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Determination of rainy season onset and cessation based on a flexible driest period

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Abstract

A fixed climatological year is generally used to determine rainy season onset and cessation. However, due to changes in climate, the fixed climatological year might not be the right basis for the onset and cessation dates estimation. This study proposes the usage of the driest period in the year to establish a flexible climatological year to determine rainy season onset and cessation dates. The driest period of a climatological year is defined as the period of 14 consecutive days, which has the lowest accumulated precipitation. The flexible climatological year begins on the first day of the driest period and ends before the driest period of next year. The onset and cessation dates resulting using this new flexible climatological year are compared against those resulting from the traditional approach. Three onset estimation methods were selected for demonstration of the method: agronomy, anomalous accumulation, and a modified local method. The results showed that overall, the three methods produced similar onsets for both types of climatological years. However, the use of a flexible year showed clear advantages in the application of anomalous accumulation for large and heterogeneous climatic zones because it helped to set a start date and an average daily precipitation, which improved the onset and cessation date calculations.

1 Introduction

Rainy season characteristics such as the date of onset, length of season, and total precipitation provide versatile data for agricultural and water management (Omotosho et al. 2000). In particular, the onset of the rainy season is an important basis for further investigation of seasonal characteristics, such as differences in precipitation during wet and dry seasons. However, the meaning of the term "rainy season" itself is subjective and highly dependent on the analysis method. Hence, estimating the start of a rainy season is a challenging task. For example, an agriculturist may define the onset of the rainy season by the day after which they can expect a continuity of wet days, indicating that water availability will meet crop water requirements (Ati et al. 2002). Meanwhile,

for the hydrologist, the onset of the rainy season is expected to be a starting condition that is followed by more intense precipitation, suggesting that the amount of precipitation is more profound than the number of wet days (Fasullo and Webster 2003). Finally, climatologists are more interested in changes in local or regional atmospheric circulation (Zhang et al. 2002; Latif and Syed 2016).

The length of a given season naturally exhibits spatial and temporal variation due to shifts in onset and cessation (Goswami and Xavier 2005; Fu et al. 2013; Misra and DiNapoli 2013; Marjuki et al. 2016). Additionally, Murray-Tortarolo et al. (2017) showed that the average global seasonal length has strong variation from year to year. Most studies, however, use the standard 12-month calendar year or 365 days, which ignores the variation in the length of rainy seasons (Seregina et al. 2019). Hence, it is very important to have a sound methodology for seasonal onset and cessation date determination that can take into account both seasonal and annual variations.

Determination of the onset of the rainy season can start at any time in the year. In response to these various definitions of the rainy season, a variety of methods has been developed to determine its onset date. Pierre and Mbaye (2003) classified methods for determining the onset date into two groups based on either rainfall only or on a combination of

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rainfall and atmospheric conditions such as humidity, wind, and temperature. Due to data availability, numerous studies have used rainfall-based indices (Cook and Buckley 2009; Ibrahim et al. 2012; Misra and DiNapoli 2013). Previous studies have also documented variation in the onset resulting from different methods and showed that the resulting onset dates differed significantly (Ati et al. 2002; Fitzpatrick et al. 2015; Marjuki et al. 2016). High variation in the onset will eventually cause discrepancies in interpreting seasonal characteristics, such as length of the rainy season, precipitation amount, and dry days.

Regardless of the climate characteristics, the driest period seems more appropriate for starting the time of onset determination as it can be connected to the following driest period to ensure that the wet period is completely included. Also, the occurrence of the driest period has the potential to be a good predictor for the onset of the rainy season. Previous studies have chosen a fixed driest month (Moron et al. 2009a, Debortoli et al. 2015) or the beginning of the year (Misra and DiNapoli 2013) as the start of the calculation. For example, Moron et al. (2009a) found that sea surface temperature in July, which is the driest month in their study area, is a good predictor for large scale rainy season onset. Due to strong spatio-temporal variation, the driest period is also expected to shift, hence it is important to use a method that allows the driest period to vary from year to year according to the actual occurrence of the driest time in the year.

Although previous studies have calculated the driest period for determining rainy season onset, they have still forced the ensuing seasons into a fixed climatological year. Given the stated variability of season length and the promise of seasons shifting in time due to climate change, we explore the use of a flexible climatological year. This study proposes to use the first day of the driest period as the starting date for the determination of the onset and cessation of the rainy season. The driest period is defined as the period of 14 consecutive days with the lowest accumulated precipitation. If there are multiple periods with a minimum accumulated precipitation, the first period is selected. This definition produces a flexible starting date and allows climatological years of varying length. Herein, the climatological year determined by the driest period is termed a "flexible year," while the climatological year based on a fixed driest month in the year is termed a "fixed year." We aim to compare the onset and cessation dates of the rainy season determined from three methods under both flexible and fixed climatological years. We also examine the relationship between the occurrences of the driest periods and the lengths of flexible years.

In order to achieve these goals, analyses on a large area with a strong heterogeneous precipitation type is required. The Indonesian Maritime Continent (IMC) was therefore selected as the study area. It is known as the largest archipelago on earth and has multiple precipitation regimes with strong influences from local and global phenomena, as described in Sect. 2. The data and methods, including the determination of the driest period, onset methods, and separation of spatial and temporal variance, are explained in Sect. 3. The results are presented in Sect. 4, followed by general discussion and conclusions in Sect. 5 and 6 respectively.

2 Study area

The IMC is comprised of more than fifteen thousand islands, including the five main islands of Sumatera, Java, Kalimantan (southern Borneo), Sulawesi, and Papua. This area spans nearly 2 million km^2, extending more than 5,000 km along the equator from 95 to142 E and more than 1,000 km in the north to south direction from 6 N to 11 S (Fig. 1).

As part of a huge maritime continent, Indonesia is also situated in the middle of the Indo-Pacific warm pool. Large amounts of atmospheric water, originating from the evaporation of warm ocean water, are transferred to the Indonesian region and result in the largest rainy area in the world (Qian 2008; Zhang et al. 2016). The huge amount of latent heat that is released to the atmosphere during the precipitation process and then transported to other regions has led to this region being called the natural broiler box for global atmospheric circulation (Simpson et al. 1993).

Precipitation in the IMC has very high spatial and temporal variance and is subject to local, regional, and global influences. Average annual rainfall ranges from 500 mm in the driest area, mostly located at the eastern edge, to more than 5000 mm in mountainous areas (As-syakur et al. 2016). Aldrian and Dwi Susanto (2003) classified the high spatial precipitation variation of the IMC into three dominant rainfall sub-regions; monsoonal, anti-monsoonal, and semi-annual (Fig. 1). The monsoonal type has one peak during the rainy season and covers most of the central part of the region from southern Sumatera, Java and all small islands to its western side, southern Kalimantan, and southern Sulawesi. The anti-monsoonal type has an opposite rainy and dry season compared to the monsoonal type. The semi-annual type, which mostly covers northern Sumatera, western and northern Kalimantan, has two peaks that occur between March and May and between October and November, of which the latter is usually stronger. The precipitation variability of the IMC increases during the rainy season. Even though there is no clear difference between the dry and rainy season for some parts of this region, most of the precipitation occurs during the rainy season.

