Advancing the characterization of dry spells during the rainy season

By

Teuku Ferijal

Thesis
Submitted to Flinders University
for the degree of

Doctor of Philosophy

College of Science and Engineering
December 2020

Declaration

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Teuku Ferijal

Date: 15 July 2020

Co-authorship

Teuku Ferijal is the primary author of this thesis, and all the enclosed documents. Chapter 2 to 4 were written as an independent manuscript in which the co-authors provided intellectual supervision and editorial comments.

Acknowledgements

Foremost, I want to offer this Endeavor to our GOD almighty for the faith, health, and peace of my mind to complete this research.

My great gratefulness is to my principal supervisor, Professor Okke Batelaan, who provided me tremendous encouragement and guidance during my PhD at Flinders University. I highly appreciate his time, effort and wisdom in helping me to complete my degree. I would also like to thanks to my co-supervisor, Dr. Margaret Shanafield for her time, support, and advice.

I also wish to thank my friends Karina, Sarah, Ganda, Ajiao, Lanry, Angkit, and Somphasith. My gratitude also goes to the Government of Aceh, which provided me a full scholarship.

I am extremely grateful to my parents and my wife, Syarifah Ayu Raihan, for their endless love and support, and for the joy of my life: Teuku Rafie, Cut Aliya Rifahana, and Teuku Muhammad Raji.

Summary

Global climate change modifies the global hydrological cycle, including precipitation. The changes that occur in precipitation are mostly a decrease in frequency and an increase in intensity. This results in an increased frequency and duration of dry spells, which aggravates the drought or dryness severity. Drought is commonly estimated using an accumulated precipitation index. However, this approach fails to detect the drought progression at a finer time scale due to the presence of dry spells. With increasing temperatures, dry spells will become an important element of drought development because it escalates more water to evaporate. During the rainy season, an increasing frequency and duration of dry spells would cause severe impact on agriculture, especially regions that depend on rainy season precipitation. Because of high temporal variation in onset and cessation dates of the rainy season, existing drought indices are not appropriate tools for drought estimation during the rainy season. Meanwhile, although dry spell has been used to assess dryness conditions, no study has linked duration and frequency of dry spells to dryness severity. Therefore, this study aims to investigate the changes in dryness level during the rainy season using frequency and duration information of dry spells. The Indonesian Maritime Continent (IMC) was selected as a study area because it is the largest rainy area on the earth and has strong heterogeneous precipitation types.

The first part of this thesis deals with the determination of rainy season onset and cessation. It investigates the usage of the driest period as a starting point for determination of onset and cessation. The driest period is simply the longest period without precipitation or the 14 consecutive days having the least amount of cumulative precipitation in the year. The definition produces a flexible starting time approach, which is different from the commonly used regional fixed starting date that is based on the regional driest month in the year. The results reveal that the proposed method prevents the occurrence of premature cessation dates and keeps the cessation dates within the corresponding year. The gap between the first day of the driest period and the onset date has a significant linear relationship with the onset date at most stations over the region, particularly with the onset of anomalous accumulation.

The second part of the thesis offers a new approach of using dry spell frequency and duration to characterise the dryness severity during the rainy season. It analyses trends in meteorological drought severity during the rainy season. The dry spell index was proposed and compared with Standardised Precipitation Index (SPI). The Mann-Kendall trend test was used to investigate the occurrence of a trend within the indices. The results suggested that increasing drought is mostly found in the southern hemisphere region, which is most likely caused by the increase in dry spell parameters such as number of dry days, contribution of long dry spells, and duration of extreme dry spells. For the 1982 to 2014 period, the DSI identified 40% more stations with increasing drought trend than that SPI identified.

The last part aims to evaluate the spatial and temporal variability in dryness severity during the rainy season. DSI was integrated with an evaporation rate to evaluate the dryness severity. The analysis uses TRMM 3B42 V7 data for daily precipitation and GLEAMS remote sensing derived data for the daily evaporation rates. Resulting DSI trends were evaluated using the Mann-Kendall test with 90% confidence level. The results demonstrate significant increasing dryness in the southern part of IMC and a significant decrease in dryness near the equator. A similar pattern was also observed in total precipitation, which indicates that the precipitation frequency reduces, and intensity increases. The identified increasing dryness severity, especially in Java, has important consequences for agricultural activities and water resources management.

The overall results of this thesis suggest there is a general tendency, supported by the precipitation station and remote sensing-based data that the southern hemisphere regions are experiencing an increase in dryness in the rainy season. The frequency and intensity of precipitation have changed toward more extreme conditions resulting in more and longer dry spells. Future research should focus on defining the driest period in real time for improving rainy season onset prediction. It is also important to standardise the dryness severity resulting from DSI, in order to obtain an index that is globally applicable.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Research problem

1.1.1 Climate change and precipitation

Global climate change is now considered the primary threat to the world's ecosystems (Mishra and Singh 2010). Climate change is a consequence of a broad range of human activities related to food and energy (Karl and Trenberth, 2003). The activities mainly involve industrialization along with land cover modification, which have increased the concentration of greenhouse gases in the atmosphere. Energy trapped within the atmosphere causes changes in the global energy balance (Karl and Trenberth, 2003, Forster et al., 2007) and eventually affects the global weather conditions by modifying the hydrologic cycle. The alteration of global precipitation patterns is one aspect of climate change that requires urgent attention because it is a real signature of global climate change (Dore, 2005).

Precipitation information is very important to understand the global hydrologic balance and complex interactions between the components in the hydrologic cycle (Adler et al., 2003). Since precipitation variability affects atmospheric circulation by modifying the availability of energy for evaporation, the change in precipitation characteristics is associated with the change in climate. Hence, the impact of human activities on the natural environment can be observed as a result of the change in precipitation characteristics (Trenberth, 2011). However, high spatio-temporal variability in precipitation, complicates generalizations based on changes in precipitation, even for locations within in the same climatic zone.

Variability in precipitation results in variation not only in its amount or in frequency, but also dry and wet spell occurrences. A wet and dry day is defined as a day with a precipitation amount respectively more and less than a certain threshold value. Hence, a dry spell can be defined as a number of consecutive days without precipitation or insufficient precipitation, occurring between two wet days. Spell characteristics have been globally studied, as due to climate change prominent alteration is occurring of temporal precipitation distributions. Li et al. (2017) have reviewed various dry and wet spells studies. They conclude that most of the studies focused on the aspect of the spatio-temporal spell characteristics and on finding the most appropriate probability distribution function.

As most of the precipitation occurs during the rainy season, the presence of dry spells within the rainy season may have an important impact in socio-economic terms because most of the agricultural activities depend on rainy season precipitation. In relation to changes in precipitation characteristics when more extreme weather conditions occur, there is a potential of changes in dry spells during the rainy season. As predicted by climate models, climate change increases the number of dry days in almost all parts of the extratropical regions between 50ºN and 50ºS, with the most significant increase in the Amazon basin and Indonesia (Polade et al., 2014). Therefore, it is crucial to understand the characteristics of dry spells during the rainy season and its correlation to extreme precipitation events.

1.1.2 Seasonal dry spells

Dry spells (DS) studies have been conducted in many parts of the world. These studies provided sound information about the characteristics of spells in term of spatial variation, temporal trend and modeling (Li et al., 2017). Contribution of spells to total dry and wet days and amount of precipitation has been also considered in the spell studies (Mandapaka et al., 2016, Li et al., 2017). In the maritime region, Deni et al. (2009b) showed an increasing trend for short (1 to 3 days) dry spells during the rainy season. However, in contrast decreasing trends were found in other dry spell indices for most parts of the Malaysian Peninsula. Mandapaka et al. (2016) noted similar results, when comparing dry spells in Jakarta and Singapore. They found that for both cities, the contribution to total dry days mostly comes from the 1-day spells. These findings agree with the results from Ratan and Venugopal (2013), who concluded that most dry days are 1-day spells.

The presence of wet spells during the dry season seems to have less impact than dry spells in the rainy season. Broadly distributed precipitation during the rainy season provides better conditions for agriculture productivity and water resource management than heavy precipitation punctuated with long dry spells (Muhammad and Reason, 2004, Kebede et al., 2017, Byakatonda et al., 2018).

Seasonal information of dry spells can only be extracted when the start and end of the season is known or can be determined. The term of onset and cessation date is used to describe the start and end of a season. A common definition used to define onset and cessation date based on precipitation is the (A) number of days where precipitation no less than (B) mm and not followed by (C) consecutive days receiving less than (D) mm. Parameters A, B, C, and D highly depend on climatological characteristics. For example, Omotosho et al. (2000) used a combination of 5, 25, 2/3 weeks, 50% of local crop water requirement to define the onset date in West African Sahel. Still in the same region Dodd and Jolliffe (2001) applied 6, 25, 15, 5 for the parameters. In the MC region Robertson et al. (2009) used 5, 40, 15, 5 for a district in Java Island, Indonesia. Similarly, Moron et al. (2010) applied a similar combination for a larger area of Indonesia but instead of using 15, they selected 10 for C. Those previous studies show a variation in threshold and values that have been used for the definition of onset around the world.

1.1.3 Precipitation in Indonesian Maritime Continent

The Indonesian maritime continent (IMC) is the largest rainy area on earth and acts as a "broiler box" for the rest of the world where huge amounts of latent heat are released during the precipitation process (Qian, 2008, Zhang et al., 2016). Therefore, precipitation in the maritime continent plays an important role in the global energy circulation. In the IMC large orographic gradients influence the energy distribution and cause strong atmospheric circulation of global climatic impact (Ramage, 1968, Neale and Slingo, 2003). Because of its location, between two oceans and two continents, and physical characteristics of the region dominated by more than a thousand islands, the influence of large-scale climatic anomalies such as monsoon and El Niño–Southern Oscillation highly varies across the region (Aldrian and Dwi Susanto, 2003). A strong land-sea interaction across the region produces a very high variability in precipitation both temporally and spatially (Mori et al., 2004, Zhang et al., 2016). Several studies on the IMC have tried to understand local and regional precipitation variation as well as its relationship with global climate variation (Aldrian and Djamil, 2008, Qian et al., 2010, As-syakur et al., 2013, As-syakur et al., 2016, Yanto et al., 2016).

Analysis of precipitation time-series indicated that the IMC region is characterized by rainy and dry seasons (Zhang et al., 2016). The seasons are associated with southeast and northwest monsoons (As-syakur et al., 2013), driven by the development of the Inter-Tropical Convergence Zone (ITCZ). The wettest period, January and February, occurs when the ITCZ is in a southern-most position while the driest period, July to September, occurs when it is located north of the equator (Yanto et al., 2016). Aldrian and Djamil (2008) suggested that early this century, the seasonal balance changed from the last five decades to a condition in which the dry season tend to last longer than six months and increased extreme conditions in both dry spells and precipitation.

Temporal and spatial precipitation variability is extensively studied. Temporal precipitation variability has been investigated at diurnal (Mori et al., 2004, Qian, 2008), seasonal and interannual (Hamada et al., 2002, Chang et al., 2004, Aldrian and Djamil, 2008, Zhang et al., 2016), and even up to multidecadal scale (Yanto et al., 2016). The development of satellite-based observations has increased the number of studies focusing on spatial variation within the region. The focus has been on examining the variability from local up to regional precipitation. At the local scale, studies have been done mostly for Java Island including Jakarta (Mandapaka et al., 2016, Siswanto et al., 2016), Indramayu – West Java (Robertson et al., 2009), and Brantas Watershed – East Java (Aldrian and Djamil, 2008). Studies have also been conducted in almost all primary islands within the region, including Java (Qian, 2008), Sumatera (Mori et al., 2004), Kalimantan (Juneng and Tangang, 2010), Sulawesi dan Maluku (Lestari et al., 2016), Nusa Tenggara Barat (Kirono et al., 2016) and Peninsular Malaysia (Richard and Walsh, 2017), as well as regional studies (As-syakur et al., 2016, Marjuki et al., 2016, Zhang et al., 2016).

Seasonal dry spells have not been well characterized for the IMC region even though the precipitation in this region is highly seasonal. Aldrian and Djamil (2008) found that precipitation in East Java exhibits a strong seasonal pattern with a possibility of an increasing number of dry spells in the early period of the wet season. Although previous studies show that no significant trends were found in most dry spells' indices during the wet period (Deni et al. 2009, Mandapaka et al. 2016), there is a tendency of increasing short dry spell's frequency during the wet period (Deni et al. 2009). Recently, Supari et al. (2018) found a significant increasing trend in the maximum dry spell duration over the eastern and southern regions of Indonesia during the wettest period (December-February). Furthermore, no regional study has focussed on the dry spells during the rainy season, hence seasonal dry spell information is crucial for the IMC region.

1.2 Research aims

Besides deficiencies in the amount of precipitation, meteorological drought can be generated by more dry spells (Huang et al., 2015). For the same amount of precipitation, more dry spells would potentially produce higher risk of e.g. agricultural drought. Moreover, the characteristics of dry spells such as length and frequency also play an important role in developing drought conditions. Although previous studies have used multiple dry spell indicators for drought assessment (Serra et al., 2013, Huang et al., 2015, Wilby et al., 2016, Pérez-Sánchez and Senent-Aparicio, 2017), none of those have developed a link between dry spell characteristic and drought severity. This will become a very important aspect in drought studies because the primary driving factor of drought development will change from deficiency in precipitation to increase in atmospheric demand as a result of rising temperatures in the future (Dai and Zhao, 2017). The amount of water loss to atmosphere by evaporation will increase, therefore it is important to integrate evaporation in drought indices.

The main objective of this research is therefore to investigate the changes in dryness level of the rainy season using the frequency and duration of dry spells. The Indonesian Maritime Continent was selected as a study area because it is the largest rainy area on the earth and has strong heterogeneous precipitation types. The objective will be achieved by the following goals:

1. Propose an approach for determining the onset and cessation of rainy season over the IMC region. The approach should be able to handle a very strong spatial and temporal variation in precipitation over the region.

2. Develop an index for wet season dryness with respect to the variables most affecting the drought severity during the rainy season, including duration and frequencies of dry spells, and length of rainy season.

3. Evaluate the spatial and temporal changes in the dryness of the rainy season based on integration of satellite data for both precipitation and actual evaporation.

4. Test with the Mann-Kendall (MK) trend test the possibility of changes in the rainy season dryness as well as all other forcing variables, such as the length, total precipitation, number of dry days, and number of dry spells during the wet season.

1.3 Contribution of this PhD

This PhD explores rainy season characteristics including the onset and cessation and the dryness. This study introduces a new approach for defining a flexible corresponding year for onset and cessation dates determination of rainy seasons. The start and end dates of a corresponding year are defined based on the driest period, which is the longest occurrence of at least 14 consecutive days with the lowest precipitation in the year. This approach allows high variation in the onset and cessation dates due to changes in climate and prevents too early or too late cessation dates of the rainy season.

This study also offers a novel approach to estimating the dryness during the rainy season by making use of the dry spell information. The benefit of using this approach is that the dry spell information can be easily extracted from daily precipitation data, which is now considered to be globally available and accessible. In general, the dryness or wetness is estimated from accumulated precipitation over a certain period of time (monthly, 3 or 6 months, or annually). Some studies argue that accumulated precipitation fails to detect drought development over finer scales (Anagnostopoulou et al., 2003, Cindrić et al., 2010, She and Xia, 2013, Huang et al., 2015). In particular, under climate change the characteristics of precipitation will change towards more intense but less frequent precipitation. This means that we may have the same monthly precipitation, but the proportion of number wet days decrease, meaning an increase in the proportion of dry days. A new index to estimate the dryness during the rainy season, called dry spell index (DSI), was introduced. The index has advantages, including its ability to record all dry spell durations and their frequency, to characterize dryness severity for flexible periods, and to integrate with evaporation rate. In comparison with the most widely used drought index, the standardised precipitation index (SPI), we found that the temporal variability in DSI is significantly different from SPI, suggesting that DSI is not a repetition or other form of SPI. Applying the method in the Indonesian Maritime Continent (IMC), we found contradictory results in which SPI suggested a strong tendency toward a wetter condition during the rainy season over the whole region while DSI showed that some regions have tendencies toward a drier condition.

Chapter 2

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

2.1 Abstract

The definition of the rainy season can be subjective and inconsistent, causing difficulties for both water management and long-term climate analysis. This study proposes the usage of the driest period in the year to determine a flexible corresponding year for the rainy season onset/cessation date calculation. The driest period of a corresponding year is defined as the longest period of at least 14 consecutive days with the lowest accumulated precipitation. The corresponding year begins on the first day of the driest period and ends before the driest period of next year (flexible year). The onset/cessation dates resulting from this approach are compared with the results of a calendar based corresponding year. Three onset definitions were selected including agronomy, anomalous accumulation and a modified local method. The gaps between the first day of the driest period and the onsets were analysed for their correlation with the onset and cessation dates. The results showed that in general, all selected definitions produced similar onsets for both types of corresponding years. The gaps were linearly correlated with the anomalous accumulation onsets for most stations. The use of a flexible year showed clear advantages as it prevented common pitfalls in determining the rainy season, including premature cessation dates and those occurring outside of the corresponding year.

2.2 Introduction

Rainy season characteristics, such as onset date, 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 hydrologists, 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 circulation (Zhang et al., 2002, Latif and Syed, 2016).

Various methods have been developed to define the onset date of the rainy season. Pierre and Mbaye (2003) classified methods for determining the onset date into two groups based on either rainfall only or on a combination of 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, 2014). Previous studies have also documented the onset variation resulting from various methods and showed that the onsets had very significant differences (Ati et al., 2002, Fitzpatrick et al., 2015, Marjuki et al., 2016). High variation in the onsets will eventually cause discrepancies in interpreting seasonal characteristics, such as length, precipitation amount, and dry days.

Seasonal lengths naturally exhibit a significant spatial and temporal variation due to shifts in the onset/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 although there is no trend in the average global seasonal length for the last 60 years, it exhibits a strong variation every 10-15 years. This variation in length of both rainy and dry season results in a changing total climatological length of each year. Most studies, however, use the standard 12-month calendar year or 365 days, which ignores the temporal variances of rainy seasons (Seregina et al., 2019). Hence, it is very important to have a sound methodology for seasonal onset/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. Previous studies have chosen a fixed driest month (Moron et al., 2009b, S. Debortoli et al., 2015) or the beginning of the year (Misra and DiNapoli, 2013) as the start of the calculation. Regardless the climate characteristic, 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 rainy season onset. For example, Moron et al. (2009b) found that July sea surface temperature, 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.

This study proposes to use the start of the driest period as the beginning for the determination of the onset/cessation of the rainy season. The driest period is defined as the longest occurrence of at least 14 consecutive days with the lowest cumulative precipitation. This definition produces a flexible starting date, which differs from a regional fixed starting date based on the regionally occurring driest month of the year. We aim to compare the onset and cessation dates of the rainy season determined from three methods, which use the flexible and regional fixed starting dates. We also examine if the onsets can be predicted using simple linear regression between the driest period and the onsets.

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 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 phenomenon, as described in Section 2. The data and methods, including the determination of the driest period, onset definitions, and separation of spatial and temporal variance, are explained in Section 3. The results are presented in Section 4, followed by general discussion and conclusions in Section 5.

2.3 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, and covers nearly 2 million square kilometres. This area spans 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 (Figure 2.1).

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 IMC has a 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 region into three dominant rainfall zones: semi-annual, monsoon and anti-monsoon. The monsoon 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-monsoon type has an opposite rainy and dry season compared to the monsoon type. The semi-annual type, which covers mostly northern Sumatera, western and northern Kalimantan, has two peaks around March to May and October to November, of which the latter is usually stronger. The precipitation variability of the IMC increases during the rainy season. Even though for some parts of this region no clear difference between the dry and rainy season exists, most of the precipitation occurs during the rainy season.

The general climatic condition is characterized by rainy and dry seasons and relatively constant sunshine duration throughout the year, which provides highly suitable conditions for crop development. Therefore, most of Indonesia's population is still very dependent on the 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, Sumatra and Sulawesi. Apart from this ideal condition, the geographical condition poses great challenges to Indonesia's agriculture, especially in relation to high rainfall variability.

