from insignificantly negative during 1951-2020 to insignificantly positive during 1971-2020.

The significance of this study is that it has made use of observations from island stations of the country and converted them into a gridded spatial resolution format. Since the rainfall reporting island stations are more or less very consistent on day to day basis, preparing real-time daily data over these two island regions has been possible. Hence this data can also be used for important operational services such as the onset of the Southwest monsoon over the Indian Islands and also for model verifications. Also while calculating the all-India rainfall time series for various time scales (1951 onwards), the rainfall over these two island subdivisions of the country can also be included, since these two major archipelagos are integral parts of the country.

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