The general climatic condition is characterized by rainy and dry seasons, as well as a relatively constant duration of sunshine throughout the year. This climate provides highly suitable conditions for crop development. Therefore, most of Indonesia's population is still very dependent on the
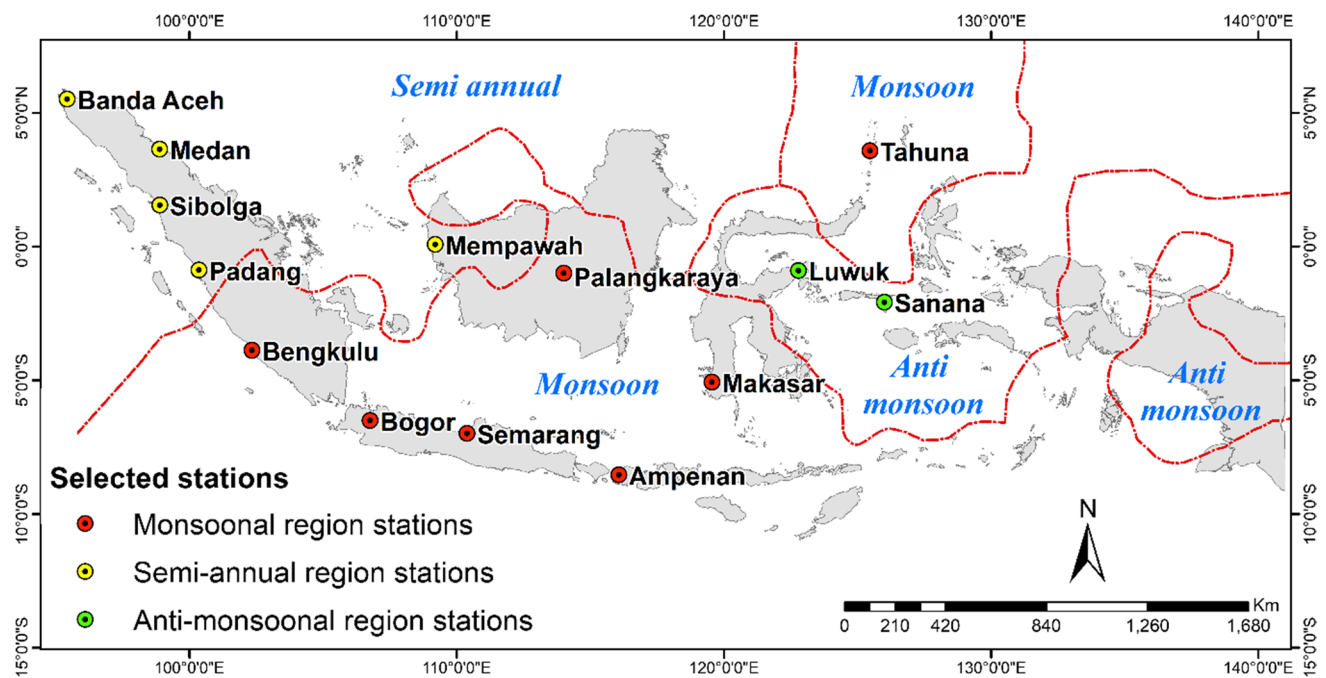
Fig. 1 Indonesian maritime continent (grey area) divided into 3 rainfall sub-regions: monsoon, anti-monsoon and semi-annual (Aldrian and Dwi Susanto 2003). Selected rainfall stations (dots) are distributed over those sub-regions and used for analysis in this study

agricultural sector. The main agricultural crop is rice, which is the staple food of most people. Rice production is spread throughout almost all parts of western and central Indonesia, especially in Java, Bali, Sumatera and Sulawesi. Apart from this ideal condition, the geographical condition poses great challenges to Indonesia's agriculture, especially in relation to high rainfall variability.

3 Data and methodology

3.1 Data selection and quality assurance

Daily rainfall recorded by meteorological stations for the Indonesian region was obtained from the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG). The stations were selected based on data availability and the spatial distribution over the three sub-regions, with at least one station for each sub-region. Ideally, 30 years (WMO recommendation) of data would have been used. However, this would have meant a too limited number of available stations with data. We also preferred to use high-quality ground-based data; hence, data such as the Global Summary of the Day (GSOD) would not be appropriate since there is too much missing data (Moron et al. 2010). After review of all available data in the IMC, a minimum of 20 complete years was selected to accommodate the long-term climate variation and also maintain the spatial distribution

of stations over all of the three sub-regions. Therefore, all selected stations had more than 20 complete years of daily precipitation data within the period 1980–2017. Data availability in the eastern part of the IMC was especially limited, and the number of minimum complete years was chosen to maximise data while maintaining spatial distribution.

BMKG daily precipitation data were quality checked by Supari et al. (2017). The main problem with the data was the inconsistencies in how the decimal separator was written and how no-precipitation days were demarcated. Further examination of the data during analysis in the present study also discovered inconsistencies in the demarcation of days with missing data and very low precipitation (< 0.1 mm), and all of the data were therefore checked for these issues, as well as for accidental repetition of data at the monthly or annual timescales. Therefore, no additional correction has been applied to the original data. We also adopted the Supari et al. (2017) complete year definition, as a year having less than 15 days of missing data and not more than three days of missing data in a month. The missing years were excluded from the analysis, while missing values in a complete year were replaced by the 10-year average of the values for the same day. The missing data in all complete years for selected stations was less than 0.03%, while the number of incomplete years varied between stations; missing years were mostly found in the beginning and end of the observation period, causing a variation in the start and end of the analysis period.

3.2 Methodology

3.2.1 Definition of the driest period and flexible climatological year

The driest period is defined as the period of 14 consecutive days with the lowest accumulated precipitation. In case there are multiple periods with the same minimum accumulated precipitation, the first 14 consecutive days is chosen as the driest period. We constrain the driest period to certain months based on regionalization, as suggested by Aldrian and Dwi Susanto (2003). Therefore, for the monsoonal and semi-annual regions, the driest period must occur between May and October, while for the anti-monsoonal region it must occur between August and January.

The onset and cessation dates of the rainy season were determined for each climatological year. The term climatological year represents the period between two driest periods, which is traditionally defined based on a calendric year starting from the driest month and has a fixed length of 12 months (Fig. 2a). Meanwhile, this study proposes a definition of the driest period, which is more flexible in terms of determining the climatological year (Fig. 2b). Hence, the climatological year represents a period between two driest periods. For example: the climatological year 2001 starts from the first day of the driest period of 2001 and ends on the last day before the driest period of 2002. Therefore, depending on the occurrence of driest period, each climatological year may have a different length. Meanwhile, considering that July to September are generally the driest months in this study area (Aldrian and Dwi Susanto 2003; Moron et al. 2009a), the traditional climatological year in

this region spans from the 1st of August to 31st of July of the following year.