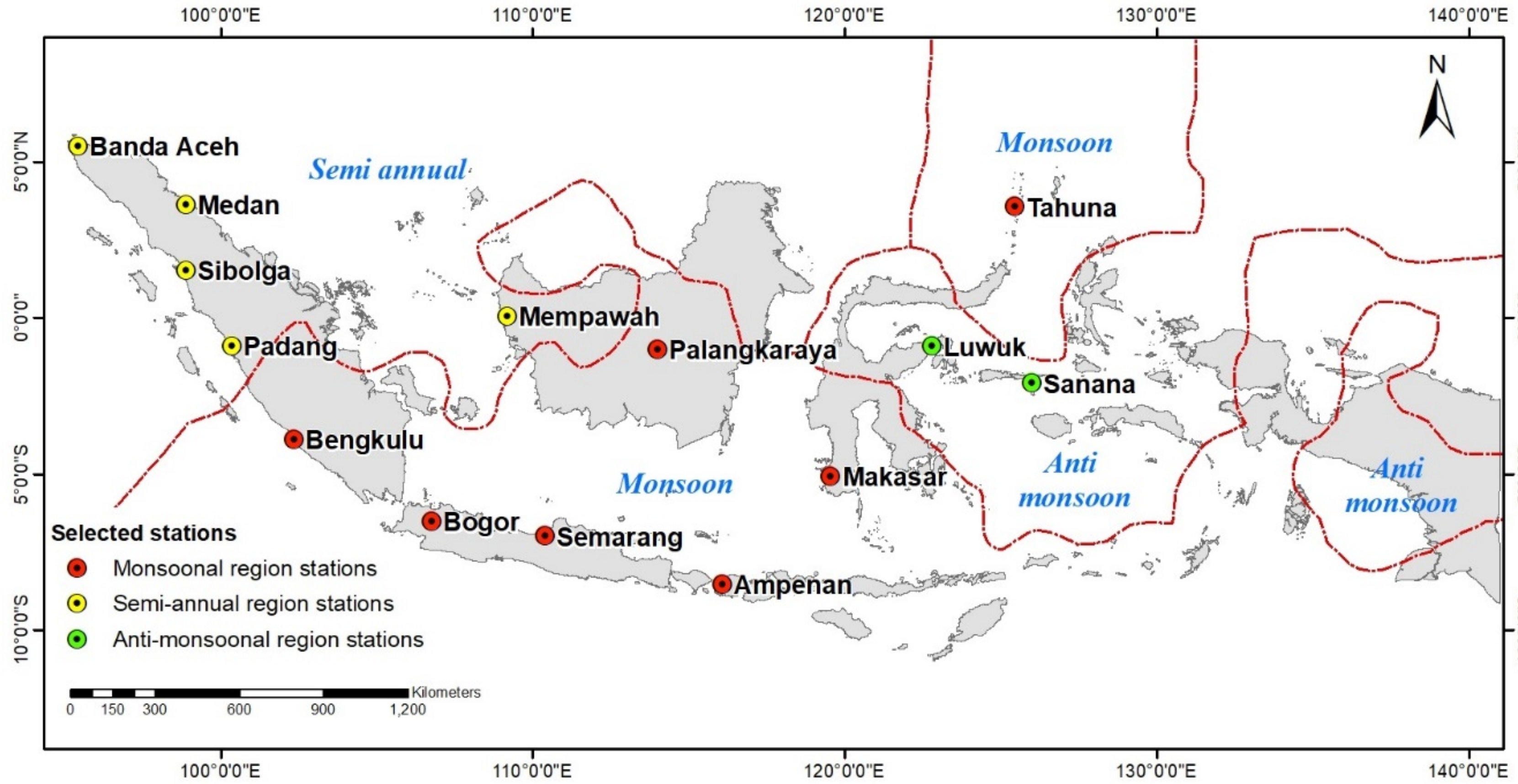


Figure 2.1 Indonesian maritime continent (grey area) divided into 3 rainfall sub-regions: monsoon, anti-monsoon and semi-annual (Aldrian and Dwi Susanto 2003). Selected rainfall stations (dots) are distributed over those sub-regions and used for analysis in this study.

2.4 Data and methodology

2.4.1 Data

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. The stations should have daily precipitation data recorded for more than 20 complete years within the period 1980 till 2017. We adopted the complete year definition from Supari et al. (2017), who defined it as a year having less than 15 days of missing data and no more than three days missing data in a month.

2.4.2 Methodology

2.4.2.1. Definition of flexible driest period and corresponding year

The driest period is defined as the longest occurrence of at least 14 consecutive days with the lowest cumulative precipitation in the year. If two or more equal long periods with the same cumulative precipitation are found, then the driest period is the first occurring period. We constrain the driest period to certain months based on regionalization, as suggested by Aldrian and Dwi Susanto (2003). Therefore, for the monsoon and semi-annual regimes, the driest period must occur between May till October, while for the anti-monsoon regime it must occur between August and January.

The onset and cessation dates of the rainy season were determined for each corresponding year. The term of corresponding 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 (Figure 2.2a). Meanwhile, this study proposes a definition of the driest period, which is more flexible in terms of determining the corresponding year (Fig. 2.2b). Hence, the corresponding year represents a period between two driest periods, for example: the corresponding year of 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 periods, each corresponding year may have a different length. Meanwhile, considering that August and September are the driest months in this study (Aldrian and Dwi Susanto, 2003, Moron et al., 2009b), the traditional corresponding year in this region spans from the 1st of

August to 31st of July of the following year. We applied these two corresponding years, named flexible and calendar years, in determining the onset and cessation dates of the rainy season.

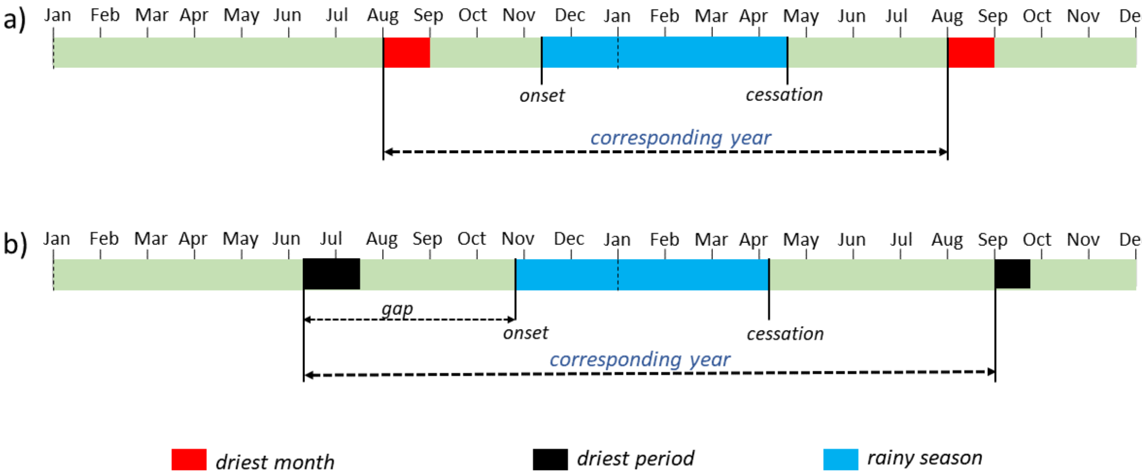


Figure 2.2 (a) Example of traditional corresponding year based on the driest month (August) as used in Indonesia; and (b) flexible corresponding year based on the driest period in the year. "Gap" refers to the number of days between the first day of driest period and the onset day. Note that the driest period may be 14 days or longer, while the flexible corresponding year may be longer or shorter than 365 days.

2.4.2.2. Definition of the onset and cessation dates of the rainy season

Various definitions have been developed to define the onset of the rainy season. A commonly used precipitation-based definition is the Agronomy definition. It is an adaptive method as its parameters are locally adjustable. The general definition of the onset day is the first day of a wet spell receiving a certain amount of precipitation and not followed by a number of consecutive dry days receiving less than 5 mm within a given time span (Figure 2.3b). 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) but slightly different number of days have been used for the consecutive dry days (d-days) (Aldrian and Dwi Susanto, 2003, Moron et al., 2009a, Moron et al., 2009b, Robertson et al., 2009). 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. This combination of parameters was similar to the ones of Moron et al. (2009b), except that they used 5 days for w in order to accommodate the use of gridded pentad data.

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

$$A_t = \sum_{n=0}^{t} (R_n - \bar{R}) \tag{2.1}$$

Where A_t is the cumulative precipitation anomaly from day 0 to t, R_n is the precipitation of day n and $\bar{R}$ is annual daily average precipitation. To ensure onset and cessation dates are found within each year, the $\bar{R}$ 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 calculated $\bar{R}$ for each corresponding 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 (Figure 2.3c). This definition produces a single rainy season period. For the semi-annual regime that has two rainy seasons, we only used the first rainy season for further analysis. The method for diagnosing multiple wet season onset/cessation dates was adopted from the method proposed by Dunning et al. (2016) with a modification to address high precipitation variability as described in the following steps and graphically displayed in Figure 2.4:

1. Determining several periods that have intense precipitation based on the minimum and maximum points in curve of a 30-day running average of anomaly accumulation. Similar to the previous method, the minimum and maximum points are the points that have respectively a lower and higher value than the four previous and four subsequent days. A period starts from the minimum and ends at the following maximum point.

2. Combining the periods of intense precipitation that meet following criteria: the gap between the maximum point of first period and the minimum point of second period is less than 5 days, and the maximum point of second period is greater than the minimum point of the first period.

3. Defining the start and end dates of multiple period of intense precipitation by determining respectively the minimum and maximum value of daily precipitation anomaly accumulation corresponding to respectively the start and end of multiple periods previously defined. Any period that has a starting date in the following year will be eliminated.

4. Selecting onset and cessation dates of the rainy season by combining multiple respectively start and end dates that form a continuously increased anomalous accumulation.

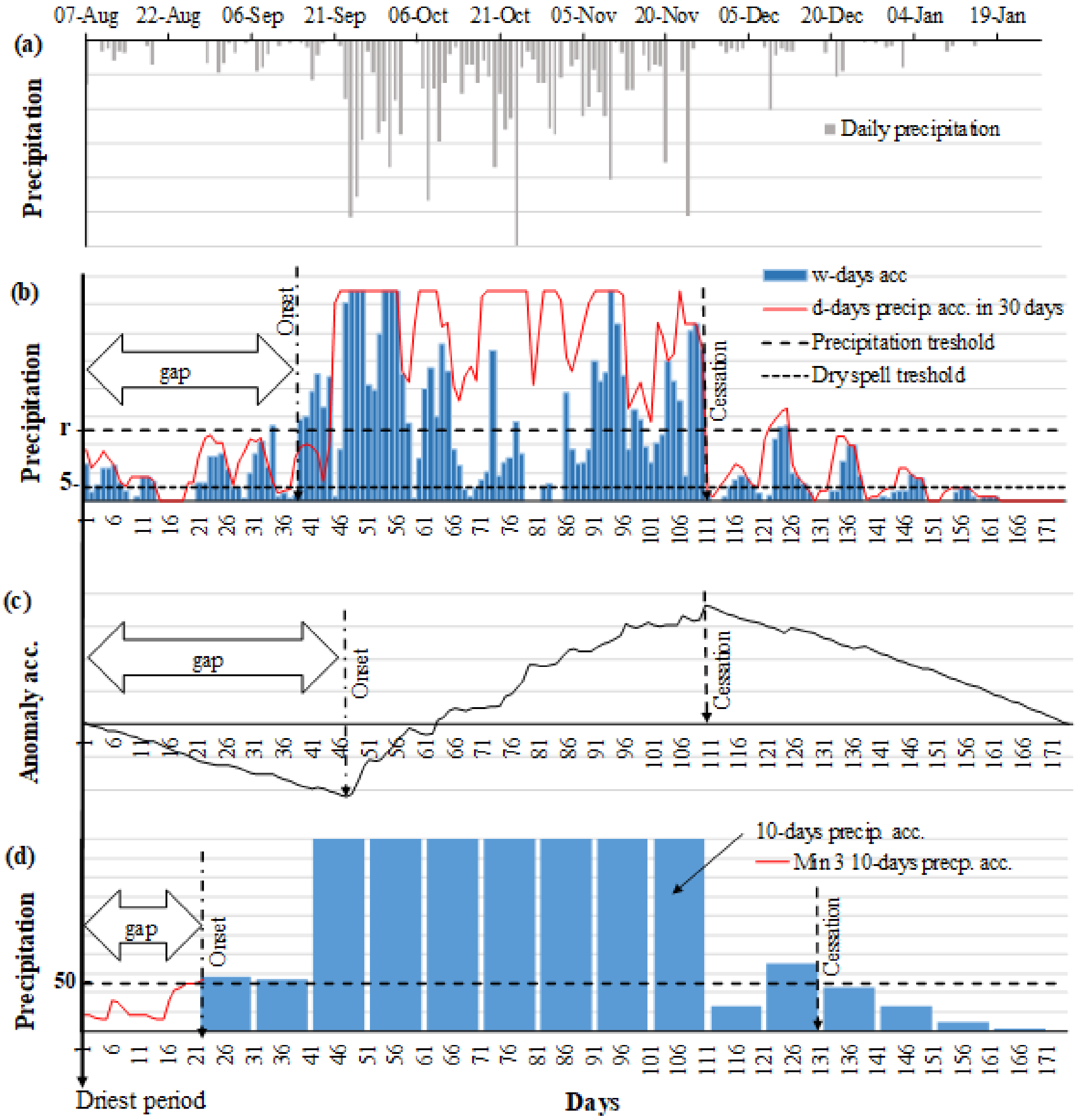


Figure 2.3 Hypothetical examples of onset and cessation dates determination for (A) a daily precipitation time series; (B) using Agronomy; (C) Anomalous Accumulation; and (D) modified BMKG definitions. The definitions used the driest period as starting day of calculation hence they have a gap until the onset. Methods D calculates precipitation accumulation for three 10-day periods and shift to the next day until all those periods have accumulation ≥ 50mm. From the onset, the accumulation is calculated every 10 days until the cessation date is found.

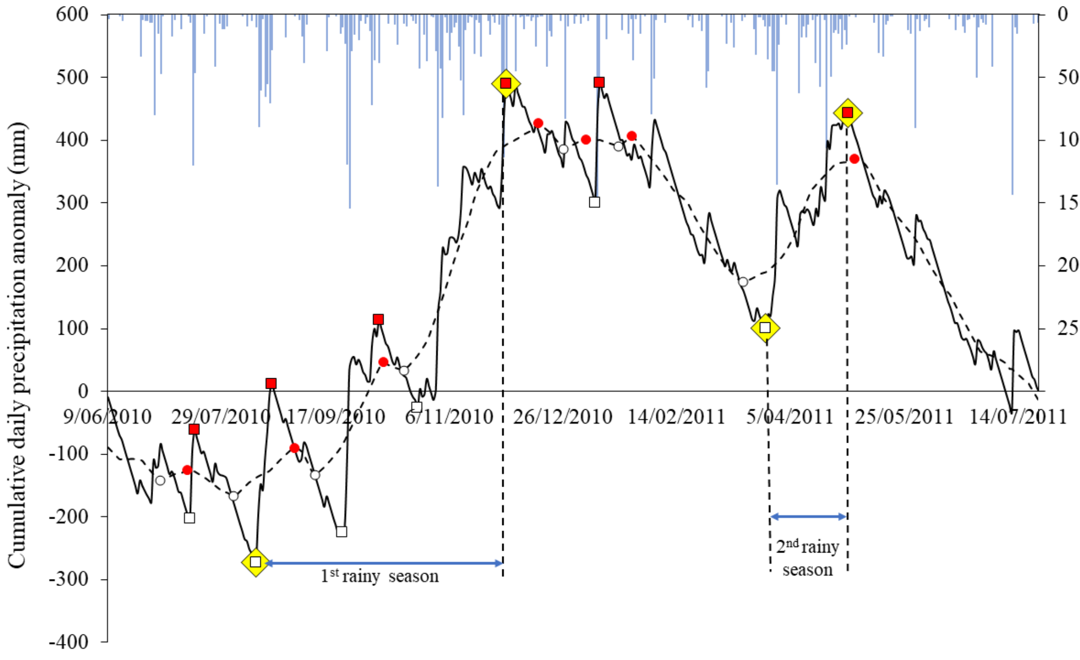


Figure 2.4 Modified anomalous accumulation method for determination of onset and cessation dates of two rainy seasons. Black line is anomalous accumulation, orange line is a 30-days running average of anomalous accumulation. Green and red dots represent the start and end of intense precipitation period. Blue and green squares are the points in anomalous accumulation curve that correspond to the black and red points in the 30-days running average curve. Yellow rimmed green and red squares are the selected start/end days of rainy season and the blue arrow line is the length of the rainy season.

The third method is a local method officially used by BMKG that is based on 10 days of precipitation accumulation. This method defines 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. After the onset, precipitation accumulation was calculated for every 10-day period until the cessation date. Originally, this method uses 1st of September as the starting date of calculation to avoid false onset, 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 had strong correlation with the La Nina.

Hence, we modified the BMKG definition by allowing the onset to occur at any time in the year and named it the modified BMKG method (mB) (Figure 2.3d).

The onset is calculated using all of the methods explained above for both definitions of corresponding year. The gap, which is defined as the number of days between the first day of driest period and the onset day (Figure 2.2b), was calculated only for the flexible year for all onset definitions.

2.4.2.3. Separation of spatial and temporal variation

Both temporal and spatial variability contributed to the timing of the onset date. Understanding those contributions could provide valuable information on assessing the performance of onset definitions based on their temporal and spatial variances. This study adopted a method proposed by Fubao et al. (2010) to examine the contribution of spatial and temporal variation to the total variance over the region. The method is based on the ANOVA variance analysis method. In this study 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

$$\sigma_s^2(\mu) \equiv \sum_{j=1}^{m}\left(\mu_t(j) - \mu_g\right)^2 / (m-1) \tag{2.2}$$

$$\overline{\sigma_t^2} \equiv \sum_{j=1}^{n} \sigma_t^2\,(j)/n \tag{2.3}$$

where z are 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:

$$\mu_t(j) = \sum_{i=1}^{n} z_{ij}/n \tag{2.4}$$

$$\mu_g = \sum_{i=1}^{m} \sum_{j=1}^{n} z_{ij}\,/(m \times n) \tag{2.5}$$

$$\sigma_t^2(j) \equiv \sum_{j=1}^{n}\left(z_{ij} - \mu_t(j)\right)^2 / (n-1) \tag{2.6}$$

2.4.2.4. Driest period and rainy season onset relationship

A simple approach to assess the predictability of rainy season characteristics is regression analysis on the predictors and predictands (Moron et al., 2010). The higher correlation exists, the higher predictability of predictands. Predictability of the onset date was evaluated by analysing its linear relationship to the number of days that separate the first day of the driest period and the onset day (gap). The significances of all correlations were tested against the one-sided 95% of confidence level.

2.5 Results

2.5.1 Selected stations

The selected stations have good spatial distribution (Figure 2.1), covering the diverse precipitation types and altitudes (Table 2.1), although only two of the stations in the anti-monsoon regime met data requirements. The number of stations for monsoon, and semi-annual regimes are five, and four, respectively. 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.

Table 2.1 Selected stations and their characteristics listed from west to east

Station	ID	Location	Start	End	Length (years)	Elevation (m)	Average Annual Precipitation
Banda Aceh[1]	96011	5.52° N, 95.42° E	1982	2014	32	21	1,544
Medan[1]	96035	3.63° N, 98.87° E	1980	2016	36	25	2,369
Sibolga[1]	96073	1.55° N, 98.88° E	1980	2016	36	3	4,545
Padang[1]	96163	0.88° S, 100.35° E	1982	2016	34	3	4,235
Mempawah[1]	96583	0.07° N, 109.30° E	1988	2012	24	3	2,808
Bengkulu[2]	96253	3.88° N, 102.33° E	1980	2012	32	16	3,341
Bogor[2]	96753	6.50° N, 106.75° E	1980	2013	33	250	3,858
Semarang[2]	96839	6.98° S, 110.38° E	1986	2016	30	3	2,281
Palangkaraya[2]	96655	2.22° S, 113.94° E	1980	2016	36	27	2,920
Ampenan[2]	97240	8.53° S, 116.07° E	1986	2016	30	3	1,734
Makasar[2]	97182	5.07° S, 119.55° E	1983	2017	33	14	2,753
Tahuna[2]	97008	3.35° N, 125.28° E	1986	2016	31	38	3,305
Luwuk[3]	97086	1.04° S, 122.77° E	1983	2011	28	17	1,243
Sanana[3]	97600	2.08° N, 126.00° E	1990	2013	23	2	1,400

Number codes indicate the station located in semi-annual (1), monsoonal (2) or anti-monsoonal (3) region.