3.2.2 Methods of estimation of the onset and cessation dates of the rainy season

Various methods have been developed to estimate the onset of the rainy season. A commonly used one is the precipitation-based Agronomy method. It is an adaptive method as its parameters are locally adjustable. The general definition of the onset day is the first day of a number of consecutive days receiving a certain amount of precipitation (wet spell) and not followed by a number of consecutive dry days receiving less than 5 mm within a given time span (Fig. 3b). Using this general definition, previous studies adopted 5 days for the wet spell (w-days), 40 mm of total precipitation during the wet spell (r) and 30 days for the time span (c), although various values have been used for the consecutive dry days (d-days) (Robertson et al. 2009; Moron et al. 2009b, 2009a). The cessation date is the last wet day followed by a period of d-days without precipitation. Here, we selected a combination of 3, 40, 30, and 10 for respectively the w-days, r, c, and d-days parameters that minimized the number of stations and years for which no onset date was found with our data. This combination of parameters was similar to the ones of Moron et al. (2009a), except that they used 5 days for w in order to accommodate the use of gridded pentad data.

The second onset estimation method used in this study was the Anomalous accumulation (Liebmann et al. 2007). This method was selected because of its flexibility in dealing with local characteristics without fixed thresholds or parameters. It is based on rainfall anomaly,
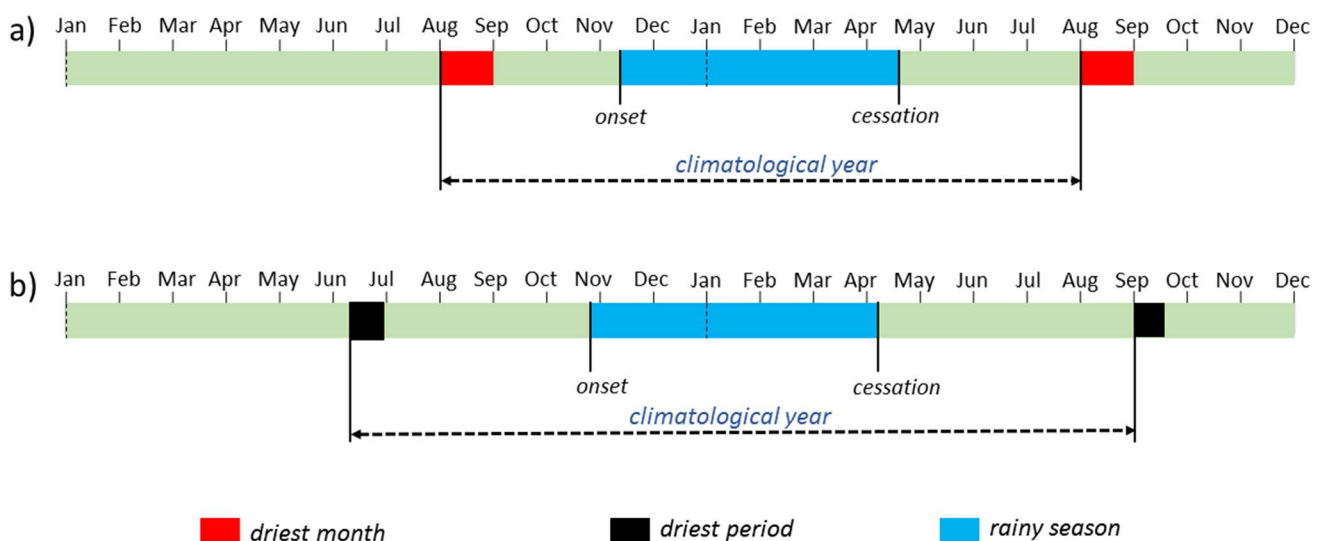

Fig. 2 (a) Example of traditional fixed climatological year based on the driest month (August); and (b) flexible climatological year based on the driest period in the year. Note that the flexible climatological year may be longer or shorter than 365 days.
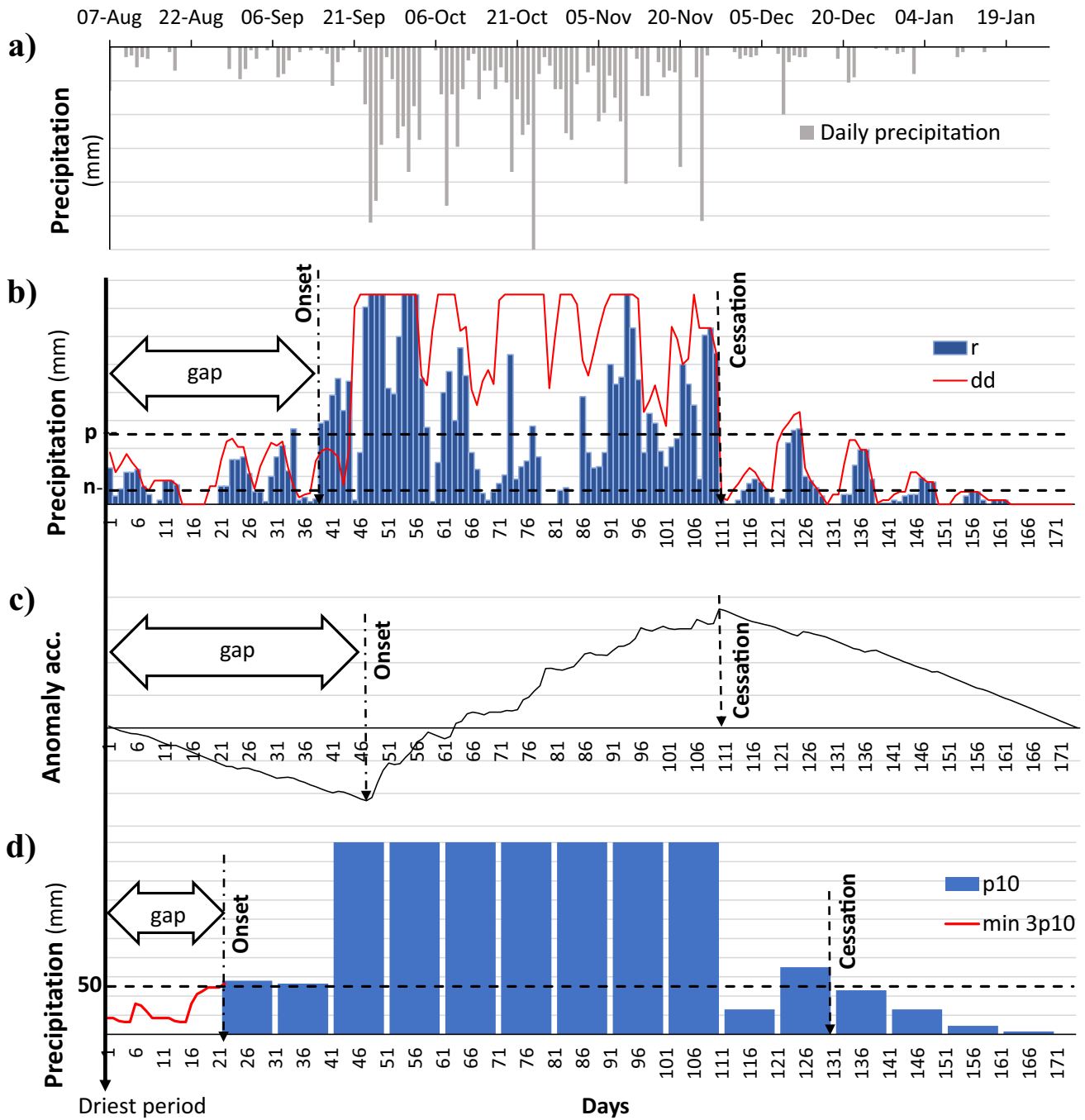
Fig. 3 Hypothetical examples of onset and cessation dates determination for (a) a daily precipitation time series using; (b) Agronomy; (c) Anomalous accumulation; and (d) modified BMKG methods. The methods used the driest period as the starting day of calculation. In the agronomy method, the onset occurrence depends on accumulated precipitation in 5 consecutive wet days (r) and threshold of precipitation (p) while the cessation depends on the number of consecutive dry days (dd) and threshold of dry days (d). The modified BMKG method calculates precipitation accumulation for three 10-day periods and shift to the next day until all those periods have accumulation (Min 3p10) ≥ 50 mm. From the onset, the accumulation is calculated every 10 days (p10) until the cessation date is found