2.5.2 The variances in the driest period and corresponding year

The driest periods show great variation in occurrence from one station to another (Table 2.2). 75% of the occurrences are distributed over three consecutive months but the highest frequency was generally found in June, August and September for respectively semi-annual, monsoon and anti-monsoon stations. Ampenan was the only station that has no precipitation during the driest period in all years. Semi-annual stations generally have a low frequency of no precipitation during the driest period indicating that the rain generally occurs throughout the year. Of all stations the highest of the recorded total precipitation during the driest period was found in Padang. The total precipitation during the driest period seems to be strong positively correlated with the average annual precipitation (Table 2.2).

Table 2.2 Frequencies of occurrence of the driest period each month from May to December, bold values indicate the highest percentage for each station.

Station	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**P=0mm (%)***	**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. Number codes indicate the station located in semi-annual (1), monsoon (2) or anti-monsoon (3) regime.

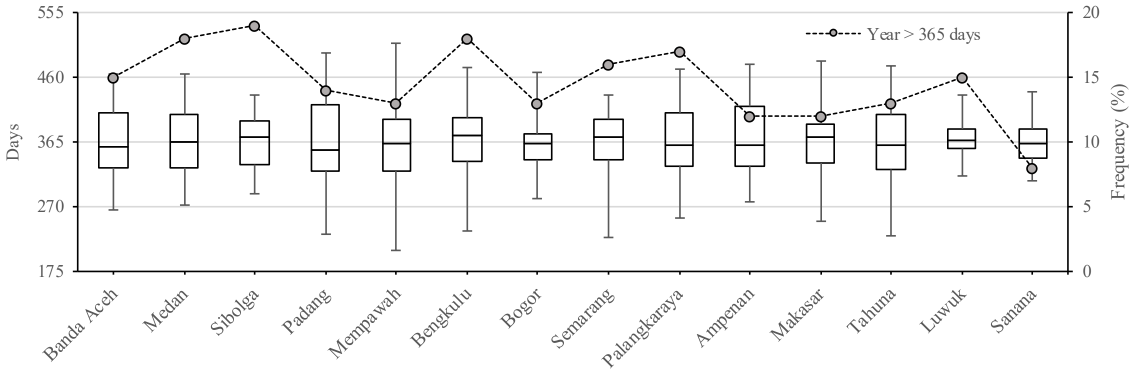


Figure 2.5 The characteristic of the driest period based on the time of its occurrences. The boxes show length of reference years quartiles and max/min values. The solid/dashed line shows the frequencies of occurrence of the corresponding years with more than 365 days.

The average lengths of the flexible year varied between 362 days and 368 days (Figure 2.5). 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. These lengths also have a strong correlation with the occurrences of the driest period. Using simple linear regression, the coefficient of determination (R^2) ranged from 0.38 in Luwuk to 0.75 in Makasar (Table 2.3). The equations show that the lengths of the flexible years were negatively correlated with the occurrences of the driest period at all stations.

Table 2.3 Linear relationship between the occurrence of first day of driest period (Julian day) and length of its corresponding year for the selected stations, coefficient of determination of relationship (R^2), and the standard deviation of average daily precipitation of flexible year over the average of daily precipitation of calendar year

Station	**Equation**	**R^2**	**Daily average standard deviation**
Bandaaceh[1]	Y = 599.4 – 1.27x	**0.64**	0.76
Medan[1]	Y = 551.7– 1.01x	**0.51**	1.20
Sibolga[1]	Y = 481.6 – 0.65x	**0.39**	1.99
Padang[1]	Y = 546.9 – 0.99x	**0.50**	1.68
Mempawah[1]	Y = 587.1 – 1.15x	**0.57**	1.04
Bengkulu[2]	Y = 538.1 – 0.90x	**0.43**	1.53
Bogor[2]	Y = 537.4 – 0.89x	**0.45**	1.26
Semarang[2]	Y = 563.4 – 0.97x	**0.49**	1.46
Palangkaraya[2]	Y = 608.7 – 1.14x	**0.57**	1.44
Ampenan[2]	Y = 606.2 – 1.24x	**0.62**	1.00
Makasar[2]	Y = 643.9 – 1.38x	**0.75**	3.04
Tahuna[2]	Y = 564.5 – 0.96x	**0.48**	1.85
Luwuk[3]	Y = 563.7 – 0.77x	**0.38**	0.84
Sanana[3]	Y = 561.8 – 0.77x	**0.39**	1.73

Number codes indicate the station located in semi-annual (1), monsoon (2) or anti-monsoon (3) regime.

2.5.3 Onset variations

The selected combination of w-days, r and d-days for the Agronomic definition parameters gave less than 5 years with no-onset out of all years with data across all stations. All of the no-onset years occurred in anti-monsoon stations. All the definitions gave similar patterns of onset development. The onset progression starts in northern Sumatera and moves southward in Sumatera and eastward to Kalimantan. After crossing to Java, the progression moves eastward along with similar movement in Kalimantan and Sulawesi.

Onset variabilities are clearly influenced by onset definitions and precipitation characteristics (Figure 2.5). The mean onsets resulting from Modified BMKG and Anomalous accumulation was the latest at stations having a precipitation of respectively less and more than 3000 mm/year. The Anomalous accumulation definition generally yielded the least variability for most of the stations, meanwhile the highest variability was mostly found for the Modified BMKG definition. The standard deviation for the Anomalous accumulation found in this study is slightly higher than by Marjuki et al. (2016) but has a similar spatial distribution. The highest variability in onsets was found in the two easternmost stations, Luwuk and Sanana, and the lowest was in Makasar.

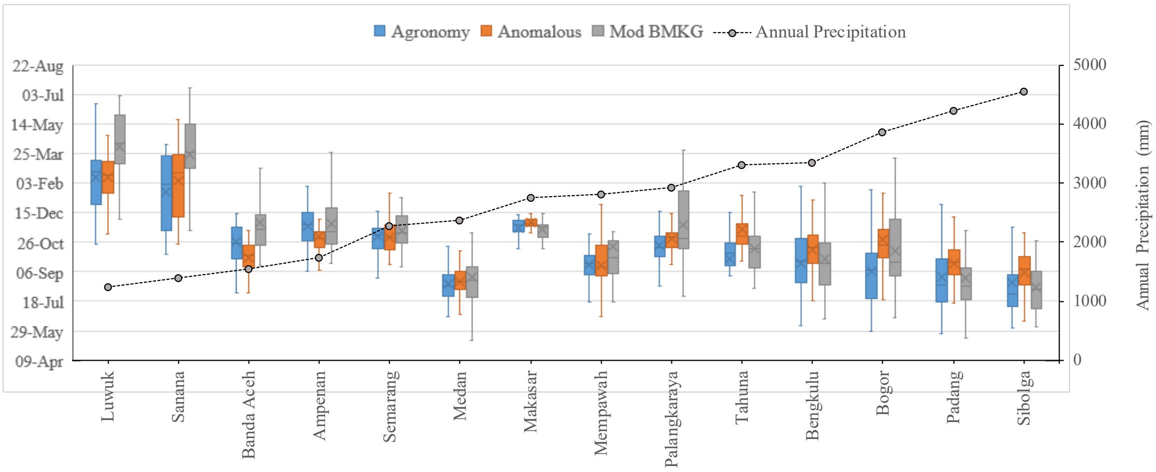


Figure 2.6 Onset of the rainy season for all selected stations based on Agronomic, Anomalous Accumulation and Modified BMKG definition. The dashed line shows the average of annual precipitation with stations ordered from the lowest (left) to the highest

The variance analysis (Table 2.4) showed that the total variance was the greatest when using Modified BMKG and the lowest for Anomalous accumulation. All definitions showed a larger contribution of the spatial than of the temporal variance to the grand variance. This confirms that huge precipitation variations exist among the locations within this region, so the parameters used in local definitions such as Agronomy and Modified BMKG must be adjusted according to the local characteristics.

Table 2.4 Total, spatial and temporal variances of onset for the three definitions

Definition	**Temporal component**		**Spatial component**		**Total variance**
	days	**%**	**days**	**%**	
Agronomy (Ag)	2279.8	38.3	3679.6	61.7	5959.4
Anomalous accumulation (Aa)	1590.7	35.5	2893.5	64.5	4484.1
Modified BMKG (mB)	3202.9	38.7	5077.4	61.3	8280.3

2.5.4 Impact of selected corresponding period on the onset and cessation date

Comparing the mean of onset and cessation dates based on flexible and calendar years for Agronomy, Anomalous accumulation and Modified BMKG definitions showed that all definitions produced slightly different onset and cessation dates, and at some stations the discrepancy was less than 3 days (Table 2.5). The differences in Julian days for the onsets and cessations of both corresponding years were mostly negative implying that using the flexible year definition gave earlier onsets and cessations than calendar corresponding years, except for anti-monsoon stations that have positive differences for all definitions. More than 60% of the stations have less than 10 days of difference between the two corresponding years for both onset and cessation. However, the maximum differences were 30 for onset and 31 for cessation, which were found for the Anomalous accumulation and Agronomy respectively. The Agronomy and Modified BMKG produced more identical mean onsets and cessations for both corresponding years, especially at Bandaaceh, Semarang and Makasar. In the total, the frequencies of same mean onset dates were 79%, 83%, 60% and same mean cessation dates were 89%, 95%, 63% for respectively Agronomy, Modified BMKG and Anomalous accumulation respectively. We also found that 95%, 98%, and 71% of the same onset dates tended to have same cessation dates for respectively Agronomy, Modified BMKG and Anomalous accumulation definitions.

The differences between the onset and cessation dates resulting from any of the definitions can be considered to be the result of applying a different approach for determining the corresponding year. The main difference is the length of the corresponding year and total amount of precipitation, leading to a different average daily precipitation. The standard deviations of average daily precipitation were generally less than 2 mm, except at Makasar where it was approximately 3 mm (Table 2.3). Since the variation in average daily precipitation has an impact only on the onset and cessation dates of Anomalous accumulation, we focussed only on the onset and cessation dates of Anomalous accumulation. The number of years for which the average daily precipitation for the flexible year is higher than for the calendar year was slightly higher than the number of years in which the flexible year has a lower average daily precipitation than for the calendar year. Both conditions produced approximately 60% of same onset and cessation dates. However, we noticed that when the flexible year has a higher average daily precipitation than the calendar year, 34% of the flexible year onsets came later than calendar year onsets. Meanwhile, when the flexible year has a lower average daily precipitation than calendar year, 38% of the flexible year onsets came earlier than calendar year onsets. Opposite patterns were found for cessation dates, the flexible year has more frequent early cessation dates when the average daily precipitation of the flexible year was higher than that of the calendar year. A more detailed explanation on how the two approaches of defining corresponding year have impact on the onset and cessation dates is presented in the Appendix B.

Table 2.5 Comparison onset and cessation dates from 3 definitions under flexible and calendar based corresponding years.

Stations	**Agronomy**		**Anomalous acc.**		**Modified BMKG**	
	Onset	**Cessation**	**Onset**	**Cessation**	**Onset**	**Cessation**
Bandaaceh^1	16/16/-5	13/19/5	0/0/0	0/0/0	0/0/0	0/0/0
Medan^1	25/10/-13	29/16/-8	29/0/-23	22/0/-31	10/0/-4	0/0/0
Sibolga^1	28/22/-30	31/16/-19	34/0/-16	25/4/-31	19/7/-15	16/0/-26
Padang^1	23/12/-5	20/9/3	28/12/-5	0/3/5	31/9/-8	3/3/-1
Mempawah^1	23/23/-2	14/19/4	0/0/0	0/0/0	0/0/0	0/0/0
Bengkulu^2	14/20/-1	10/10/-8	17/4/-5	7/0/-13	10/7/1	0/0/0
Bogor^2	19/10/-5	16/10/-3	39/6/-9	3/12/17	33/6/-9	3/3/2
Semarang^2	17/17/1	14/14/-2	0/3/2	6/6/5	3/0/-1	0/3/2
Palangkaraya^2	14/17/5	17/24/-2	4/4/-3	4/4/1	4/0/-2	4/0/-2
Ampenan^2	20/14/3	20/20/-1	0/0/0	0/0/0	0/0/0	0/0/0
Makasar^2	38/18/-13	12/15/-3	50/14/-9	14/14/24	37/20/-5	6/3/-11
Tahuna^2	34/24/-29	40/17/-28	14/14/3	10/7/-4	7/4/-13	10/4/-1
Luwuk^3	41/32/15	14/41/18	0/14/16	0/14/34	0/10/17	0/10/14
Sanana^3	21/25/13	11/45/12	0/4/13	0/4/14	0/11/15	0/11/15

The values arranged per column as a/b/c represent the frequencies (%) that the date resulting from flexible year definition comes earlier (a) or later (b) than when using the calendar year, and the differences between those dates in days (c) where positive values indicate that dates using flexible year definition occurred earlier than if the standard year was used. The superscript of the station name indicates the station's location in semi-annual (1), monsoon (2) or anti-monsoon (3) regime.

Depending on the occurrence of the driest period, the flexible years may start earlier or later than the calendar year. We found across the region that 18% of flexible years started later than the calendar years and those flexible years ended either before (56%) or after (44%) next calendar year. Meanwhile, the flexible years that started earlier than the calendar years usually ended before the next calendar year (88%).

When the driest period occurred after 1st August, less than 15% onsets based on calendar years were earlier than based on flexible years. For some years, due to the fixed cut-off approach used in the calendar year, some cessation dates were not defined. This mostly occurred in the Agronomy (7.5%) and Modified BMKG definitions. Ideally, the parameters of Agronomy should be determined on the basis of the precipitation characteristics of each station, but in this study, they were calculated on the basis of the minimum total number of years without onset at all stations. Therefore, in some years, the precipitation characteristics failed to meet the requirements of the cessation date of the rainy season causing it to occur outside the corresponding year (Table 2.6). Likewise, in some years, lack of precipitation caused the cessation date to be immediately found leading to the premature cessation date.

Table 2.6 The years without cessation date for each station when the rainy season was defined using the Agronomy and Modified methods.

Stations	**Years without cessation date**	
	Agronomy	**Modified BMKG**
Bandaaceh[1]	-	-
Medan[1]	1992, 1999, 2008	-
Sibolga[1]	1980, 1982, 1992, 1997, 2003, 2005, 2007, 2010, 2014, 2015	1990, 2006
Padang[1]	1984, 1990, 2000, 2009	1996, 2009
Mempawah[1]	2009	-
Bengkulu[2]	1983, 1994, 2000, 2008	-
Bogor[2]	1981, 1983, 1988, 1989, 1994, 1997, 2004, 2005, 2012	1980, 2004
Semarang[2]	1988, 1997, 2009, 2012	-
Palangkaraya[2]	1994, 1998, 2001, 2004, 2006, 2010	2009
Ampenan[2]	-	-
Makasar[2]	1987, 1990, 1995, 2000, 2001, 2010, 2011, 2012, 2015	2011
Tahuna[2]	2007, 2010	-
Luwuk[3]	1999, 2010	-
Sanana[3]	-	-

The cut off did not affect cessation dates of the Anomalous accumulation definition, because the dates are associated with the maximum of anomalous accumulation. During the corresponding years, the maximums were always found, although they were false maximum values. To investigate whether true maximum values occurred inside or outside the corresponding year, we extended the end of the onset calculation date to one of the latest dates of the two corresponding years. As a result, we found across the region that only 5 cessation dates of Anomalous accumulation (1%) were outside the corresponding year.

2.5.5 Driest period and onset relationship analysis

The first day of the driest period and the gap to the selected onset showed a strong relationship for most stations for all onset definitions (Table 2.6). The strongest relationship was found in Makasar for all the definitions. Most stations have a negative slope indicating that the earlier the driest period occurs the shorter the gap to the onset. There were six stations with a consistently significant relationship for all definitions (Bandaaceh, Semarang, Palangkaraya, Ampenan, Makasar and Luwuk), while some stations have no significant relationship for any definition (Padang and Bogor). Accumulated precipitation-based definitions (Agronomy and Modified BMKG) generally have a lower relationship at semi-annual stations.

Table 2.7 Linear relationship between the first day of the driest period and the number of days that separate this date and the onset date of the rainy period for the three onset definitions using the flexible corresponding year.

Stations	**Agronomy**			**Anomalous acc.**			**Modified BMKG**		
	b_0	**b_1**	**R^2**	**b_0**	**b_1**	**R^2**	**b_0**	**b_1**	**R^2**
Bandaaceh[1]	315.7	-1.1	**0.4**	213.9	-0.7	**0.5**	392	-1.3	**0.4**
Medan[1]	58.3	-0.1	0	130.9	-0.4	**0.3**	91.1	-0.2	0
Sibolga[1]	48.5	-0.01	0	159.8	-0.5	**0.3**	115.9	-0.4	**0.2**
Padang[1]	24.5	0.2	0	182.9	-0.6	**0.4**	105.7	-0.2	0.1
Mempawah[1]	176.3	-0.5	**0.2**	168.9	-0.5	**0.2**	228.1	-0.7	0.1
Bengkulu[2]	121.2	-0.2	0	219.8	-0.7	**0.4**	125.4	-0.2	0
Bogor[2]	-8.7	0.3	0.1	165.7	-0.4	0	141.2	-0.3	0
Semarang[2]	309.3	-1.0	**0.5**	261.4	-0.8	**0.3**	294.3	-0.9	**0.4**
Palangkaraya[2]	229.4	-0.7	**0.2**	255.5	-0.8	**0.4**	463.4	-1.5	**0.4**
Ampenan[2]	36.8	-0.9	**0.4**	279.6	-0.8	**0.4**	387.7	-1.3	**0.5**
Makasar[2]	345.0	-1.1	**0.7**	341.3	-1.0	**0.9**	372.4	-1.3	**0.8**
Tahuna[2]	160.7	-0.5	**0.2**	292.7	-0.9	**0.6**	189.9	-0.5	0.1
Luwuk[3]	575.8	-1.7	**0.2**	474.1	-1.2	**0.2**	742.8	-2.1	**0.4**
Sanana[3]	517.9	-1.5	**0.4**	319.0	-0.7	0.1	486.1	-1.2	**0.3**

Number codes indicate the station located in semi-annual (1), monsoon (2) or anti-monsoon (3) regime. Bold indicates significant at 95%.

2.6 Discussion

We proposed a driest period-based approach to define the corresponding years for onset and cessation date determination. This is important for defining the starting point of the onset calculation and, particularly, the length of the corresponding year for the onset and cessation dates' determination. The corresponding year traditionally has a fixed starting and ending date. It starts from the driest month and end before the driest month of the following year, referring to a calendar year (Ati et al. 2002; Liebmann et al. 2007). Using the same approach, instead using a fixed driest month, the corresponding year can also be determined by a flexible driest period. The driest period is defined as the longest occurrence of at least 14 consecutive days with the lowest cumulative precipitation within the May-October period for monsoon and semi-annual regimes or July-December for anti-monsoon regime. Using this new approach, we found that the driest periods were distributed over 3 months and shifted between the 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 stations' precipitation characteristics, sometimes the precipitation did not cease completely, especially at semi-annual stations, and therefore the precipitation accumulation during the driest period was sometimes significantly greater than zero. This is mostly found at semi-annual stations, which is strongly related to its precipitation pattern that has continued precipitation throughout the year (Aldrian and Dwi Susanto 2003; Moron et al. 2009b). Consequently, in such cases it is hard to define the driest period while it is happening. Therefore, developing a robust method for defining the driest period in real time provides a challenging topic for future studies.

The average length of the flexible years varied across the region; none were significantly different from 365 days. The minimum and maximum length of the flexible year were 206 and 508 days; approximately 5 months deviation from a normal calendar year and occurred in 2010 and 2011 at Mempawah. In 2011, the driest period occurred early (in May) resulting in very short and long flexible years for respectively 2010 and 2011. This pattern generally existed across all stations, resulting in a strong negative correlation between the first day of the driest periods and the length of the flexible years.

We selected three onset definitions to compare the onset and cessation dates resulting from the two approaches to define a corresponding year. The definitions are Agronomy, Anomalous accumulation and a modification of the local IMC definition, named modified BMKG. The first two definitions are the most widely used definition and have been applied in various regions, including IMC (Marjuki et al. 2016; Moron et al. 2009b; Moron et al. 2010; Robertson et al. 2009), Southern America (Liebmann and Marengo, 2001, S. Debortoli et al., 2015), Northern America (Misra and DiNapoli 2013), Asia (Misra and DiNapoli 2014; Moron et al. 2009a) and Africa (Ati et al., 2002, Segele and Lamb, 2005, Dunning et al., 2016). The Anomalous accumulation definition produced the least variability across the region. This confirms the flexibility of this method and its ability to define 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 definitions have a greater total onset variation.

The difference between the two corresponding years is minor but has important implications on the onset and cessation dates of the rainy season. The three onset definitions used in this study have different average onset and cessation dates for the flexible and calendar corresponding years. However, interannual variation of onset and cessation dates showed that the majority of the onset and cessation dates were the same for both corresponding years. Those cover 60% to 83% of onset dates across the definitions and 63% to 95% of cessation dates. The onsets of calendar years were sometimes earlier than onsets of flexible years particularly when the driest period occurred after the starting date of calendar year (1st August). Due to its high sensitivity to the accumulation of precipitation (Ati et al. 2002; Boyard-Micheau et al. 2013), the accumulation-based definitions sometimes found the onset of the rainy season between 1st August and the driest period. In addition, the use of a fixed end of corresponding year caused that some cessation dates could not be determined within the current calendar year due to intense precipitation throughout the year. These findings are important for climate change studies, and in particular those that focus on trend analysis. Premature onset or delayed cessation dates result in sudden changes and may cause significant impacts on the determination of trends. Supari et al. (2017) argued that the presence of sudden changes in the data, particularly at the end of the observation period, had changed the trend from insignificant to significant.

Boyard-Micheau et al. (2013) showed the onset dates of Anomalous accumulation definition shifted by a few days, depending on the average daily precipitation selected for the calculation, but they did not explain the impact on cessation dates. In this study, we found that in all onset dates of Anomalous accumulation, approximately 62% of the cessation dates were the same for both corresponding years. However, the chance to have earlier or later onset or cessation dates was affected by the variation in average daily precipitation. The results suggested that the higher the average daily precipitation, the higher the possibility of earlier and later anomalous accumulation for respectively onset and cessation dates.

The relationship between the occurrence of driest period and the onset of the rainy season suggests a strong predictability of the rainy season onset over the region. The coefficients of determination of the linear regressions were mostly significant for the stations under the

Anomalous accumulation. However, the correlations for the onsets of the two precipitation accumulation-based definitions were generally weak at semi-annual station. It indicated that likely other variables play an important role. This result agrees with a previous study by Moron et al. (2009b; 2010) that found strong correlation between agronomic onset dates and sea surface temperature over the tropical Pacific and Indian Oceans during July. Our method offers a simplification for field and real time projection once the driest period can be precisely determined. However, as the current method for determination of the driest period for the semi-annual and monsoonal regimes can only be established after October, an alternative definition for the driest period needs to be developed for forecasting purposes. A possible alternative definition of the driest period, to be tested in the future, is the first n-consecutive days receiving a precipitation less than the 5th percentile of long-term n-days accumulated precipitation.

Considering the very varied conditions of precipitation and geography of the study area, the existence of a strong correlation between the driest period and the onset of the rainy season suggests that this method may be adopted in other regions with similar climatology. It should also be noted that the precipitation regime over the interested area need to be firstly identified to properly determine the driest period.

2.7 Conclusion

Changes in rainy season characteristics due to 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 corresponding year for rainy season onset and cessation date determination. Limited knowledge on how the selection of a corresponding year may affect the onset and cessation date determination, was identified as a scientific gap. Moreover, also an open question was what the potential of the flexible driest period is to predict the onset date of the rainy season. The goal of this research was to test a method to define a flexible corresponding year for onset and cessation date determination based on the driest period in the year. The results showed that this method is advantages over the commonly used fixed calendar based corresponding year: the flexible year prevents the occurrence of premature cessation dates and keeps the cessation dates within the corresponding year. The occurrence of premature cessation dates when using the calendar year is generally caused by the presence of a significant long dry period within the year. Likewise, a decrease in precipitation events sometimes occurs outside the calendar year, causing the end of the rainy season to occur outside of the year. The gap between the first day of the driest period and the onset date has significant linear relationship with the onset date of the rainy season for all stations over the region, particularly with the onset of anomalous accumulation definition.

Further research is needed to refine this method so that the driest period can be identified during the year in real time, especially in areas where rainfall occurs all year. Although, the methodology has so far only been tested and applied to the IMC, the developed method could potentially offer a promising approach for calculating rainy season onset and length in other tropical regions of the world. If the method is successful in other regions, use of this method may aid not only in trend analysis for calculation of climate change impacts, but also real time prediction of the onset of the rainy season across many regions.

Chapter 3

Rainy season drought severity trend analysis of the Maritime Continent

This chapter is based on the published paper: Ferijal, T., O. Batelaan, and M. Shanafield. Rainy season drought severity trend analysis of the Indonesian maritime continent. *International Journal of Climatology*. DOI: 10.1002/joc.6840

3.1 Abstract

Drought is generally associated with a long-term reduction in total precipitation. However, changes at shorter time-scales can also induce drought conditions. This study analyses trends of meteorological drought severity during the rainy season in the Indonesian maritime continent. We propose a new dry spell index to characterize this drought severity. The anomalous accumulation definition was used to define a single most intense rainy season for region with one or two rainy seasons per year. The Mann–Kendall test was applied for trend analysis of the index. Temporal and spatial drought characterisations were compared between the dry spell index and standardized precipitation index. The results show that in semi-annual and anti-monsoonal regimes the rainy season precipitation increases, the number of dry days decreases, and long dry spell contribution decreases, overall causing a decrease in drought severity. Over the same period, the number of dry days, duration of the extreme dry spell, and long dry spell contribution increased in the monsoon regime, indicating a tendency towards a drier condition. In contrast, standardized precipitation index showed a strong tendency towards a wetter condition during the rainy season over this region.

3.2 Introduction

Drought is a complex and recurring global phenomenon that has devastating effects on large and important ecosystems. Increased intensity and frequency have increased the impact of drought during the last three decades financially (Tsakiris, 2017). Spatio-temporal discrepancies in water demand, along with climatic and geographic variability, have hampered the development of a unified definition of drought (Mishra and Singh, 2010). This complexity also has stimulated the development of various drought indices to provide a simple representation of the severity of drought induced by multiple variables (Tsakiris 2017). Current drought studies agree that precipitation is not the only cause of drought; however, the precipitation variability is believed to be the main driving factor in drought development (Van Loon, 2015).

Precipitation variability is highly affected by the availability of energy in the atmosphere. Global change in atmospheric conditions due to human activities has resulted in a warmer earth, providing more energy and creating a more active atmosphere that increases precipitation variability (Karl and Trenberth, 2003, Fischer and Knutti, 2016). The indication of this change can be observed through the increase in the intensity of extreme precipitation, which was found in many parts of the world (Groisman et al., 2005, Qian et al., 2007, Allan et al., 2010). Trenberth et al. (2003) argued that the fundamental change in precipitation due to the increase in intensity is the decrease in the duration and frequency of precipitation events. This implies that we might not find meaningful changes in accumulated precipitation, despite changes in the number of dry/wet days.

Analyses based on accumulated precipitation over a period of time have failed to detect drought occurrences at finer time-scales (Anagnostopoulou et al., 2003). Dry spell analyses have therefore been used globally in drought studies (Anagnostopoulou et al., 2003, Cindrić et al., 2010, Sushama et al., 2014), as the presence of dry spells contributes to an increase in drought severity (Lana et al., 2008, Huang et al., 2015, Pérez-Sánchez and Senent-Aparicio, 2017). A dry spell is defined as a consecutive number of dry days, while the dry day is a day without precipitation or precipitation less than a threshold value. The two most commonly used parameters in drought studies are duration and frequency of dry spells. In terms of duration, some studies focused only on the maximum duration of spells (Kostopoulou and Jones, 2005, Seleshi and Camberlin, 2006, Singh et al., 2014, Kebede et al., 2017), while others considered grouping multiple dry spells (Anagnostopoulou et al., 2003, Tolika and Maheras, 2005, Dash et al., 2009, Huang et al., 2015).

Both the seasonal change of drought and the increase in precipitation variability have begun receiving attention. The differences between rainy and dry season precipitation are expected to increase with the changes in the global water cycle (Trenberth et al., 2013). In general, for the last 30 years the global mean precipitation tends to increase during the rainy season and decrease during the dry season (Chou et al., 2013). However, when the analysis was extended to the last 90 years, no change was found in total rainy season precipitation, while total dry season precipitation increased (Murray-Tortarolo et al., 2017). The increase in total dry season precipitation was attributed to higher precipitation rates. This increased precipitation rate would also occur during the rainy season, hence, changes in the structure of wet and dry spells are expected.

Considering the severity of drought is site specific and influenced by several factors, a relative condition of drought is more appropriate than an absolute value (Wilhite and Glantz, 1985) in both the spatial and temporal context. Increases in dry and wet spell intensities have been observed in South Asia (Singh et al., 2014) and India (Singh and Ranade, 2010). Recently, Supari et al. (2018) found the maximum dry spell duration during the El Nino years significantly increased in some parts of Indonesia, even within the wettest period in the year. However, they did not analyse the possibility of change in the frequency of shorter dry spells, which would also aggravate drought severity. Although these short dry spells may not produce severe drought condition, dry spells just a few days in length during the rainy season will result in reduced water availability, which is the initial stage of drought development. Hence, it is important to consider all changes in the dry spell structures to analyse the variation in drought severity resulting from the presence of dry spells during the rainy season.

Therefore, the objective of this study is to analyse trends in meteorological drought severity during the rainy season. We propose an index to estimate the drought severity during the rainy season which is defined using anomalous accumulation method. The index is generated from the dry spell characteristics, hence we named it the dry spell index (DSI). As opposed to the consecutive dry day (CDD) index, which only accounts for the maximum duration of dry spells (Zhang et al., 2011), the DSI integrates both dry spell frequency and duration , as well as the total number of dry days and the length of rainy season into a single estimate of drought severity. Since a strong correlation exists between standardised precipitation index (SPI) and dry days (Fischer et al., 2011) and more consecutive dry days increase drought severity (Huang et al., 2015), we hypothesize that DSI can capture the changes in the level of drought due to the variability in precipitation as well as dry spells. Contrary to other existing drought indices which are only applicable for a fixed duration, DSI can be used to measure the drought severity over flexible duration. However, we also compare the DSI trends derived over flexible rainy season with the DSI and SPI trends derived from a fixed rainy season which is defined base on regional mean onset and cessation dates. We selected the Indonesian Maritime Continent as a study region, considering that this region experiences rainy and dry seasons with strong local features and influence from El Nino-Southern Oscillation (Zang et al. 2016).

3.3 Study Area

The IMC has unique and complicated spatial and temporal precipitation variability. Located in the middle of the indo-pacific warm pool, the IMC receives large amounts of precipitation and also releases enormous amounts of latent heat to the surrounding areas, causing it to be known as the "broiler box" (Simpson et al. 1993; Qian 2008; Zhang et al. 2016). The IMC covers more than fifteen thousand islands including five main islands, namely Sumatera, Java, Kalimantan (southern Borneo), Sulawesi and Irian Jaya (New Guinea), as well as other small islands, which stretch along the equator from 95° E to 142° E and across the equator from 6° N to 11° S (Figure 3.1). The region consists of lowlands, highlands and huge mountains causing strong variation in precipitation and other climate parameters. The higher altitude areas usually have more intense precipitation and lower temperature. Western Sumatera and central Kalimantan generally receive more precipitation while the south eastern region, and in particular the eastern part of Lesser Sunda Island, receives the least precipitation (Mandapaka et al. 2017).

This region is also influenced by a strong monsoon as the result of the movement of the Inter-Tropical Convergence Zone (ITCZ). Dry and rainy seasons are associated with the southeast and northwest monsoon, respectively (Aldrian and Dwi Susanto 2003; As-Syakur et al., 2016), driven by the development of the ITCZ. The wettest period, January and February, occurs when the ITCZ is located in its southern-most position, while the driest period, July to September, occurs when it is positioned north of the equator (Yanto et al. 2016). The rainy season lasts for approximately 6 months, but according to Aldrian and Djamil (2008) the length of the dry season has increased in recent decades, especially in coastal areas.

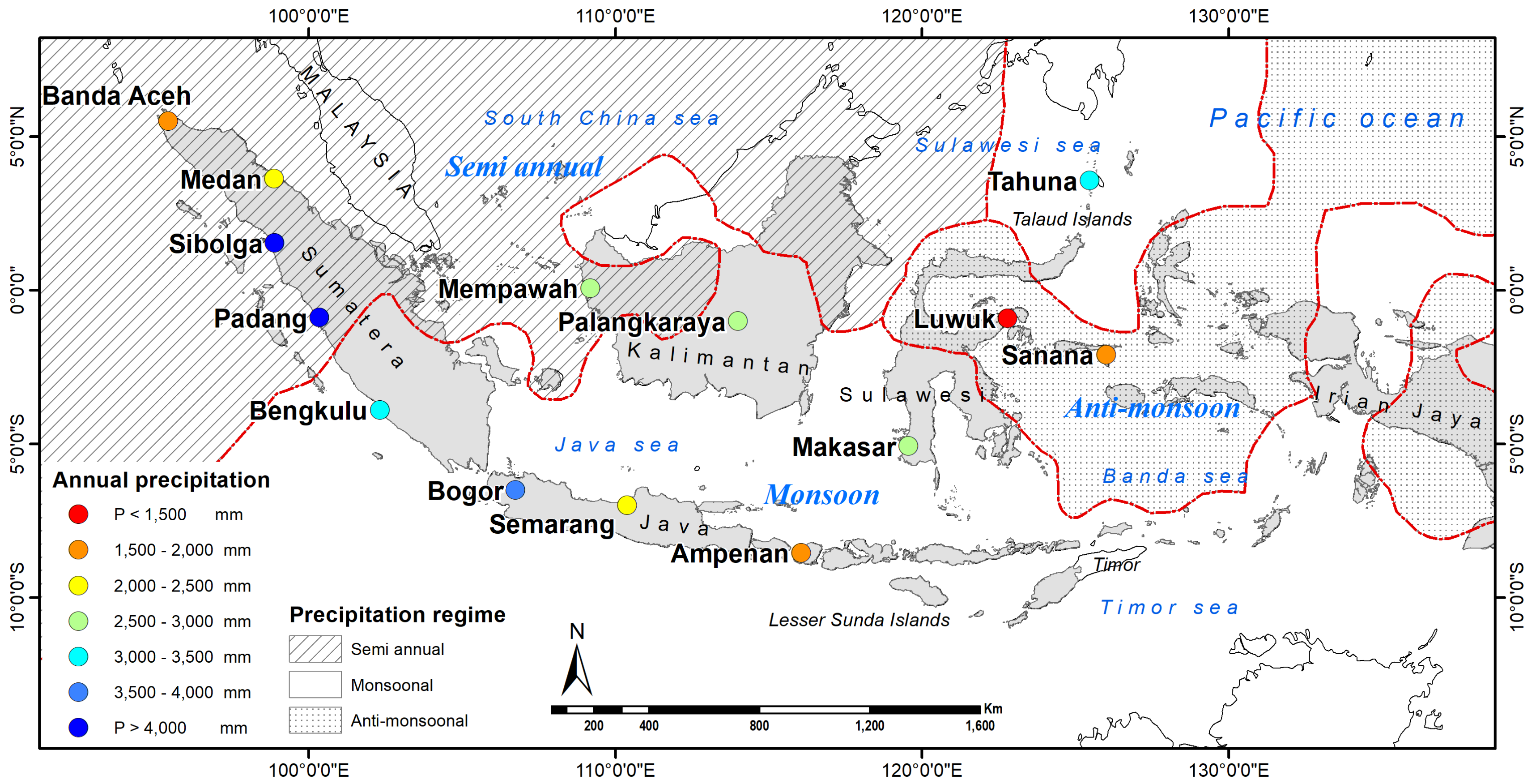


Figure 3.1 Mean annual precipitation for period 1980-2016 of selected stations over Indonesian Maritime Continent based on daily precipitation recorded by BMKG during the period of 1980-2015. The region divided into 3 precipitation regimes: monsoon, anti-monsoon and semi-annual (Aldrian and Dwi Susanto 2003).

The annual precipitation variability of the IMC can be classified into three regimes (Aldrian and Dwi Susanto 2003). The first monsoon regime is strongly influenced by the NW monsoon, usually from November to March, bringing precipitation to the region, while the NE monsoon, from May to September, causes a dry condition in the region. Most of the IMC area falls under this monsoon type of precipitation. The second regime is semi-annual, which is characterised by a quasi-absence of a rainy and dry season, because rain events occur over the entire year. This regime has two more intensive precipitation periods: October-November, which is the main rainy season and March-May. The last regime is the anti-monsoon, which covers most of the eastern part of the IMC. It has one precipitation period occurring from June to July.

3.4 Data and Methodology

3.4.1 Data

This study used daily precipitation collected from the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG). The BMKG also provides information on CDD for daily operations. The stations were selected for good spatial coverage over the region and cover all the precipitation regions as well as the range of annual precipitation. Although precipitation data has been collected for two centuries in Indonesia, the number of stations that have complete data is very limited for the eastern, mostly anti-monsoon, region (Table 3.1). Analysis was limited to stations that have data for at least 20 complete years after 1980. A complete year is defined as a year that has 12 complete months of data, while for a complete month we adopted the definition of maximum 3 days of missing data (Supari et al. 2017). The missing data was simply replaced by zero. The data in missing months were replaced by the daily average of the whole period. However, years with missing months were excluded from the analysis if a missing month occurred within the rainy season.

Table 3.1 Selected stations their characteristics and data availability. The stations are listed from west to east according to their precipitation regime.

Station	Location	ID	Lat/Long	Elevation (m)	Start	End	Missing (years)	Average Annual Precipitation
Banda Aceh[1]	Blangbintang	96011	5.52° N, 95.42° E	21	1982	2016	2	1,544
Medan[1]	Kualanamu	96035	3.63° N, 98.87° E	25	1980	2016	1	2,369
Sibolga[1]	Pinangsari	96073	1.55° N, 98.88° E	3	1980	2013	3	4,545
Padang[1]	Tabing	96163	0.88° S, 100.35° E	3	1982	2016	6	4,235
Mempawah[1]	Sungainipah	96583	0.07° N, 109.30° E	3	1986	2016	0	2,808
Bengkulu[2]	Padangkemiling	96253	3.88° N, 102.33° E	16	1980	2013	0	3,341
Bogor[2]	Darmaga	96753	6.50° N, 106.75° E	250	1980	2013	0	3,858
Semarang[2]	Ahmadyani	96839	6.98° S, 110.38° E	3	1986	2016	0	2,281
Palangkaraya[2]	Panarung	96655	2.22° S, 113.94° E	27	1980	2016	1	2,920
Ampenan[2]	Selaparang	97240	8.53° S, 116.07° E	3	1986	2016	2	1,734
Makasar[2]	Paotere	97182	5.07° S, 119.55° E	14	1983	2017	5	2,753
Tahuna[2]	Naha	97008	3.35° N, 125.28° E	38	1986	2016	0	3,305
Luwuk[3]	Bubung	97086	1.04° S, 122.77° E	17	1981	2016	8	1,243
Sanana[3]	Emalmo	97600	2.08° N, 126.00° E	2	1980	2012	7	1,400

[1]semi-annual, [2]monsoon and [3]anti-monsoon precipitation regime

3.4.2 Methodology

3.4.2.1 Definition of the rainy season and dry spell

In characterizing the rainy season, the most challenging task is determining the onset and cessation. While many methods have been developed, none of them have been broadly accepted (Fitzpatrick et al., 2015, Bombardi et al., 2020). Generally, the method used is based on the data available and the purpose of the analysis. In this study, we selected one of the most widely used precipitation-based methods, namely Anomalous accumulation. In order to deal with the characteristics of the study area, the modified of Anomalous accumulation (as described in section 2.4.2.2) was selected to determine onset/cessation dates of rainy season.