$$A_t = \sum_{n=0}^{t} \left(R_n - \overline{R} \right) \tag{1}$$

where A_t is the cumulative precipitation anomaly from day 0 to t, R_n is the precipitation of day n and $\overline{R}$ is annual daily average precipitation. To ensure onset and cessation dates are found within each year, the $\overline{R}$ should be calculated for each year (Marjuki et al. 2016) instead of using a long-term annual mean daily average as suggested by Liebmann et al. (2007). Therefore, in this study we used two approaches to estimate $\overline{R}$. The $\overline{R}$ calculated over each climatological year ($\overline{R_i}$) was used for flexible climatological year and the $\overline{R}$ calculated over the whole period of observation ($\overline{R_a}$) was used for fixed climatological year. The rainy season onset and cessation dates correspond to the day after the beginning of the longest increase in anomaly accumulation and the day when the increase reaches a maximum (Fig. 3c). This method results in the estimation of one rainy season per year. Therefore, as the semi-annual regime has two rainy seasons, the method was modified to detect multiple rainy seasons (Ferijal et al. 2021). Only the first rainy season was selected for further analysis. The first rainy season generally peaks during October–November and has a higher peak than the second rainy season.

The third method is a local approach based on 10 days of precipitation accumulation, which is officially used by BMKG. This method sets the onset date as the first day of three consecutive 10-day periods after 1 September, each with a cumulative precipitation of ≥ 50 mm (Marjuki et al. 2016). When three consecutive 10-day rainfall accumulation periods drop below 50 mm, then the first day of the first period is assigned to be the cessation day. In this study, the minimum value of three consecutive 10-day precipitation accumulation periods was calculated for each day after the starting day until the onset was found. Next, precipitation accumulation was calculated for every 10-day period until the cessation date was found. Originally, this method used 1st of September as the starting date of calculation to avoid false onsets, because the rainy season historically occurs after that date. However, Hamada et al. (2002) have shown that delays in the onset of the rainy season correlated strongly with the La Nina. Hence, we modified the BMKG method by allowing the onset to occur at any time in the year and named it the modified BMKG method (Fig. 3d). The onset and cessation dates were calculated using the three methods explained above for both definitions of climatological year.

3.2.3 Separation of spatial and temporal variation

This study adopted a method proposed by Sun et al. (2010) to examine the contribution of spatial and temporal variation to the total variance in a dataset. The method is based on the ANOVA variance analysis. The time-first approach was selected, hence the grand variance $\left(\sigma_g^2 \right)$ is the sum of the spatial variance of temporal mean $(\sigma_s^2(\mu))$ and the mean temporal variance of all stations $(\overline{\sigma_t^2})$. Those variances are calculated as

$$\sigma_s^2(\mu) \equiv \sum_{j=1}^{m} \left(\mu_t(j) - \mu_g \right)^2 / (m-1) \tag{2}$$

$$\overline{\sigma_t^2} \equiv \sum_{j=1}^{n} \sigma_t^2(j) / n \tag{3}$$

where z is observations of n years, m stations, $\mu_t(j)$ is temporal mean for the jth station, μ_g is the grand mean and $\sigma_t^2(j)$ is temporal variance of the jth station:

$$\mu_t(j) = \sum_{i=1}^{n} z_{ij} / n \tag{4}$$

$$\mu_g = \sum_{i=1}^{m} \sum_{j=1}^{n} z_{ij} / (m \times n) \tag{5}$$

$$\sigma_t^2(j) \equiv \sum_{j=1}^{n} \left(z_{ij} - \mu_t(j) \right)^2 / (n-1) \tag{6}$$

4 Results

4.1 Selected stations

The selected stations have a wide spatial distribution (Fig. 1), covering the diverse precipitation types and altitudes (Table 1). We analysed data from five monsoonal and four semi-annual sub-regions, while only two stations in the anti-monsoonal region met data requirements. The annual precipitation across all stations varied from less than 1500 mm to more than 4500 mm, which represents well the variation in annual precipitation in this region.

4.2 The variances in the driest period and climatological year

The driest periods varied between stations (Table 2). Seventy-five percent of the occurrences were distributed over three consecutive months, but the highest frequency was generally found in June, August, and September for semi-annual, monsoonal, and anti-monsoonal stations, respectively. Ampenan was the only station that had no precipitation during the driest period in all years. Semi-annual stations generally had a low frequency of no precipitation during the driest period, indicating that the rain generally occurs throughout the year. The highest recorded total precipitation during the driest period was found in Padang. The maximum recorded precipitation during the driest period was strongly correlated with the average annual

**Table 1** Selected stations and their characteristics listed from west to east

Station	ID	Location	Precipitation sub-region	Start	End	Length (years)	El (m)	Average Annual Precipitation
Banda Aceh	96,011	5.52° N, 95.42° E	Semi annual	1982	2014	32	21	1,544
Medan	96,035	3.63° N, 98.87° E	Semi annual	1980	2016	36	25	2,369
Sibolga	96,073	1.55° N, 98.88° E	Semi annual	1980	2016	36	3	4,545
Padang	96,163	0.88° S, 100.35° E	Semi annual	1982	2016	34	3	4,235
Mempawah	96,583	0.07° N, 109.30° E	Semi annual	1988	2012	24	3	2,808
Bengkulu	96,253	3.88° N, 102.33° E	Monsoonal	1980	2012	32	16	3,341
Bogor	96,753	6.50° N, 106.75° E	Monsoonal	1980	2013	33	250	3,858
Semarang	96,839	6.98° S, 110.38° E	Monsoonal	1986	2016	30	3	2,281
Palangkaraya	96,655	2.22° S, 113.94° E	Monsoonal	1980	2016	36	27	2,920
Ampenan	97,240	8.53° S, 116.07° E	Monsoonal	1986	2016	30	3	1,734
Makasar	97,182	5.07° S, 119.55° E	Monsoonal	1983	2017	33	14	2,753
Tahuna	97,008	3.35° N, 125.28° E	Monsoonal	1986	2016	31	38	3,305
Luwuk	97,086	1.04° S, 122.77° E	Anti-monsoonal	1983	2011	28	17	1,243
Sanana	97,600	2.08° N, 126.00° E	Anti-monsoonal	1990	2013	23	2	1,400

Table 2 Frequencies of occurrence of the driest period each month from May to December for the selected stations, bold values indicate the highest percentage for each station