Various threshold values, ranging from 0.1 to 25 mm, are used to define the dry days (Mathugama and Peiris, 2011). However, due to the high evaporation rate for the IMC, Marjuki et al. (2016) suggested applying a threshold value in the range of 2.5-5 mm. Additionally, Wati et al. (2019) found that the evapotranspiration in Java and Bali Islands is generally lower than the 5 mm/day threshold typically used by BMKG to define the rainy season onset in Indonesia. Therefore, we selected 2.5 mm as the threshold to differentiate between wet and dry days. Based on the definitions, we extracted parameters related to the rainy season characteristics and dry spells, as shown in Table 3.2.

Table 3.2 List of rainy season parameters used in this study

Name	**Definition**	**Unit**
RSL	Total length of rainy season	days
RSTP	Total precipitation during the rainy season	mm
NDD	Number of dry days	day
FDS	Frequency of dry spells	-
CNDD	Contribution of total NDD to the RSL	%
CSDS	Contribution of short dry spells (duration less than 4 days) to the RSL	%
CLDS	Contribution of long dry spells (duration at least 4 days) to the RSL	%
XDS	Maximum length of dry spells during the rainy season	days
R90	The 90th percentile of daily precipitation rate	mm/day

3.4.2.2 Dry spell index

To understand changes in the level of drought over time, a single value is needed to characterize drought severity. Here, we define a dry spell index (DSI) that takes into account the characteristics of dry days, dry spell and seasonal length:

$$DSI = \frac{1}{RSL} \sum_{i=1}^{NDD} w_i \quad (3.1)$$

where NDD is the number of dry days, RSL is rainy season length, and w_i is the weight assigned for each day within a given dry spell, with the weights increasing linearly with the length of the dry spell. This is based on the assumption that the impact of consecutive dry days to the drought increases from the first day to the last. This weighted index allows differentiation between the impacts of various dry spell durations on drought severity; for example, a 6-day dry spell has a bigger impact than a 3-day dry spell. But, the distribution of dry days is also important. For example, a 2 month long rainy season (RSL = 60) where the total number of dry days is 30 (NDD = 30). If there is rain every other day, $w_i = 1$ for all dry days, so here $w = 30$ in total. In contrast, if there are 30 consecutive dry days, then $w = 465$ (i.e. $w_1 = 1$, $w_2 = 2 \ldots w_{30} = 30$). The second scenario produces a much higher index than the first one due to variation in the dry spell structure. A similar weighted method has been used in previous studies (Byun and Wilhite, 1999, Laux et al., 2009) to quantify drought severity based on the daily depletion of water resource. However, this method is far from ideal for the IMC as water resources during rainy season generally show an increase in the storage due to the high precipitation.

3.4.2.3 Standardised Precipitation Index

Drought severity assessment based on a Standardised Precipitation Index (SPI) was chosen as a method for comparison with DSI. SPI is the most widely used index to assess the level of dry or wet conditions (McKee et al., 1993). The index is based on the deficits and excesses of the accumulated precipitation over a selected period; usually 1, 3, 6 or 12 months. The calculation procedure includes the process of fitting the precipitation to a gamma distribution and transforming to a standardized normal distribution (Fischer et al. 2011), which makes it possible to compare observation or simulation data of distinct climatic or hydrological regions (Bordi et al., 2004). The SPI values range from greater than 2 (extremely wet) to lower than -2 (extremely dry). The drought severity simply increases if the SPI decreases and vice versa. In this study, the SPI index was calculated using the SPI program from the National Drought Mitigation Centre (https://drought.unl.edu/). We used daily data as input for the program to generate a monthly time step SPI information of accumulated precipitation over the defined time scale. From the output, we then created time series for the selected period only. Hence, to create the time series of SPI for period September-November, we used only the September index from the output of

3 months' time-scale. The time series were then used for further analysis such as comparison or trend test for September-November SPI.

3.4.2.4 Trend test

The non-parametric Mann-Kendall (MK) trend test evaluates the significance of monotonic trends in data series of selected parameters. The test has been widely used in hydrology and climatology. It tests the null hypothesis (H_0) that no trend exists in the series. The statistics of the test are defined as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(X_j - X_i\right) \tag{3.2}$$

where n is the number of observations, X_j or X_i are the j^{th} or i^{th} data, and

$$sign(\theta) = \begin{cases} 1 & if\ \theta > 0 \\ 0 & if\ \theta = 0 \\ -1 & if\ \theta < 0 \end{cases} \tag{3.3}$$

The statistic S is approximately normally distributed, it has a mean equal to zero and a variance defined as

$$Var(S) = \left[n(n-1)(2n+5) - \sum_{j=1}^{m} t_j\left(t_j - 1\right)\left(2t_j + 5\right)\right]/18 \tag{3.4}$$

where t_j is number of tied observations, and m is the number of tied groups. The test uses the standard normal distribution to evaluate the standardized test statistic of Z_S calculated using:

$$Z_S = \begin{cases} S - 1/\sqrt{Var(S)} & if\ S > 0 \\ 0 & if\ S = 0 \\ S + 1/\sqrt{Var(S)} & if\ S < 0 \end{cases} \tag{3.5}$$

The H_0 will be rejected if the absolute standardized test statistic of Z_S is greater than the critical value of Z_{crit} at significance level $\alpha/2$ for normal distribution. At this condition, the test suggests that the observed trends in the series are significant. However, failing to reject H_0 does not mean a trend does not exist in the series rather than that there is not enough evidence to conclude that there is a significant trend. The sign of the Z_S value indicates the direction of change, positive or negative. To quantify the slope of change, this study used Sen's slope that is calculated using Theil-Sen's slope estimator, which has been considered to be a robust slope estimator. The Theil-Sen's slope estimator is defined as

$$s = Median\left(\frac{X_j - X_l}{j - l}\right)\ l < j \tag{3.6}$$

where s is the estimated slope, X_l is the l^{th} data. This method has been widely used to define the slope along with trend analysis (Yue et al., 2002).

We assume that the data used for trend analysis are serially independent. This assumption is based on the fact that all parameters (as listed in Table 3.2) are seasonally and independent of each other. There is a probability that for some years the method fails to find the onset or cessation date. For that reason, only stations that have minimum 20 continuous years of data were tested for a trend.

3.5 Results

The 14 selected stations used in the analysis are well distributed over the region and precipitation regime. However, a smaller number of stations occur in the eastern part of the region, which mainly has an anti-monsoon precipitation regime. Figure 3.1 shows the annual precipitation of the selected stations in the IMC region, with distinctive annual precipitation patterns varying from less than 1500 to more than 4000 mm/year. The stations located in the western region have larger annual precipitation than in the eastern region. Monthly precipitation patterns show the differences between the regimes (Figure 3.2). The precipitation concentrates mainly at the beginning of the year for monsoon, at the end of the year for semi-annual, and at the middle of the year for anti-monsoon stations. The bulk of the precipitation amount is generally distributed over the months Nov-Feb for monsoon stations and Sept-Oct for semi-annual stations.

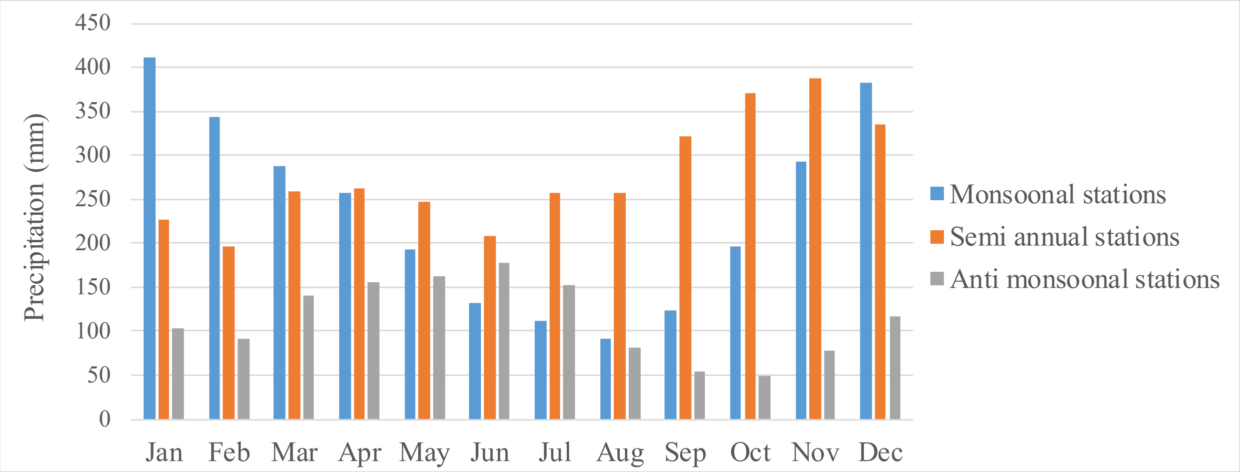


Figure 3.2 Monthly mean precipitation of 7, 5 and 2 stations in the monsoon, semi-annual and anti-monsoon regimes, respectively, for the period 1980-2014.

3.5.1 Comparison of indices

The DSI and SPI indices have strong negative correlation ($r < -0.4$) at all stations except at Bengkulu and Luwuk. Medan station was selected for detailed comparison between DSI and SPI. Both indices were calculated at a 3-month time scale (September – November, SON). For the comparison, the anomaly SPI was created and compared with the inverse anomaly of DSI because these indices have an opposite progression. That is, a higher index of SPI indicates lower drought severity, while a higher DSI indicates higher drought severity. Temporal variation showed good agreement between the methods for changes in drought severity (Figure 3.3), particularly for wet years such as 1982, 1987, 1998, and 2012. Meanwhile lack of agreement between the indices was found for dry years (1984, 1990, and 2009). Those patterns were also observed at Bengkulu (Figure 3.3.b), Semarang (Figure 3.3.c) and Luwuk (Figure 3.3.d). Any time when the total precipitation was higher than average, i.e. wetter conditions, the number of dry days generally decreased, resulting in a decrease in DSI. Therefore, DSI was capable to capture wet conditions although it does not consider the precipitation amount. Comparing two years with similar precipitation (2005 and 2006, with 527 and 513 mm of rainfall, respectively), the SPIs were similar but DSIs were significantly different because the number of dry days in 2006 was higher than in 2005. The impact of dry days on DSI can also be observed in 1993 and 2011 at Semarang or in 2010 at Luwuk. Those years had high in both total precipitation and number of dry days causing huge different between the indices.

The precipitation amount showed a strong correlation with the number of wet days but less strong with distribution of dry spell durations. Therefore, SPI could perfectly capture the wet condition but was unable to capture the dryness related to the presence of dry spells. A clear example on how variation in number of dry days and dry spells impacted the variation in DSI can be clearly seen at Luwuk which generally has low annual precipitation. For example, a significant impact of duration of dry spells on the index can be illustrated by comparing dry days in 1986 with 1991 in which during those years the number of dry days was similar but the DSI was different. A similar condition was also found in the comparison between the dry spells in 1989 and 1983. The impact of dry spell duration can also be seen in 1984 and 1990 at Medan in which the number of dry days, number of dry spells and total precipitation in those years were relatively similar. The SPI, in those years, showed a similar level of dryness but DSI indicated that 1990 was dryer than 1984 because the maximum duration of dry spell in 1990 was higher than in 1984. Paired T-test on in verse DSI and SPI anomalies showed a poor and positive correlation ($r=0.26$). On average, the inverse DSI anomalies were slightly larger than the SPI anomalies, but they were not significant at a 95% confidence level ($t_{401}=1.569$, $p=0.12$).

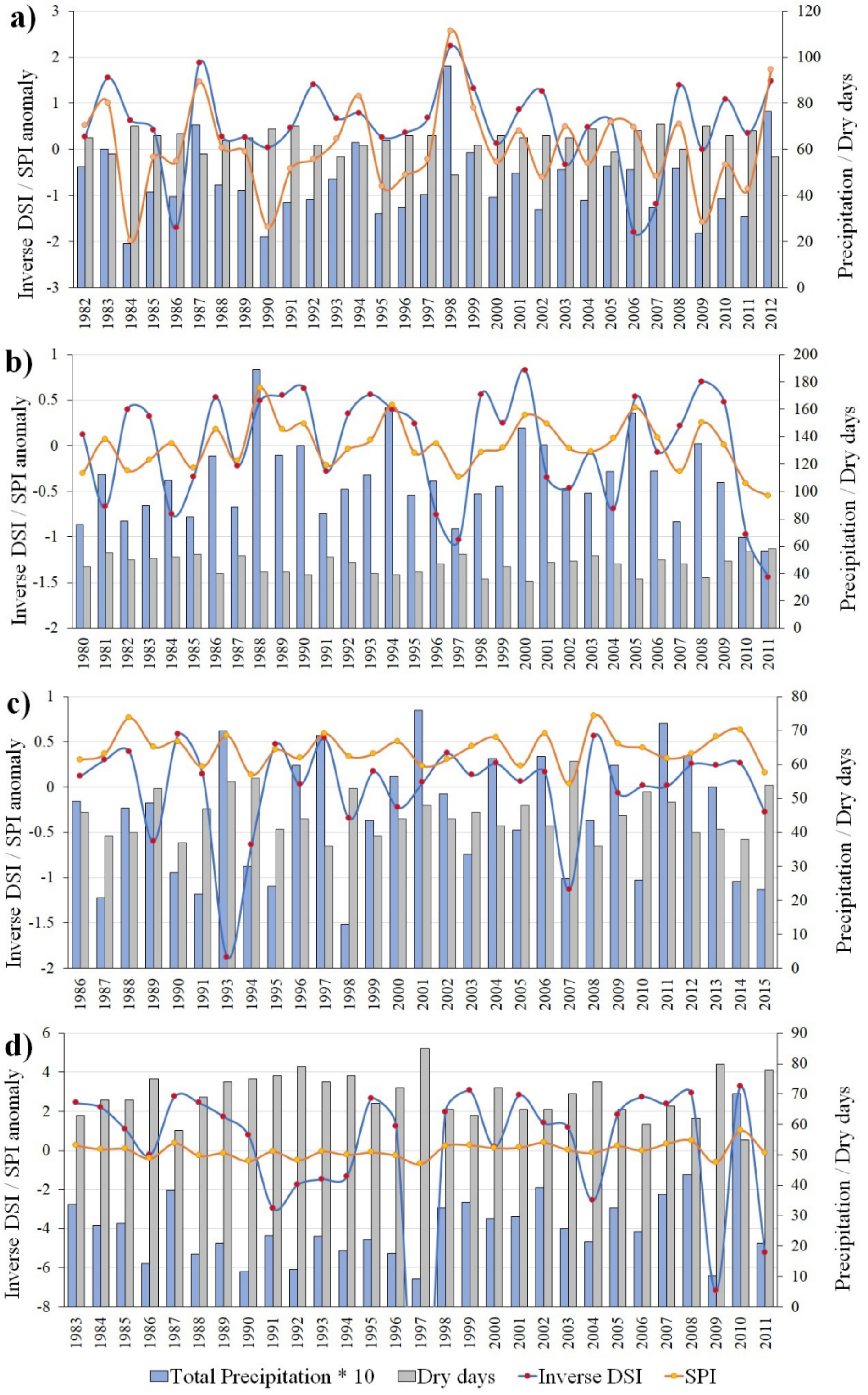


Figure 3.3 Comparison between Dry between Dry Spell Index (DSI) and Standardised Precipitation Index (SPI) at the (a) Medan, (b) Bengkulu, (c) Semarang, and (d) Luwuk stations. For comparison purposes, the inverse DSI anomaly was plotted against SPI. Both indices were calculated over a 3-month (September-November) period.

3.5.2 Seasonal characteristics

3.5.2.1 Onset and cessation of rainy season

High precipitation variability in this region caused some years to have a very short rainy season. In this study we only considered the rainy seasons that last longer than 45 days for further analysis. Based on this criteria, in total, about 5% of all station years were discarded from the analysis. Semi-annual stations generally had mean onset in September and cessation in December. Monsoon stations had a start of rainy season in October or November and end in March or April. Anti-monsoon regime had a rainy season from February to July. These results suggest that the rainy season of the IMC starts in northern Sumatera and moves southward in Sumatera and eastward to Kalimantan. After crossing to Java, the progression moves eastward along with similar movement in Kalimantan and Sulawesi. A similar pattern was also observed in rainy season cessation particularly for the semi-annual regime. Another route of cessation progression starts from south east (Lesser Sunda Islands and East Java) and moves westerly along Java and northerly toward Sulawesi and Kalimantan.

Time of occurrence of the onsets and cessations generally were found within a similar time frame for monsoon and semi-annual stations. Most of the onsets (90%) occurred within a 4-month time frame i.e. Sep-Dec for monsoon and Aug-Nov for semi-annual regime. Meanwhile, the cessation dates were found mostly within a 5-month range, Feb-Jun and Oct-Feb for monsoon and semi-annual respectively. For the same frequency of occurrence, the onsets and cessations spread into a 6-month period for the anti-monsoon regime.

Variability is noticed in the most-advanced and most-delayed onset and cessation dates (Table 3.3). In the semi-annual regime, the most advanced and delayed onsets were recorded at Mempawah, while for cessations, they were recorded at Sibolga and Padang, respectively. For the monsoon regime, the most advanced onset and cessation were recorded at Bogor, while for the most delayed onset and cessations were recorded at Ampenan and Tahuna. In the anti-monsoon regime, Luwuk had the most advanced onset and cessation and Sanana had the most delayed onset and cessation.

The variability in onset and cessation was greatly influenced by the occurrence of El-Nino and La-Nina years in the region. For instance, the most-advanced onset dates at monsoon stations were found in 2010, which was one of the strongest La Nina years. Likewise, the most-delayed onset in some stations was found to occur during the strongest El-Nino year, 1997-1998. To investigate this influence, the five earliest and latest onsets/cessations were selected from each station and classified as advanced and delayed occurrences. These occurrences then were classified into El Nino, La Nina or normal year based on the Oceanic Nino Index (https://ggweather.com/enso/oni.htm). The results (Figure 3.4) suggest that most of those advanced/delayed onsets occurred during La Nina/El Nino years. Similarly, this pattern was also observed in cessation. During La Nina years, in which the region receives more precipitation, the onset and cessation dates occurred earlier. Likewise, during the El Nino, when drier conditions were generally dominant, the onset and cessation dates were late. These results are in line with Marjuki et al. (2016).

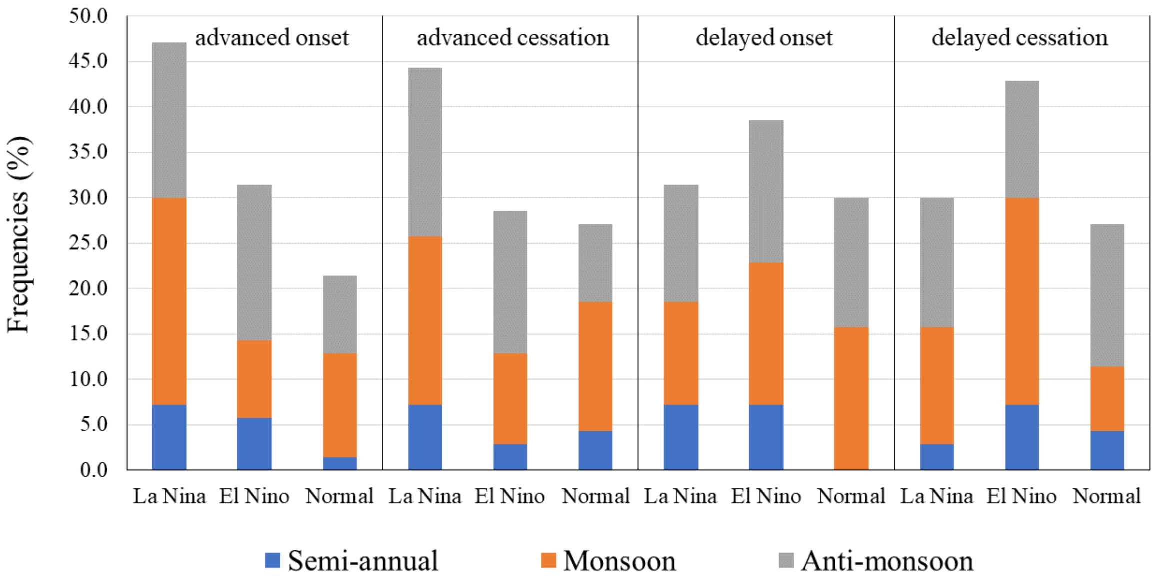


Figure 3.4 Total frequency of occurrence of the five most advanced and delayed onset and cessation dates for normal and ENSO years.

Negative and positive trends are detected in the onsets and cessations but only few of them are significant. Positive trends are mainly found in the onsets of semi-annual and anti-monsoon stations, which is significant at Bandaaceh. On the contrary, most of the monsoon stations have negative trends in onsets indicating that the onset tends to occur earlier than in previous years. Meanwhile, no clear spatial pattern is found in the cessations although they exhibit more significant trends. Significant increasing trends are detected at two semi-annual stations

(Bandaaceh and Mempawah), while decreasing trends are found for two monsoon stations (Semarang and Tahuna).

3.5.2.2 Length and total precipitation of rainy season

The average length of the rainy season (RSL) ranged from 97 days in Padang to 194 days in Bogor (stations 4 and 7 in Figure 3.5). The monsoon stations generally had an RSL of approximately six months, which is longer than the semi-annual and anti-monsoon stations. Although they had longer RSL, anti-monsoon stations generally had lower total rainy season precipitation (RSTP) than semi-annual stations. Based on the mean onset and cessation dates, we selected October as starting month of the rainy season for the semi-annual and monsoon regime, and February for the anti-monsoon regime. The seasonal lengths for the stations were 3, 6 and 5 months for semi-annual, monsoon and anti-monsoon regimes, respectively. Therefore, we defined the fixed regional rainy seasons as Oct-Dec for semi-annual, Oct-Mar for the monsoon and Feb-June for the anti-monsoon regime.

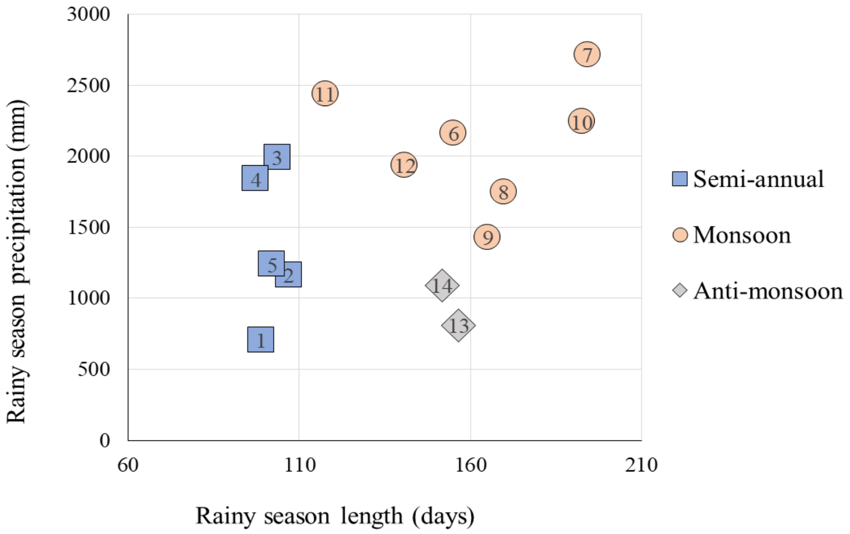


Figure 3.5 Strong regional characteristic in relationship between the average of rainy season length vs total precipitation. The numbers in each symbol refer to the stations given in Table 3.2.

Table 3.3 Characteristics and trend test result of onset and cessation dates

No	Stations	Annual precipitation (mm)	Onset				Cessation			
			Most advanced	Most delayed	Mean	Change rate[1]	Most advanced	Most delayed	Mean	Change rate[1]
1	Bandaaceh	1,544	20/07/1991	15/11/1992	29-Sep	12*	4/11/1986	3/03/2013	6-Jan	11*
2	Medan	2,369	18/06/2003	6/11/2010	23-Aug	6	24/10/2009	15/02/1999	7-Dec	3
3	Sibolga	4,545	15/06/1983	10/11/1985	1-Sep	1	17/08/2003	11/02/1994	12-Dec	-3
4	Padang	4,235	2/06/1995	7/12/1996	17-Sep	6	23/09/2001	15/05/1997	23-Dec	-4
5	Mempawah	2,808	22/05/2008	30/12/2015	16-Sep	17	29/09/1988	4/03/2016	27-Dec	15*
6	Bengkulu	3,341	11/07/2010	6/01/1998	13-Oct	3	30/11/1980	9/07/2007	16-Mar	4
7	Bogor	3,858	3/06/2005	18/01/2002	16-Oct	-14	30/10/2010	26/07/2001	28-Apr	-16*
8	Semarang	2,281	8/08/2010	13/01/1994	1-Nov	-9	8/02/2011	11/07/2016	18-Apr	12
9	Ampenan	1,734	9/09/2010	15/03/1998	5-Nov	-2	5/02/2011	31/07/1998	18-Apr	11
10	Palangkaraya	2,920	5/09/2010	5/02/1981	1-Nov	-6	13/11/2010	25/07/1998	11-May	-2
11	Makasar	2,753	16/10/2005	6/01/1995	26-Nov	-2	19/02/2003	2/08/1998	23-Mar	9
12	Tahuna	3,305	24/09/1996	13/02/1989	9-Nov	-4	28/12/2015	4/08/1995	29-Mar	-35**
13	Luwuk	1,243	14/10/2008	26/04/2002	4-Feb	-6	20/02/2011	5/10/1998	16-Jul	-7
14	Sanana	1,400	13/11/2001	22/05/2000	4-Feb	24	19/03/2009	7/11/2010	4-Jul	19

[1] rate of change per decade calculated in days

*/** indicates that the trend is significant at 90/95% confidence interval

3.5.3 Spatial and temporal patterns of rainy season characteristics

Very few significant trends were detected in parameters at the selected stations over the IMC region (Figure 3.6). Positive and negative trends in RSL were found (Figure 3.6a), but the trends were significant at only two monsoon stations: an increasing trend at Semarang (8) and a decreasing trend at Tahuna (12). The observed regional pattern is decreasing trends over the northern and middle Sumatera and increasing trends in the central region covering Java and Kalimantan. Less spatial coherence was observed in the eastern part although one station showed a significant decreasing trend. Although RSL decreases, some stations in the semi-annual regime also have an increasing trend in RSTP (Figure 3.6b), which was more likely related to the decline in CNDD (Figure 3.6c). Increasing RSLs, found in most monsoon stations, also correlated with the increase in CNDDs. Stations in the anti-monsoon regime had increasing RSTP and decreasing CNDD indicating a tendency towards wetter conditions. Meanwhile, a tendency toward drier conditions was detected at three monsoon stations in the southern part [Bengkulu (6), Bogor (7) and Selaparang (9)], due to the decreasing RSTP and increasing CNDD. Positive correlations between the changes in RSL, RSTP and CNDD, were noticed for some stations: Padang (4), Mempawah (5) and Tahuna (12), which caused difficulties in interpreting the severity of changes at those stations. In average, during rainy season, the CNDD ranged from 36% in Palangkaraya (10) to more than 65% in Makasar (11).

The average of FDS ranges from 18 in Bandaaceh (1) to more than 41 in Palangkaraya (10) (Figure 3.6d). In comparison with CNDD, some opposite trends were detected, and more significant trends were found in FDS: increasing at Semarang (8) and decreasing at Padang (4) and Tahuna (12). The FDSs tended to decrease over half of the IMC, covering Sumatera, western Java and western Kalimantan, while the other part tended to increase. The short spells (<4 dry days, Table 3) were the main contributor to NDS (70-90%) and to the total dry days in the season (22-33%). However, the CSDS generally decreased in Sumatera and Java islands except for the two northernmost stations but increased at the three eastern most stations (Figure 3.6e). CSDS and CLDS generally had opposite trends except at two the monsoon stations Bogor (7) and Makasar (11). CSDS was 10% higher than CLDS in both semi-annual and monsoon regimes, but it was 12% lower in the anti-monsoon regime. On average, the CLDS tended to decrease 12% per decade at anti-monsoon stations and increase by approximately 7% per decade at some monsoon stations (Figure 3.6f).

The averages of XDS durations of 8 and 9 days were similar for the semi-annual and monsoon regimes, respectively, and almost double that of the anti-monsoon regime at 14 days (Figure 3.6g). The XDSs had a tendency to increase in the monsoon regime and were significant at Bogor (7), meanwhile both semi-annual and anti-monsoon regimes had shorter XDSs. The stations that had shorter duration of XDS tended to have higher R90. This negative correlation, however, was also noticed in the trends of 50% of stations, which were mainly located in the eastern part of the region. The R90 trends significantly decreased at Bandaaceh (1), Mempawah (5) and Semarang (8), but increased at Sibolga (3) (Figure 3.6h). Generally, increasing trends were detected at stations near the equator, with the exception of Mempawah (5), while decreasing trends were found in the southern hemisphere (e.g. mostly monsoon regime). Overall, the average of R90 ranged from 32 mm/day at Luwuk (13) to 71 mm/day at Makasar (11).

3.5.4 Spatial and temporal pattern of drought severity

The DSIs generally had decreasing trends at all stations north of the equator but the trend was significant only at Bandaaceh (1) (Figure 3.7a). The decreasing trends were also found at all stations in Sulawesi and its surrounding region (11, 12, 13 and 14). Meanwhile, the other stations, located mostly in the semi-annual regime, had increasing trends and were significant at Bogor (7). Comparing with DSI (Figure 3.7b) and SPI (Figure 3.7c) derived from a fixed rainy season period, the number of decreasing and increasing trends was the same but spatial patterns changed. This was especially the case for the centre part of region [Mempawah (5), Semarang (8), Palangkaraya (10), and Tahuna (12)], which had opposite trends. However, both indices detected a significant increasing trend at Bogor (7).

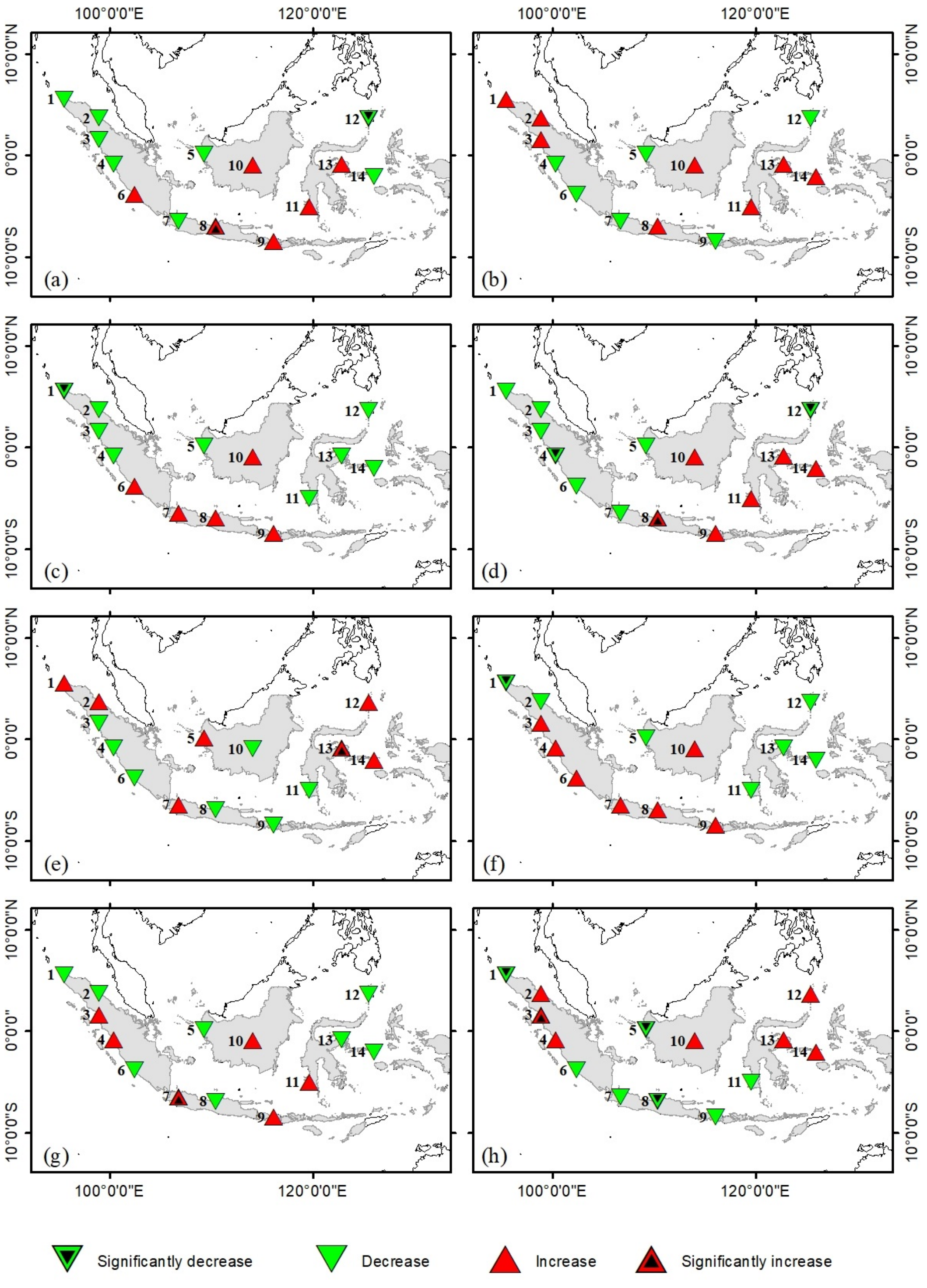


Figure 3.6 Trends in rainy season characteristics in the Indonesian Maritime Continent, including length (a), total precipitation (b), contribution of total dry days to the rainy season length (c), frequency of dry spells (d), contribution of short (e) and long (f) dry spells to the rainy season length, maximum duration of dry spell (g), and 90% of precipitation rate (h). The numbers to the left of each symbol refer to the stations given in Table 3.1.

Using the same fixed rainy season definitions to compare drought severity resulting from SPI and DSI, more decreasing trends were found in SPI than DSI and opposite trends were recorded at Mempawah (5), Bogor (7) and Tahuna (12). SPI produces a general tendency of decreasing trends in drought severity over the region, with significant decreasing trends found at Tahuna (12) and Sanana (13).

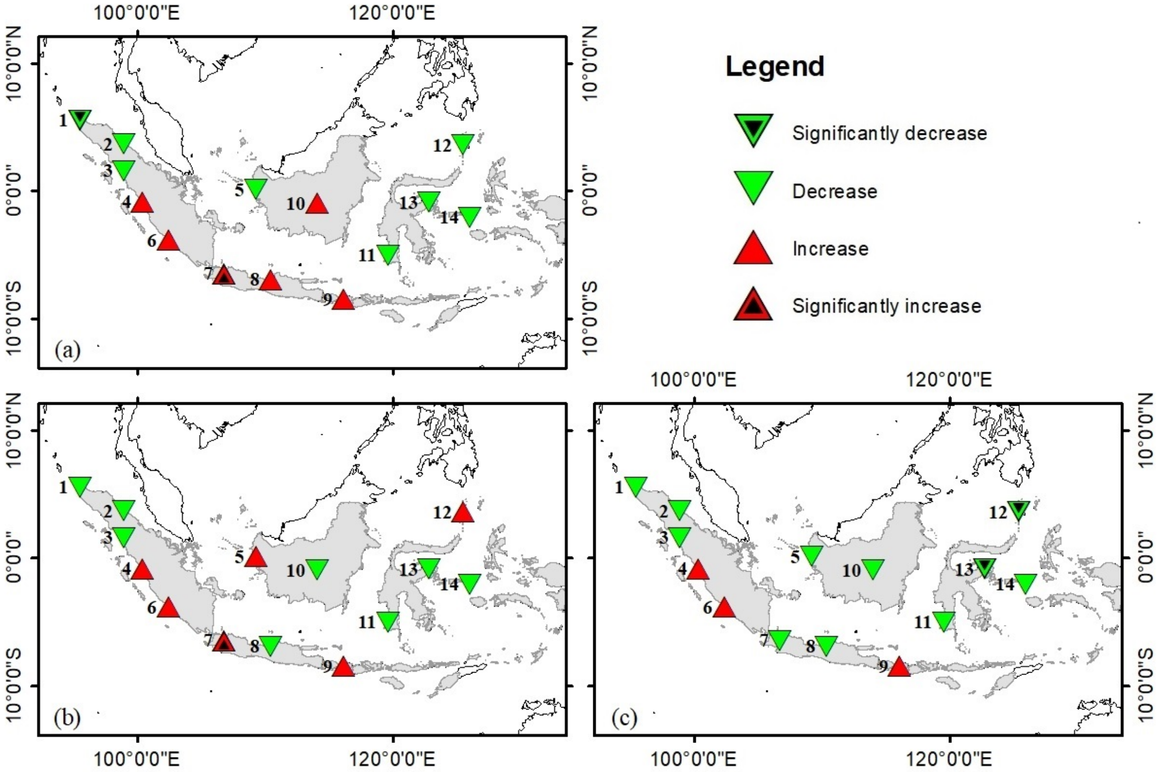


Figure 3.7 Spatial patterns of drought severity based on dry spell index (a). The index calculated over fixed rainy season definition (b) was compared with Standardised Precipitation Index calculated over the same duration (c). The numbers to the left of each symbol refer to the stations given in Table 3.1.

3.6 Discussion

In response to global warming, the difference between dry and rainy season is likely to change spatially and temporally. Seasonal variability causes variation in not only the amount or frequency of rainfall, but also the occurrences of wet and dry spells. In this study, we focussed on the rainy season over the Indonesian Maritime Continent to observe potential changes in dryness due to dry spells within the years 1980 - 2016. The onset/cessation of the rainy season was defined using the anomalous accumulation method. We found that the variability in the onsets and cessations were strongly affected by ENSO, confirming the findings of earlier studies (Moron et al. 2009; 2010; Marjuki et al. 2016; Zhang et al. 2016). Delayed onsets were detected at semi-annual and anti-monsoon stations, while most of monsoon stations tended to have earlier onsets. There were no clear patterns in the cessations over the semi-annual regime, but tendencies of delayed cessations were detected in monsoon and anti-monsoon regimes.

Changes in the onsets/cessations result in changes in rainy season length, which positively correlates with the changes in the precipitation amount. The changes also modified the number of dry days as well as the drought severity. Our analysis revealed that for the stations that have a significantly increased rainy season length, not only was there an increase in total precipitation but also a significant increase in the number of dry days. We found that more than 70% of stations with an increasing rainy season length (and 85% with a decreasing rainy season length) had a positive correlation with the change in the number of dry days, but a positive correlation with total precipitation only for 57% of stations. This indicates that the spatial pattern of rainy season length was more strongly correlated with the pattern in the number of dry days than the pattern in total precipitation. This evidence supports the fact that relying only on accumulated precipitation may result in an underestimation or even a false conclusion on drought severity by ignoring the potential drought triggers at a finer scale (Anagnostopoulou et al., 2003). It also will be difficult to draw a general impression of whether the drought severity is increasing or decreasing when the parameters, such as length, total precipitation and dry spell of rainy season, had increasing trends. The impression of changes toward a wetter condition in semi-annual and anti-monsoon regimes and toward a dryer condition in monsoon regime found in this study are in line with previous studies in this region by Supari et al. (2017).