Station	May	Jun	Jul	Aug	Sep	Oct	Nov	P=0 mm (%)*	Max P**
Bandaaceh[1]	18.8	**43.8**	15.6	9.4	12.5			62.5	2.7
Medan[1]	19.4	**33.3**	30.6	8.3	8.3			25.0	38.1
Sibolga[1]	25.0	25.0	**33.3**	8.3	5.6	2.8		13.9	46.0
Padang[1]	**29.4**	26.5	17.6	11.8	14.7			35.3	89.2
Mempawah[1]	20.0	23.3	20.0	23.3	10.0	3.3		53.3	23.9
Bengkulu[2]	18.8	**31.3**	21.9	15.6	12.5			53.1	21.0
Bogor[2]	6.1	27.3	30.3	**36.4**				27.3	57.8
Semarang[2]	6.7	16.7	33.3	**40.0**		3.3		96.7	12.0
Palangkaraya[2]	2.8	16.7	27.8	**33.3**	16.7	2.8		63.9	38.3
Ampenan[2]	20.0	13.3	**36.7**	26.7	3.3			100.0	0.0
Makasar[2]	8.7	13.0	**39.1**	34.8	4.3			95.7	6.0
Tahuna[2]	20.0	6.7	16.7	**40.0**	10.0	6.7		46.7	32.0
Luwuk[3]				24.1	**51.7**	17.2	6.9	82.8	6.0
Sanana[3]				36.4	36.4	22.7	4.5	77.3	12.0

*Number of years in which precipitation accumulation during the driest period is zero. ** Maximum precipitation accumulation recorded during the driest period. The superscript of the station name indicates the station's location in semi-annual (1), monsoonal (2) or anti-monsoonal (3) region.

Fig. 4 The characteristics of the driest period based on the time of its occurrences for 14 stations in the Indonesian Maritime Continent. The boxes show length of flexible years, quartiles and max/min values. The dashed line shows the frequencies of occurrence of the flexible years with more than 365 days
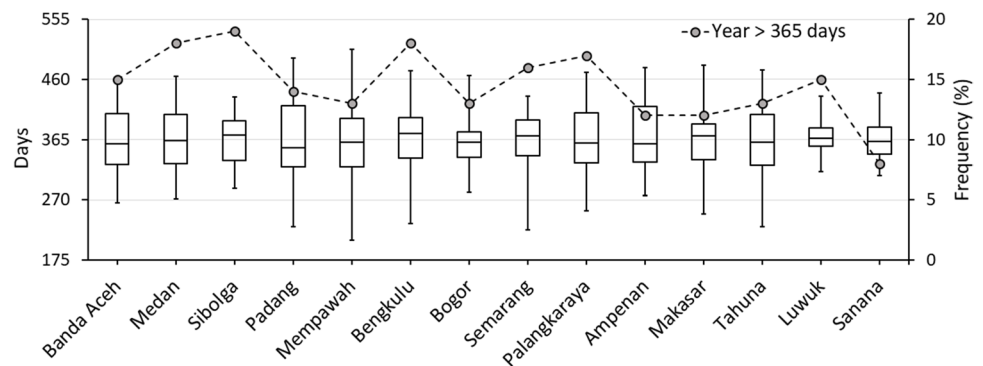
precipitation. Higher annual precipitation corresponded to higher maximum recorded precipitation during the driest period.

The average lengths of the flexible year varied from 362 to 368 days (Fig. 4). The interannual variations found within the stations were not statistically different from 365 days, although the standard error of the length ranges from 5.3 days at Luwuk to 12 days at Mempawah. The frequencies of the flexible year having a length longer than 365 days ranged from 41% in Sanana to 62.5% in Bengkulu. The relationship between the occurrence of driest period and length of the flexible year was assessed using simple linear regression. The results showed a negative correlation with a coefficient of determination (R^2) ranging from 0.38 in

Table 3 Linear relationship between the occurrence of first day of driest period (x) (Julian day) and length of its climatological year (Y) for the selected stations and the coefficient of determination of relationship (R^2), and the standard error of the regression

Station	Equation	R^2	Standard error of the regression
Bandaaceh[1]	Y = 367.7 − 0.50x	0.64	37.3
Medan[1]	Y = 366.5 − 0.50x	0.51	37.8
Sibolga[1]	Y = 401.0 − 0.60x	0.39	32.5
Padang[1]	Y = 366.7 − 0.50x	0.50	46.2
Mempawah[1]	Y = 376.0 − 0.50x	0.57	43.8
Bengkulu[2]	Y = 365.8 − 0.48x	0.43	44.1
Bogor[2]	Y = 380.1 − 0.50x	0.45	29.6
Semarang[2]	Y = 388.6 − 0.51x	0.49	32.7
Palangkaraya[2]	Y = 393.0 − 0.49x	0.56	33.7
Ampenan[2]	Y = 373.9 − 0.49x	0.62	35.5
Makasar[2]	Y = 398.9 − 0.54x	0.75	26.4
Tahuna[2]	Y = 390.7 − 0.50x	0.48	44.2
Luwuk[3]	Y = 442.0 − 0.50x	0.38	22.7
Sanana[3]	Y = 440.6 − 0.51x	0.39	31.1

The superscript of the station name indicates the station's location in semi-annual (1), monsoonal (2) or anti-monsoonal (3) region.

Luwuk to 0.75 in Makasar (Table 3). The standard error of estimated value from linear regression ranged from 22 days in Luwuk to 46 days in Padang.

4.3 Onset variations

Overall, the selected combination of w-days, r, and d-days parameters for the Agronomic method resulted in less than 5 years with no-onset across all stations. All of the no-onset years occurred in anti-monsoonal stations. All the methods yielded similar patterns of onset development. The onset progression started in northern Sumatera and moved southward in Sumatera and eastward to Kalimantan. After crossing to Java, the progression moved eastward along with similar movement in Kalimantan and Sulawesi.

Onset variabilities were clearly influenced by onset methods and precipitation characteristics (Fig. 5). Mean onset for the modified BMKG was found to be later than for the other onset methods for stations having an average annual precipitation less than 3000 mm. The Anomalous accumulation method generally yielded the least variability for most of the stations, meanwhile the highest variability was generally found for the modified BMKG method. The standard deviation for the Anomalous accumulation found in this study is slightly higher than observed by Marjuki et al. (2016) but has a similar spatial distribution. The highest variability in

Table 4 Temporal, spatial, and total variances of onset for the three methods

Method	Temporal variance		Spatial variance		Total variance
	Days	%	Days	%	
Agronomy	2279.8	38.3	3679.6	61.7	5959.4
Anomalous accumulation	1590.7	35.5	2893.5	64.5	4484.1
Modified BMKG	3202.9	38.7	5077.4	61.3	8280.3

Fig. 5 Onset of the rainy season for all selected stations based on Agronomic, Anomalous Accumulation and Modified BMKG method. The dashed line shows the annual average precipitation per station ordered from the lowest (left) to the highest (right)
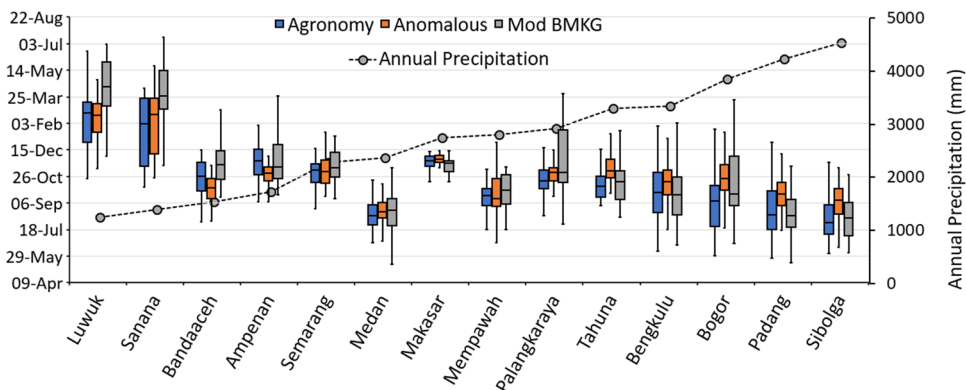
onsets was found for the two easternmost stations, Luwuk and Sanana, and the lowest was in Makasar.

The variance analysis (Table 4) showed that the total variance in the onset was the greatest for the modified BMKG and the lowest for Anomalous accumulation method. All methods showed a larger contribution of the spatial than of the temporal variance to the grand variance. The selected parameters used in this study caused the Agronomy and modified BMKG methods to fail in finding an onset for the rainy season for some years. The frequency of failure to find an onset were 1.2% for Agronomy and 3.5% for modified BMKG method for both flexible and fixed years. Meanwhile, the frequency of Anomalous accumulation failing to find onsets was 0.0% for the flexible and 0.9% for the fixed year.

4.4 Impact of selected climatological year on the onset and cessation date

Comparing the onset and cessation dates based on flexible and fixed years for Agronomy, Anomalous accumulation and modified BMKG methods showed that all methods generally produced the same onset and cessation dates. The frequencies of same onset and cessation dates varied between the methods but were mostly greater than 50% (Table 5). The modified BMKG method produced the largest number of stations having more than 85% of occurrence of the same onset and cessation date, while the least number of stations was produced by the Anomalous accumulation.

The driest periods were mostly found before August (66%) across the Monsoon and Semi-annual regimes, which range from 43% at Tahuna to 83% at Sibolga and Medan. When the driest period occurred before August (early driest period), the flexible year started earlier than the fixed year. Regardless of when the driest period occurs, same onset and

cessation date occurred more frequently than late or early onset/cessation date for all definitions (Table 6). However, the frequency of early and late onset/cessation dates was the highest for Anomalous accumulation (39.6%) followed by Agronomy (21.4%) and Anomalous accumulation (17.4%). The differences in Agronomy and modified BMKG onsets were mainly featured by early onsets in early driest period years, which accounted for more than 16% of onsets in Agronomy and 12% in modified BMKG. Meanwhile, the occurrences of early and late onsets of Anomalous accumulation were found in both early and late driest period year. There were modest differences between the climatological years for the onset (0–16.2%) and smaller differences for the cessation (0.5–9.8%).

Early and late driest period means the driest period occurs respectively before and after 1 August. Same/early/late onset or cessation indicates the method found the onset or cessation date within flexible year at the same date/earlier/later that the date found in fixed year.

The main differences between flexible and fixed years are the start and end dates of the climatological year. These variable start and end dates caused differences in lengths of the climatological year, total amount of precipitation, and average daily precipitation ($\overline{R}$). The calculation of $\overline{R}$ for flexible years ($\overline{R_i}$) was different from that for fixed years ($\overline{R_a}$). Since the variation in $\overline{R}$ has an impact only on the onset and cessation dates of Anomalous accumulation, we focussed on these. Overall, 47% of the years had an $\overline{R_i}$ greater than $\overline{R_a}$, and are called high $\overline{R}$ years. Conversely, the 53% of the years with an $\overline{R_i}$ lower than $\overline{R_a}$ are called low $\overline{R}$ years. In both low and high $\overline{R}$ years, the method produced relatively similar percentage of the years that have the same onset and cessation (Table 6). However, there were tendencies that during high $\overline{R}$ years, the late onsets and early cessations were more

Table 5 Frequencies of Agronomy, Anomalous accumulation and Modified BMKG methods producing the same onset or cessation dates of the rainy season for all selected stations

Stations	Agronomy		Anomalous		Modified BMKG	
	Onset	Cessation	Onset	Cessation	Onset	Cessation
Bandaaceh	100.0	100.0	68.8	68.8	90.6	90.6
Medan	58.3	94.4	63.9	69.4	58.3	91.7
Sibolga	36.1	72.2	44.4	75.0	44.4	91.7
Padang	55.9	85.3	70.6	73.5	61.8	94.1
Mempawah	80.0	93.3	66.7	80.0	83.3	100.0
Bengkulu	71.9	78.1	68.8	56.3	90.6	100.0
Bogor	66.7	72.7	48.5	54.5	75.8	84.8
Semarang	100.0	100.0	66.7	60.0	100.0	100.0
Palangkaraya	97.2	88.9	66.7	72.2	97.2	97.2
Selaparang	93.3	93.3	70.0	60.0	96.7	96.7
Makasar	100.0	100.0	52.2	65.2	100.0	100.0
Tahuna	73.3	83.3	46.7	50.0	90.0	86.7
Luwuk	86.2	86.2	51.7	44.8	62.1	62.1
Emalmo	81.8	81.8	27.3	45.5	77.3	77.3

Table 6 Frequencies of onset and cessation date on basis of a flexible year occurring earlier, later or at same date for all onset methods and related to the characteristic of the driest period and annual average daily precipitation

Methods	Variables		Onset			Cessation		
			Same	Early	Late	Same	Early	Late
Agronomy	Driest period	Early	41.6	16.2	0.9	52.4	5.1	1.2
		Late	34.2	0.2	4.2	33.7	1.6	3.2
		Total	97.2			97.2		
Anomalous accumulation	Driest period	Early	35.7	15.2	7.9	39.6	7.9	11.2
		Late	23.1	6.8	9.8	23.8	7.5	8.4
		Total	98.4			98.4		
Modified BMKG	Driest period	Early	45.7	12.2	2.4	57.2	2.6	0.5
		Late	35.2	0.0	2.9	35.6	0.5	1.9
		Total	98.3			98.3		
Anomalous accumulation	Avg. daily Precipitation	High	27.7	5.5	13.4	28.9	13.4	4.4
		Low	31.2	16.9	4.4	34.4	2.3	15.7
		Total	99.1			99.1		

frequent; conversely during low $\overline{R}$ years early onset and late cessation were dominant. Opposite patterns were detected for cessation dates; the early and late cessation dates were dominant in the high and low $\overline{R}$ years, respectively.

5 Discussion

We proposed a driest period-based approach to define the climatological year for the determination of the date of onset and cessation of the wet season. The climatological year traditionally has fixed starting and ending dates. It starts from the driest month and ends before the driest month of the following year (Ati et al. 2002; Liebmann et al. 2007). However, we defined the driest period as the occurrence of 14 consecutive days with the lowest cumulative precipitation. We applied this approach to one of world's most diverse climatic regions, the IMC, which generally has the lowest accumulated precipitation during July to September. Using this new approach, we found that the driest periods were distributed over 3 months and shifted between regimes. The spatial progress of the driest period between stations was very similar to the progress of the onset of the rainy season. Depending on the precipitation characteristics of the stations, the precipitation did not always cease completely, and therefore the precipitation accumulation during the driest period was sometimes significantly greater than zero. This mostly occurred at semi-annual stations and is explained by a precipitation pattern that has continued precipitation throughout the year (Aldrian and Dwi Susanto 2003; Moron et al. 2009a). Consequently, in such cases it is hard to define the driest period while it is happening. However, since the onset prediction is not the focus of this study, we left this challenging topic of developing a robust method for defining the driest period in real time for future study.