The drought severity is not only affected by the number of dry days but also by the distribution of dry days into various durations of dry spells. A longer duration will generate a higher severity than a shorter duration of dry spells. Therefore, dry spells have been used in many previous studies to analyse drought (Anagnostopoulou et al., 2003, Deni et al., 2009a, Cindrić et al., 2010, Huang et al., 2015). Our findings suggest that short dry spells were the main contributors to the total dry days and tend to increase in northernmost Sumatera and Easternmost IMC. Meanwhile, long dry spells showed stronger spatial patterns with increasing trends along

Sumatera and Java. These results are in agreement with the results of previous dry spell studies in the Malaysian Peninsula that found a regional impression of increasing/decreasing trends in short/long dry spells during the wet period (Deni et al. 2009).

The Dry Spell Index (DSI) that we proposed in this study uses the number of dry days, number of dry spells, and the seasonal length to quantify the seasonal drought into a single value. This is an important approach to have stronger confidence in the prevailing change due to dry spells compared to the common analysis relying on single or multiple selected dry spell-based parameters. For the comparison purpose, we calculated DSI over the same rainy season period as the Standardised Precipitation Index (SPI). DSI showed the capability of preserving the temporal variation in both precipitation and dry days. This feature is important for drought monitoring, since the changes in dry spell duration have a significant impact on the dryness level, even if total precipitation and dry days are the same. Temporal variability in inverse DSI is weakly correlated with the variability in SPI anomaly, suggesting that the DSI is not a repetition or other form of SPI. However, the selection of the threshold value for dry day might change the correlation between these indices. Increasing the dry day threshold value will produce more dry days and longer dry spell durations. It will also make both inverse DSI anomaly and SPI anomaly more similar especially during conditions with low average daily precipitation. The fact that they would be more similar reduces the value of DSI over SPI. Hence, in order to get reliable drought information, it is strongly suggested to consider the purposes of the application in selecting the threshold for dry day (Mathugama and Peiris, 2011) and the site characteristic such as daily evaporation.

Spatial variability suggested a good agreement between the indices, although some stations (mainly monsoon) show discrepancies mainly caused by the increase in extreme dry spells, which were not captured by SPI. For example, the increase in drought severity at Bogor was the result of the increase in the number of dry days and both short and long dry spell durations, although total precipitation also increased. The increased in total precipitation at Bogor was most likely due to the increase in total annual precipitation, which was also found by (Aldrian, 2006). Significant decreases in SPIs' drought in the northern Sulawesi (Tahuna) were caused by increases in precipitation but DSI suggests an opposite change because of the increase in the number of dry days and duration of extreme dry spells. A similar trend was also observed in western Kalimantan (Mempawah). These changes suggest that higher precipitation intensities, which cause increases in total precipitation without significantly changing the proportion of wet/dry days in the rainy season, may not be captured by the DSI. Interestingly, with the exception of Tahuna, both methods gave the same trends over Sumatera and the eastern region covering Sulawesi and the Lesser Sunda Islands. The differences were all found in the central region with mostly monsoon stations.

Our findings help to understand the complexity in drought development, particularly meteorological drought, which can be modified by the changes in the number of dry days and duration of dry spells. Overall, the results agree with a previous global drought study (Damberg and AghaKouchak, 2014) that found increasing global area under drought in the southern hemisphere while no significant change was found in the northern hemisphere. Adopting precipitation as the only parameter for drought investigation potentially weakens the trend toward drier conditions (Damberg and AghaKouchak, 2014), due to insignificant changes in total precipitation and increasing precipitation intensities (Murray-Tortarolo et al. 2017) that produce more precipitation amount in shorter wet spells. It was obvious that the number of significant drying trends increased when potential evapotranspiration was considered in drought estimation (Asadi Zarch et al., 2015). In this study, we showed that dry spells can also be used in drought quantification. In contrast to PET, which requires more data and involves a complex calculation, dry spells can be easily extracted from daily precipitation data and also have a strong relationship with temperature (Dabanli, 2019), which is a major factor in potential evapotranspiration calculations.

3.7 Conclusion

Based on the dry spell index, the drought severity of the rainy season over the IMC region decreased in semi-annual and anti-monsoon regimes but increased in the monsoon regime, except for two stations in Sulawesi that show opposite changes. The results also imply that the southern hemisphere region is dominated by increasing drought while the opposite trend is observed in the northern hemisphere. The decrease/increase in some parameters such as the number of dry days, contribution of long dry spells, and duration of extreme dry spells, seem to be the main factors in decreasing/increasing drought severity over the IMC region. Similar indications of change toward wetter or drier conditions over the IMC were also found in previous studies (Deni et al., 2010, Li et al., 2016, Supari et al., 2017). Those changes may impact the future agricultural production in this region, particularly on Java, Bali and Nusa Tenggara, where all three stations showed increasing drought severity. Prolonged dry days would have a serious impact on crop production by interfering the crop development. Meanwhile, as most of the stations in Sumatera experience a shortening rainy season and increasing daily precipitation rates, surface water management needs to be optimized to extend the water supply for crop cultivation.

The proposed dry spell index has the capability to capture the variability in both total precipitation and dry days. This method produces different drought indications than SPI, confirming that DSI is not replicating SPI. Drought severities become less pronounced with SPI with nearly 40% more decreasing trends. DSI has not been standardised because it is intended to monitor the changes in drought severity. As a result, the value given by DSI cannot be transferred to other indices. In this study, we assumed that the weight factor increases linearly with the dry days. However, since the dry spell duration has a strong correlation with the evaporation rate, the increment of the weight factor could be evaluated by establishing the correlation between those parameters. Strong correlation existed between the rate of evaporation and consecutive dry days may be used to obtain a more comprehensive DSI. Therefore, future attention should be given to developing relationship between dry spells and evaporation rates, so that the evaporation rates can be used to better inform the weighting procedure for consecutive dry days.

Chapter 4

Spatial and temporal analysis of rainy season dryness severity

4.1 Introduction

Drought is an unpredictable, recurring natural phenomenon caused by a deficiency in precipitation, which results in decreases in water storage in the long-term. Due to global population growth and agricultural expansion, there is increasing pressure on water supplies, causing more frequent and severe drought (Vicente-Serrano and López-Moreno, 2005, Hao and Singh, 2015). Drought has caused annual financial losses of more than 3 billion Euros in Europe (Tsakiris, 2017) and 6-8 billion US dollars in the United States (Dai, 2011). Compared to other natural disasters, drought is a creeping phenomenon that progresses slowly and for which it is more difficult to characterize a start and end date of the occurrence. It also covers a wider area (Vicente-Serrano and López-Moreno, 2005, Mishra and Singh, 2010, Tsakiris, 2017), therefore, drought may occur anytime anywhere. In addition, no single drought definition is universally acceptable (Tsakiris et al., 2013), making it difficult to quantify and monitor drought progression and severity.

Several indices have been used globally to estimate drought severity. These indices are generated from either a single variable or a combination of drought related variables (Hao and Singh, 2015). The main parameter controlling drought development, precipitation, is the primary input used in drought indices. Hence, most indices require accumulated precipitation over a particular period. However, several studies have found a consistent change in precipitation characteristics in which extreme precipitation has increased in frequency and magnitude due to global warming (Trenberth, 2011, Ye and Fetzer, 2019). For example, increases in dry spells frequency stimulate drought development even when accumulated precipitation does not change (Huang et al., 2015).

Due to this increasing importance of dry spells under climate change, dry spells studies are important to establish a sound understanding of spatial variation and temporal trend in dry spell occurrence (Li et al., 2017). The term dry spell refers to consecutive days with precipitation below a certain threshold. The subject of previous dry spell studies was primarily identifying maximum duration and frequency (Mupangwa et al., 2011, Ngetich et al., 2014, Raymond et al., 2016, Kebede et al., 2017), which were mostly found during the dry season. Meanwhile, the rainy season naturally exhibits more wet days with short dry spell interferences. Li et al. (2017) found that most of dry days were contributed from very short dry spell durations of 1 or 2 days. However, poor precipitation distribution over time and space resulting from high precipitation variability, potentially causes high dry spell frequency and duration during the rainy season. In addition to that, the occurrences of dry spells in the rainy season have more destructive impacts for agriculture and water resources management in particular.

Globally, dry spells during the rainy season have been shown to increase in frequency and duration, causing impacts to water availability as well as crop growth and production. For example, Byakatonda et al. (2018) found some locations in Botswana are experiencing increasing trends in dry spell frequency during the rainy season, rendering these areas unsuitable for rainfed farming. Although they were not significant, some stations in the Upper Baro-Akobo Basin, Ethiopia, showed increasing trends in maximum duration and frequency of dry spells during the rainy season, indicating the need for better water management planning to minimize future climate risks (Kebede et al. 2017). Meanwhile, extreme dry spells during the wettest period in the eastern and southern parts of Indonesia have increased significantly due to the El Nino (Supari et al. 2018). Hence, dry spells have become an important indicator to understand the dryness of the wet season particularly in the region where wet season precipitation is the primary source of water. However, focussing only on the extreme dry spell duration would neglect dry spells with shorter duration. Thus, it is important to consider all durations of dry spells, which potentially contribute to the increase in the severity of dryness. Additionally, increasing air temperatures are predicted, which will shift the driving force for drought development from precipitation deficit to atmospheric demand, resulting in more water losses by evaporation (Dai and Zhao, 2017). Dabanli (2019) showed that the change in temperature can be directly linked to the characteristics of dry days and dry spells. The frequency and duration of dry spells is highly correlated with the evaporation rate: the longer the dry spell duration, the higher the evaporation rates. Thus, it is important to integrate temperature into drought indices.

Given the need for a better understanding of how dryness severity is related to dry spell occurrence in the rainy season, the objective of this study is to evaluate the spatial and temporal variations of dryness severity during the rainy season. The dryness severity is estimated using the dry spell index (DSI). Because of the strong correlation between dry spell and evaporation we use evaporation rate to define the weight of consecutive dry days in the DSI calculation. We selected the Indonesian Maritime Continent (IMC) as a study area because this region is one of the most rainy areas on earth. Additionally, the IMC precipitation characteristic is also highly influenced by local and global circulation, which results in high variation in rainy season precipitation.

4.2 Study area

Indonesia is an archipelago that has more than 17,000 large and small islands. Indonesia geographically covers a region of 6°N - 11°S and 95 - 141°E and has an area of approximately 2 million km^2 (Figure 4.1). It consists of five big islands, namely Java, Sumatera, Kalimantan, Sulawesi and Irian Jaya and is characterized by complex topography. Java is the most populous island and plays a very important role in agricultural and industrial activities. Complex interaction between land and sea in the IMC caused this area to be depicted as a miniature of the earth, in which land and sea coexist side by side (Yamanaka, 2016).

Because the IMC is sandwiched between two continents (Asia and Australia) and two oceans (Pacific and India), the precipitation is strongly affected by the movement of the Inter-Tropical Convergence Zone (ITCZ). When the ITCZ is in its southernmost position, this region experiences wet periods, which peak in January and February, while when the ITCZ is in its northernmost position this area is relatively dry, peaking in July and August. In addition, Indonesia is also located between the Indo and Pacific warm pools, and hence receive a lot of water vapor originating from the surrounding oceans, making Indonesia one of the highest rainfall areas in the world. The IMC also has high precipitation variability, with three types of precipitation characteristics occurring: monsoon, anti-monsoon, and semi-annual (Aldrian and Dwi Susanto 2003). Monsoon and anti-monsoon have one peak of precipitation, which occurs Dec-Feb and Jun-Jul, respectively, while semi-annual has two peaks in one year, which occur in Oct-Nov and Mar-May.

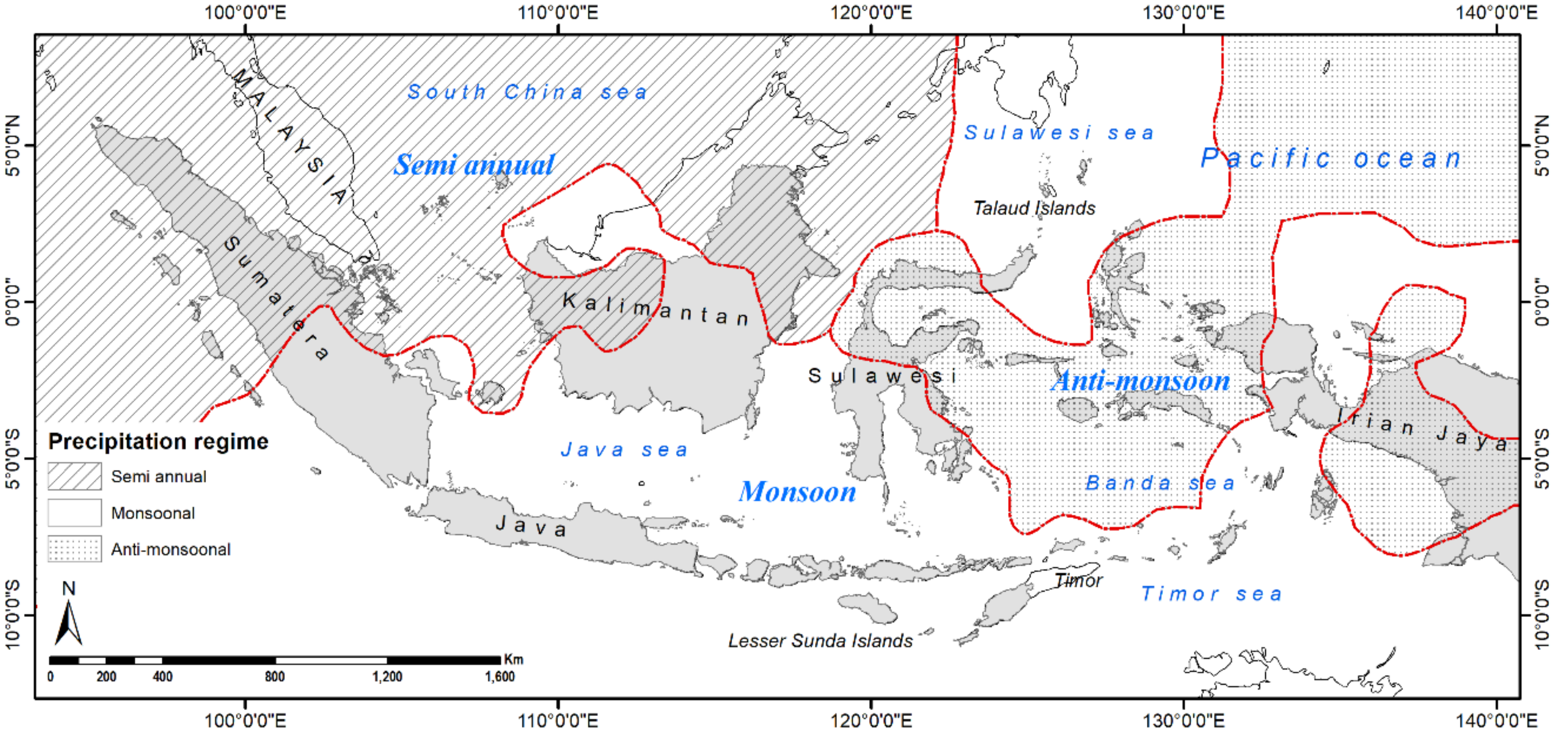


Figure 4.1 The Indonesian maritime continent, showing three climate regimes, which are based on their precipitation characteristics (Aldrian and Dwi Susanto 2003).

4.3 Data and methodology

4.3.1 Data

This study used daily precipitation sourced from Tropical Rainfall Measuring Mission (TRMM) Multi-Satellite Precipitation Analysis (TMPA) 3B42 V7 (https://mirador.gsfc.nasa.gov/) for the time period 1998-2018. This TRMM product has been widely used for precipitation analysis because of its accuracy (Sahoo et al., 2015). GLEAMS data (https://www.gleam.eu/) was used to extract daily actual evaporation data from 1998 to 2014. Both data have 0.25° spatial resolution and were extracted for the IMC region only. The analysis on precipitation data was performed on the inland area only by making use of the GLEAMS data as the masking coverage.

4.3.2 Methodology

4.3.2.1 Definition of rainy season

The onset and cessation of the rainy season were determined using the anomalous accumulation method, applied for each corresponding year. The corresponding year starts from the driest period in the current year and ends before the next driest period. Previous analysis (Chapter 2) suggested that the definition of corresponding year has minor impacts on the onset and cessation date determination. Although the inter-annual difference in corresponding year length may be up to 3 months, the average length of the corresponding year was very similar to the calendric year, i.e. 365 days. Hence, to accommodate the variation, we allow the corresponding year to overlap for 3 months. Thus, the corresponding year is defined as the period from 1 July to 31 August of following year for monsoon and semi-annual regimes and from 1 November to 31 December of following year for the anti-monsoon regime.

The anomalous accumulation method uses the accumulation of the daily precipitation anomaly to determine the onset and cessation of the rainy season. The rainy season is the period with the most intense precipitation, characterised by the increase in anomalous accumulation. The onset of the rainy season is marked by the day after which the anomalous accumulation increases. The increase continues to a maximum point, called the cessation, i.e. the moment when the anomalous accumulation decreases. To deal with a strong variation in precipitation over the study area, we adopted the modified anomalous accumulation, which has been applied in the previous analysis (Section 2.4.2.2).

4.3.2.2 Dry spell index

The dry spell index (DSI) proposed in the previous chapter was used to estimate the dryness severity during the rainy season. The method is time independent and is able to handle strong variation in the onset and cessation of the rainy season. The DSI is calculated using the following formula:

$$DSI = \frac{1}{RSL} \sum_{i=1}^{NDD} w_i \tag{4.1}$$

Where *NDD* is the number of dry days, *RSL* is the rainy season length, and w_i is the weight assigned for each day within a given dry spell. Instead of using sequential numbers for the weight (Section 3.4.2.2), in this study the weights were obtained from the relationship between dry spell and evaporation rates. This is based on the assumption that increasing dryness severity is equivalent to the amount of water loss due to evaporation. Evaporation rates for each dry day in all dry spells during the rainy season were extracted for 50 randomly selected points over the land area of the IMC. For every dry spell, the weight of the dry day was calculated as:

$$w_i = \frac{E_i}{E_1} \tag{4.2}$$

Where w_i is weight on i^{th} day, E_i and E_1 are the average daily evaporation rates for respectively the i^{th} and 1^{st} day in dry spell. Hence, the weight of the first dry day (w_1) within any dry spells will always equals to 1. The relationship between dry spell and evaporation rate was obtained from the dry spells that have duration between 3 to 10 dry days. The reason to use only those dry spells for evaporation rate estimation because the number of dry spell duration lower/greater than 3/10 days was very high/small (>75%/<0.15%). This too high/small number may affect the mean evaporation rate as well as the strength relationship between dry spell and evaporation rate.

4.3.2.3 Trend analysis

We plotted the average total precipitation over the rainy season and average dry spell index for all precipitation regimes for the period 1998 – 2018. We used the Mann-Kendall trend test to detect the possibility of trends in the time series. MK is a non-parametric trend test that is distribution free (Mann, 1945, Kendall, 1975) and has been widely used to detect monotonic trends in many hydro-climatological time series (Hamed and Ramachandra Rao, 1998). We applied the MK on the original time series with the assumption that the data is serially independent because it was derived from onset data of rainy seasons, which are independent from each other. The MK test assesses the null hypothesis (H_0) that no trend exists in the time series. The H_0 will be rejected if the absolute standardized test statistic (Z_S) is greater than the critical value (Z_{crit}) at significance level $\alpha/2$ for the normal distribution. We selected 90% for α and the standardized test statistic is calculated as:

$$Z_S = \begin{cases} S - 1/\sqrt{Var(S)} & if\ S > 0 \\ 0 & if\ S = 0 \\ S + 1/\sqrt{Var(S)} & if\ S < 0 \end{cases} \tag{4.3}$$

where S is the statistic of test defined as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(X_j - X_i\right) \tag{4.4}$$

The statistic S has a mean equal to zero and a variance:

$$Var(S) = \left[n(n-1)(2n+5) - \sum_{j=1}^{m} t_j\left(t_j - 1\right)\left(2t_j + 5\right)\right]/18 \tag{4.5}$$

where t_j is number of tied observations, and m is the number of tied groups. The sign of the Z_S value indicates the direction of change, positive or negative.