Because of high variation in the occurrences of the driest period, the average length of the flexible years varied across the region; but none were significantly different from 365 days. The minimum and maximum length of the flexible year were 206 and 508 days, respectively, and occurred in 2010 and 2011 at Mempawah. In 2011, the driest period occurred early (in May), which meant that 2010 was a very short climatological year and 2011 because very long. This pattern generally existed across all stations, resulting in a strong negative correlation between the first day of the driest period and the length of the flexible year. This suggests that earlier driest periods correlate with longer flexible years. Nevertheless, although the length of climatological year was not significantly different than 365 days, the variation in the start and end of the climatological year determine the range of periods when the rainy season occurs.

We applied three onset methods to find rainy season onset and cessation dates for the two types of climatological years, flexible and fixed years. The methods were Agronomy, Anomalous accumulation and a modification of the local IMC method, named modified BMKG. The first two methods have been widely used and applied in various regions, including IMC (Marjuki et al. 2016; Moron et al. 2009a, 2010; Robertson et al. 2009), Southern America (Liebmann and Marengo 2001, Debortoli et al. 2015), Northern America (Misra and DiNapoli 2013), Asia (Misra and DiNapoli 2014; Moron et al. 2009b) and Africa (Ati et al. 2002; Dunning et al. 2016; Segele and Lamb 2005). The Anomalous accumulation method produced the least variability across the region. This confirms the flexibility of this method and its ability to estimate the onset for a wide range of climatic regions, such as semi-annual, which have multiple peaks in annual precipitation and no clear difference between wet and dry season (Boyard-Micheau et al. 2013). Meanwhile, other methods have a greater total onset variation.

All methods generally produced the same onset and cessation dates for both flexible and fixed climatological years. However, differences in onset and cessation dates were also found between the two climatological years. Overall, the differences ranged from 19 to 41% for onset date and from 7 to 37% for cessation date. Most of these significant differences were found at stations located in the semi-annual and anti-monsoon regions. It implies that the selected parameter used for Agronomy and modified BMKG were unsuitable for those regions.

The onset dates seemed to be affected by the starting dates of the onset and cessation determination, particularly for the two accumulated precipitation-based methods, Agronomy and modified BMKG. This was due to the fact that Agronomy and modified BMKG are highly sensitive to the accumulation of precipitation (Ati et al. 2002; Boyard-Micheau et al. 2013). Agronomy and modified BMKG methods produced more frequent different onsets for both flexible and fixed years when the driest period occurred before August. The main source of the disparity between the onset of rainy season in those two climatological years was the rigid starting year, which is 1 August, for fixed climatological year and which has not allowed to take into account the possibility of an early rainy season starting before August. It was clear that when the driest period occurred after August, both methods generally produced the same onsets for both flexible and fixed climatological years. However, the onset

disparities were also found when the driest period occurred after August. In that case 9% of the Agronomy and 5% of Anomalous accumulation onsets in fixed years occurred before the driest period causing the premature end of the rainy season. The driest period occurrences have less impact on the end of the rainy season as nearly 85% of those years still had the rainy season ending at the same date.

The impact of a defined starting year was more pronounced in the onset of Anomalous accumulation. The results indicated that 26% of the Anomalous accumulation onsets in flexible years came earlier or later than those in fixed years depending on the occurrence of the driest period. The onsets in flexible years were earlier when the driest period occurred before August, and vice versa. Ideally, the anomaly curve should fall to the minimum point (onset) and then rise to the maximum (cessation). The declining part of the anomaly curve indicates the period with no precipitation or precipitation less than the average daily precipitation. On the other hand, the increasing part of the anomaly curve indicates the period during which precipitation having rates greater than daily average more frequently occurred. However, the curve is often not well established, especially for the IMC, where precipitation occurs almost all year long. The horizontal part of the anomaly curve indicates the precipitation rates were similar to the average of the daily precipitation. When this horizontal line occurs during the initial year, it indicates that the onset calculation started during the
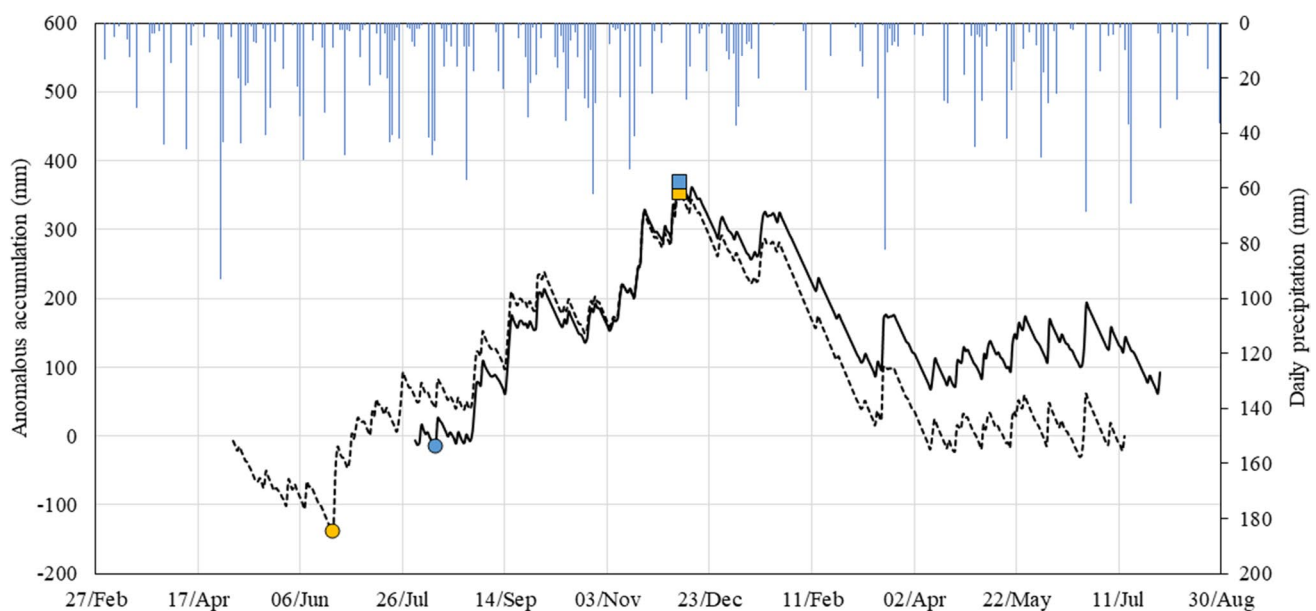

Fig. 6 The comparison of the Anomalous accumulation curves resulting from the fixed and flexible method for the Medan station in 1988. The fixed year curve (solid line) begins with a horizontal line and then increases, indicating that the calculation started in the middle of the rainy period. The flexible year curve (dashed line) begins with a declining line (a period when daily precipitation is zero or less than the daily average) and is followed by an increasing line (a period when daily precipitation is greater than the daily average). The onset in the flexible year (yellow circle) was earlier than the onset in the fixed year (blue circle), but their cessation dates (rectangle) were the same

rainy period, and onsets that occurred earlier were neglected (Fig. 6). The results suggested that the variation in starting date caused 7 and 4% differences in onset and cessation dates, respectively.

Boyard-Micheau et al. (2013) showed that variations in the average daily precipitation have shifted the onset dates of Anomalous accumulation by a few days. In this study, we found that approximately 35% of the onsets shifted due to variation in average daily precipitation. Additionally, we also found an impact of this variation on the cessation dates with nearly the same frequency as for the onset dates. The results, furthermore, suggested that the decreases and increases in average daily precipitation both impacted the onset dates,

with opposite relationships observed for onset and cessation dates. Traditionally, Anomalous accumulation uses a fixed mean daily precipitation for the whole period of observation. Consequently, the value is sometimes too high for dry years or too low for wet years, which eventually results in high variation in curve progression. To show how the variation in average daily precipitation shifted the cessation, we simulated the progression of the Anomalous accumulation curves for three different average daily precipitations, including a normal, a 10% increased and a 10% decreased average daily precipitation. The simulations were conducted using the adapted precipitations for two stations: Medan (1992) and Semarang (1997) (Fig. 7). The simulations found that the
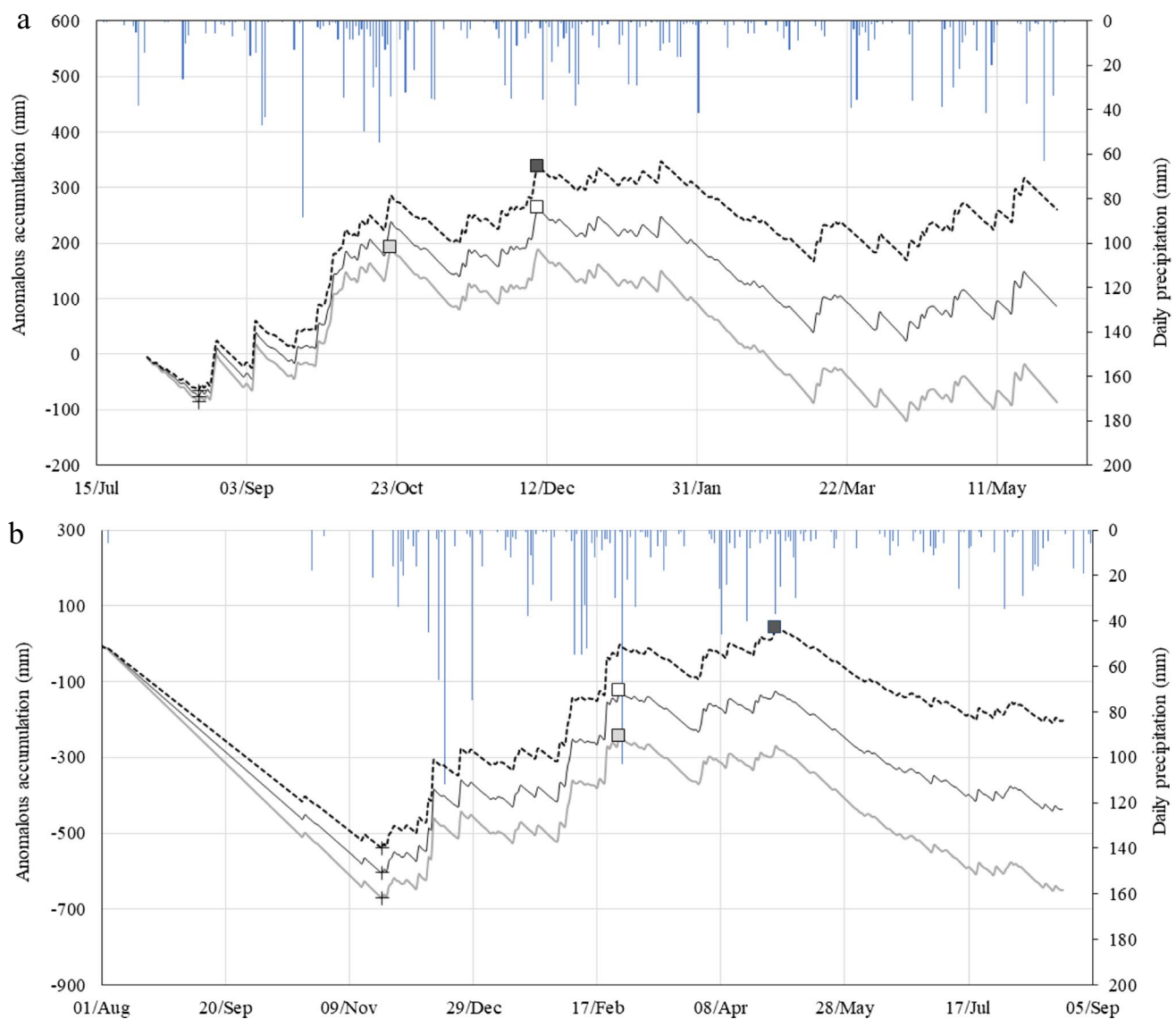
Fig. 7 The comparison of the progression of the anomalous accumulation curves resulting from different annual average daily precipitation at (a) Medan 1992 and (b) Semarang 1997. Anomalous accumulation curves resulting from normal (solid black), 10% increased (grey) and 10% decreased (dashed black) precipitation produced the same onset (plus signs) but different cessation dates (rectangles)

rainy season ended at different dates due to changes in average daily precipitation, although started at the same date.

6 Conclusion

Climate change may result in increased daily precipitation, decreased number of rainy days, and delays in the onset of the rainy season (Dunning et al. 2018). Hence, it is important to take into account all possible variables characterizing the climate, including the climatological year for rainy season onset and cessation date determination. Limited knowledge of the impact of climatological year selection on onset and cessation date determination was identified as a scientific gap. The goal of this research was to compare the onset and cessation dates of the rainy season determined by three methods under both flexible and fixed climatological years. The results showed that although the climatological years had no significant impact on two selected precipitation-based onset methods: Agronomy and modified BMKG, the flexible climatological year was able to prevent the presence of a dry period after the onset, which caused premature cessation of the rainy season. Anomalous accumulation is also sensitive to the start of the calculation and annual daily average precipitation, which have strong variations in large and heterogenous climate regions. The flexible year has been shown to be able to find the appropriate start and daily average to avoid false onset and cessation date determination.

Further research is needed to refine the flexible climatological year approach such that the driest period can be identified during the year in real time, especially in areas where rainfall occurs all year. The goal would be to find a correlation between the driest period and the onset of the rainy season, which would be a very useful approach for onset prediction. Although the flexible climatological year based on the driest period approach has so far only been tested and applied to the IMC, it potentially offers a promising approach for calculating rainy season onset and length in other tropical regions of the world. The use of this method may aid trend analysis for the calculation of climate change impacts by allowing the variation in onset and cessation date occurrences, especially for large and heterogeneous climate areas.

Declarations

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