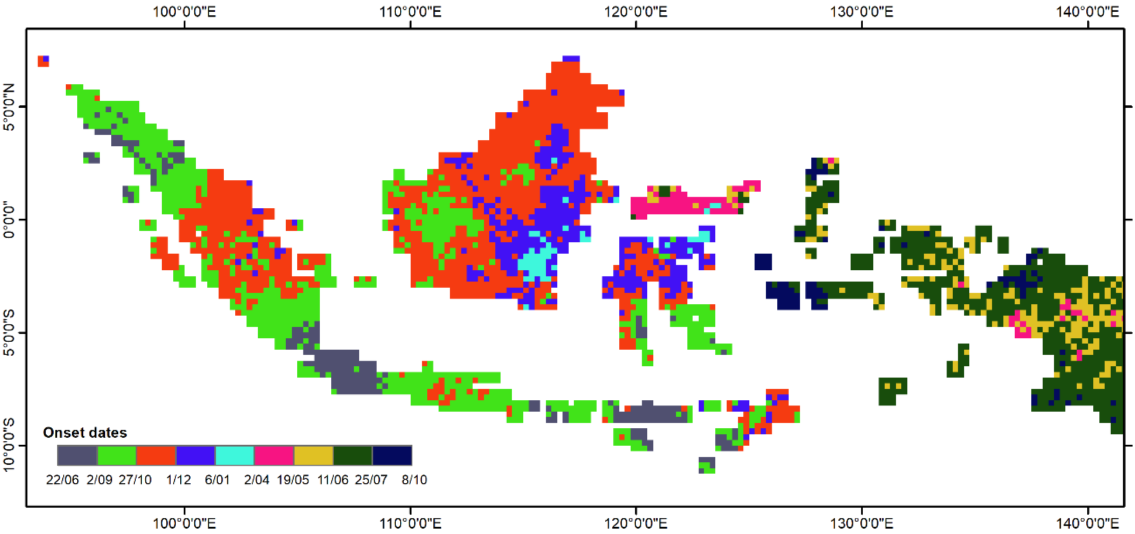
4.4 Results

4.4.1 Onset, length and total precipitation of rainy season

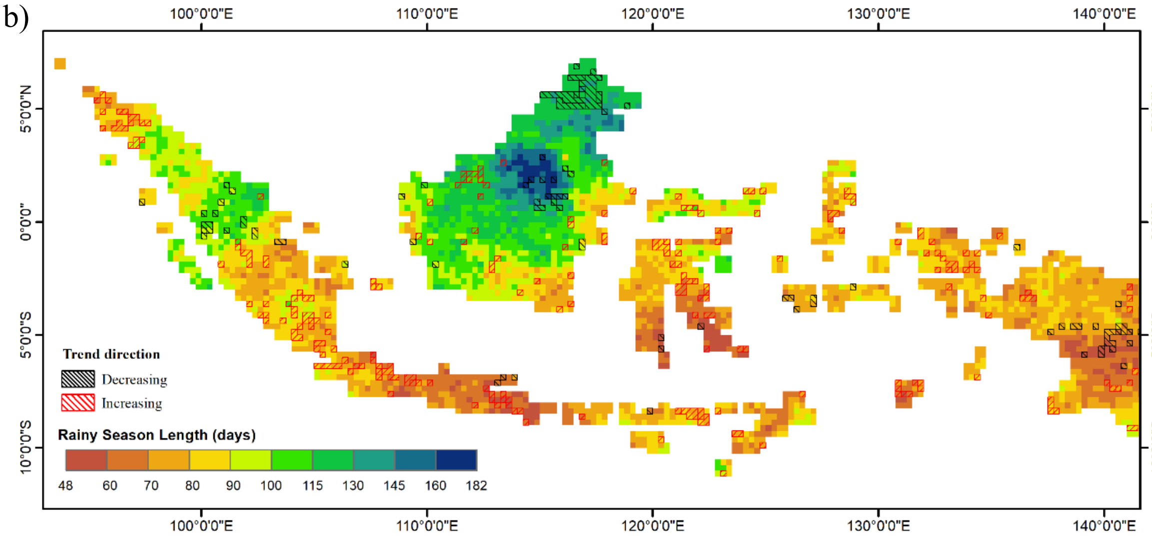
The mean onset of the rainy season over the IMC showed a clear spatial difference between the western and eastern regions (Figure 4.2a). The onset of the rainy season generally occurs between mid-June and early January for the western and central regions. More particular, those occurrences are mid-June to September for Java and middle part of Lesser Sunda Islands, September to October for Sumatera (northern and southern), October to December for middle Sumatera, Kalimantan and middle Sulawesi, and December to January for eastern Kalimantan and middle Sulawesi. Meanwhile, for the eastern region covering Irian Jaya and Maluku islands, the onset occurs within the period mid-Mayl to end-July of the following year.

The rainy season lengths vary from 48 to 182 days (Figure 4.2b). The locations that have rainy seasons up to 6 months were found mainly in central Kalimantan, while only small parts have rainy seasons less than 2 months, such as in eastern Java, southern Sulawesi and middle Irian Jaya. Rainy season in monsoon and anti monsoon regimes generally last from 70 to 90 days while semi annual regime has longer rainy season which is up to 160 days. Significant increasing lengths of the rainy season were found in northern and southern Sumatera, Java and some parts of Lesser Sunda Islands. These trends were also found in the eastern region of IMC distributed over Sulawesi and Irian Jaya. Significant decreasing trends were found mostly in the middle parts of 3 main islands: Sumatera, Kalimantan and Irian Jaya.

High accumulated precipitation during the rainy season was found in middle Kalimantan and northern Sumatera, while low precipitation was found in Sulawesi, northern Maluku and Timor (Figure 4.2c). Significantly, increasing and decreasing trends in rainy season precipitation were found across the region. The increasing trends dominate over the IMC region which were found in all main islands, while decreasing trends were mostly found in middle Sumatera and northern Kalimantan. However, the temporal variability of the average rainy season total precipitation over the whole region has not changed for the last two decades (Figure 4.3a). Regional temporal variation showed that the total precipitation was low in 2002 and 2015 and high in 2010 and 2012. The monsoon and semi-annual rainy season precipitation show increasing slopes (Figure 4.3b, d), meanwhile the anti-monsoon precipitation has a decreasing slope (Figure 4.3c), but none of those slopes were significant. The anti-monsoon rainy season total precipitation exhibits the highest slope of change.


100°0'0"E
110°0'0"E
120°0'0"E
130°0'0"E
140°0'0"E
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
Onset dates
22/06
2/09
27/10
1/12
6/01
2/04
19/05
11/06
25/07
8/10

b)


100°0'0"E
110°0'0"E
120°0'0"E
130°0'0"E
140°0'0"E
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
Trend direction
Decreasing
Increasing
Rainy Season Length (days)
48
60
70
80
90
100
115
130
145
160
182

c)

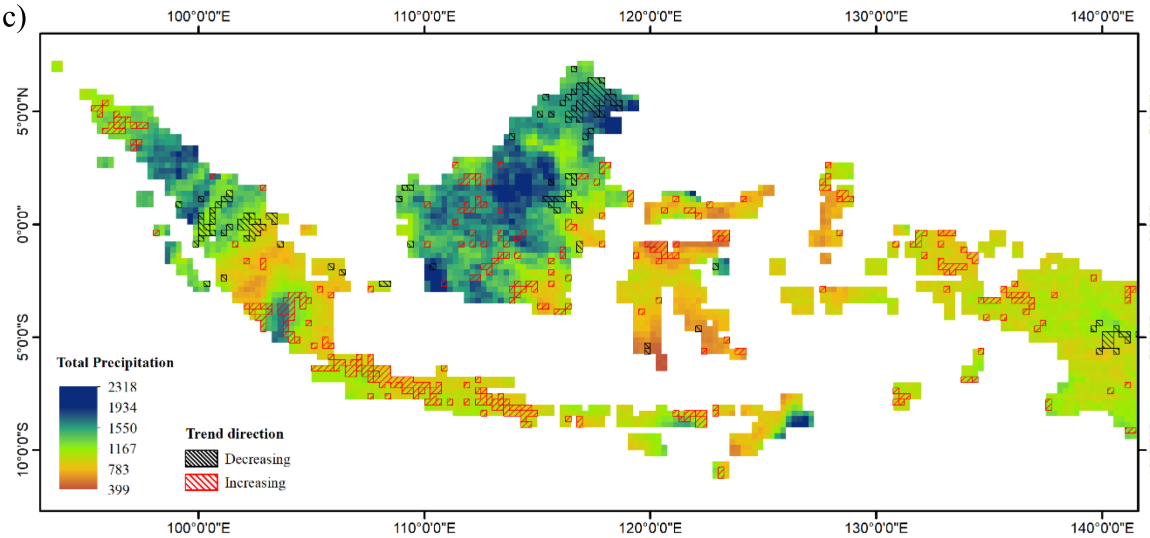

100°0'0"E
110°0'0"E
120°0'0"E
130°0'0"E
140°0'0"E
5°0'0"N
0°0'0"
5°0'0"S
10°0'0"S
Total Precipitation
2318
1934
1550
1167
783
399
Trend direction
Decreasing
Increasing

Figure 4.2 Rainy season (a) onset date, (b) length defined by modified anomalous accumulation, and (c) total precipitation over the land area of the Indonesian Maritime Continent.

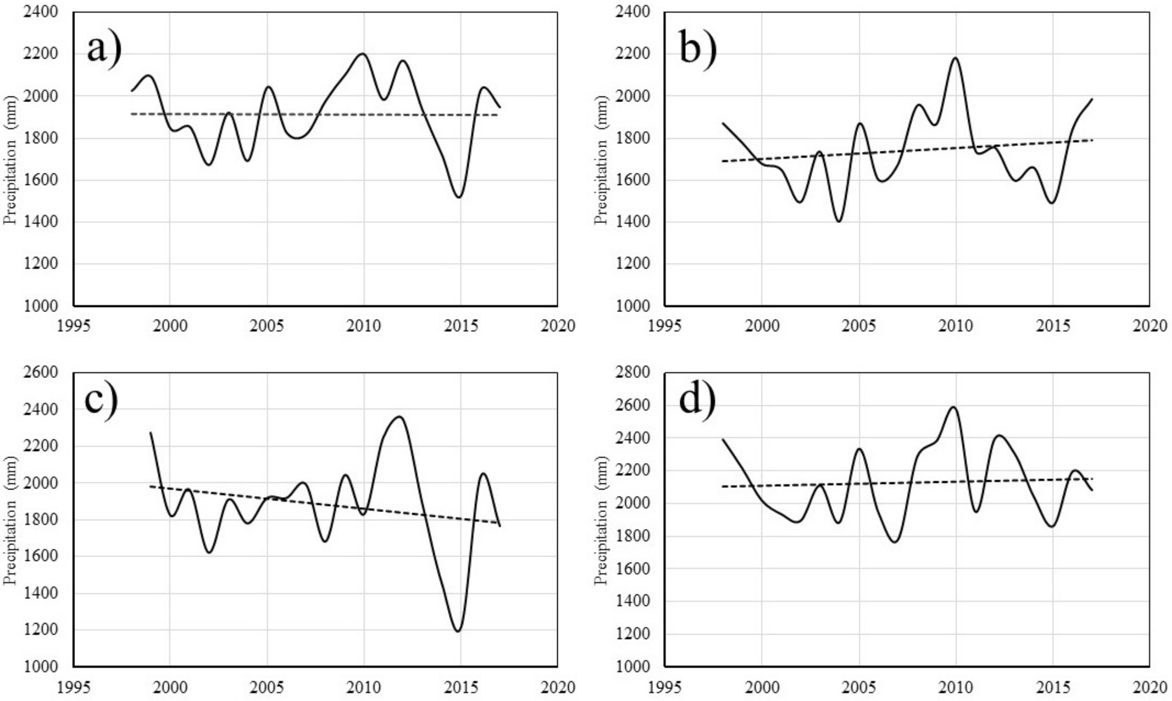


Figure 4.3 Temporal variability in rainy season total precipitation over (a) the Indonesian Maritime Continent, (b) Monsoon, (c) Anti-monsoon, and (d) Semi-annual regimes.

4.4.2 Evaporation rates

Dry spells (DS) over the IMC are dominated by very short spells, approximately 90% of total dry days are contributed by 1 to 3-day DS. Using only dry spells that have duration between 3 and 10 days, the variabilities of evaporation rate were relatively same although their mean tended to increase (Figure 4.4). The mean and standard deviation ranged from 3.5 to 4.3 mm/day and from 0.71 to 0.89, respectively. The ratio of the evaporation rate of the first ten dry days to the evaporation rate of the first dry day is well explained by the equation $y = 0.99x0.08$ with the coefficient determination 0.83.

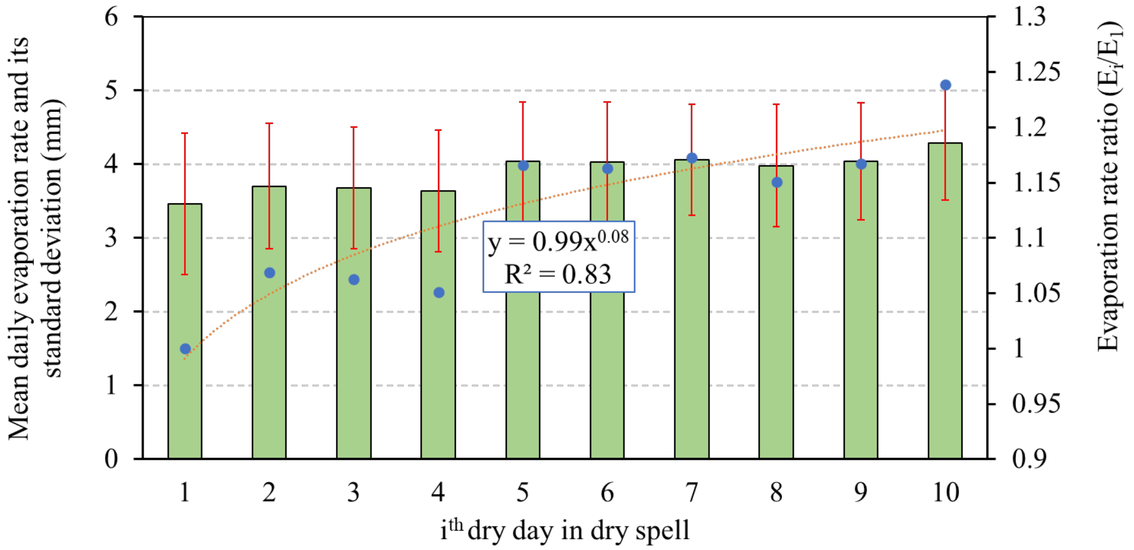


Figure 4.4 Mean evaporation rate (green bar) and standard deviation (red lines) of ith day in dry spells during rainy season are extracted from 50 random points over the IMC region. The ratio of evaporation rate of ith day compared to day 1 (blue dots) is used for the weight factor in DSI.

4.4.3 Dry spell index

The spatial distribution of DSI showed an opposite pattern to the rainy season total precipitation. High DSI was found in southern Sumatera, western Java, Sulawesi and east Timor, while southern Kalimantan and middle Sumatera generally had low DSI (Figure 4.5). Significant increasing and decreasing trends in DSI were found over the IMC region. The increasing trends were found mostly in southern Sumatera, Java, Lesser Sunda Islands, and northern Kalimantan. Significant increasing and decreasing trends in DSI were found over the IMC region. With exception the northern Sumatera, in general the high DSI areas tended to have increasing trend and vice versa. Temporal variation showed positive change with an increase of approximately 2% from the last two decades at regional scale (Figure 4.6a). The increases were also observed in all precipitation regimes, particularly in the monsoon (2.5%) (Figure 4.6b) and anti-monsoon (2.2%) (Figure 4.6c) regimes. On a regional scale, several years show a high DSI, i.e. 2002, 2004 and 2015 (Figure 4.6a). Meanwhile the lowest DSI occurred in 1999. A stronger variation was found in the anti-monsoon DSI, with had a similar peak/trough pattern to the regional with an additional trough in 2011.

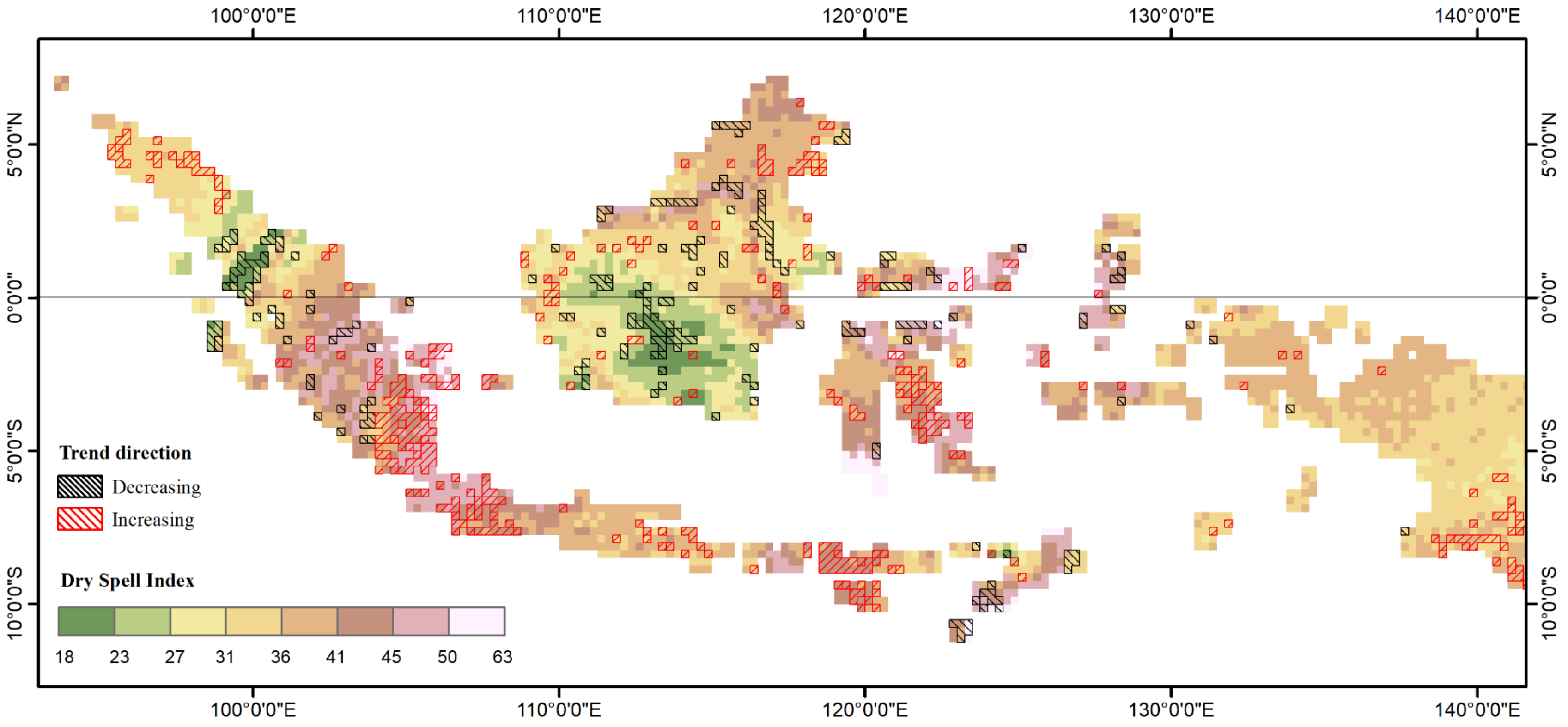


Figure 4.5 Average and significant trends of dry spell index during the rainy season for period 1998-2018.

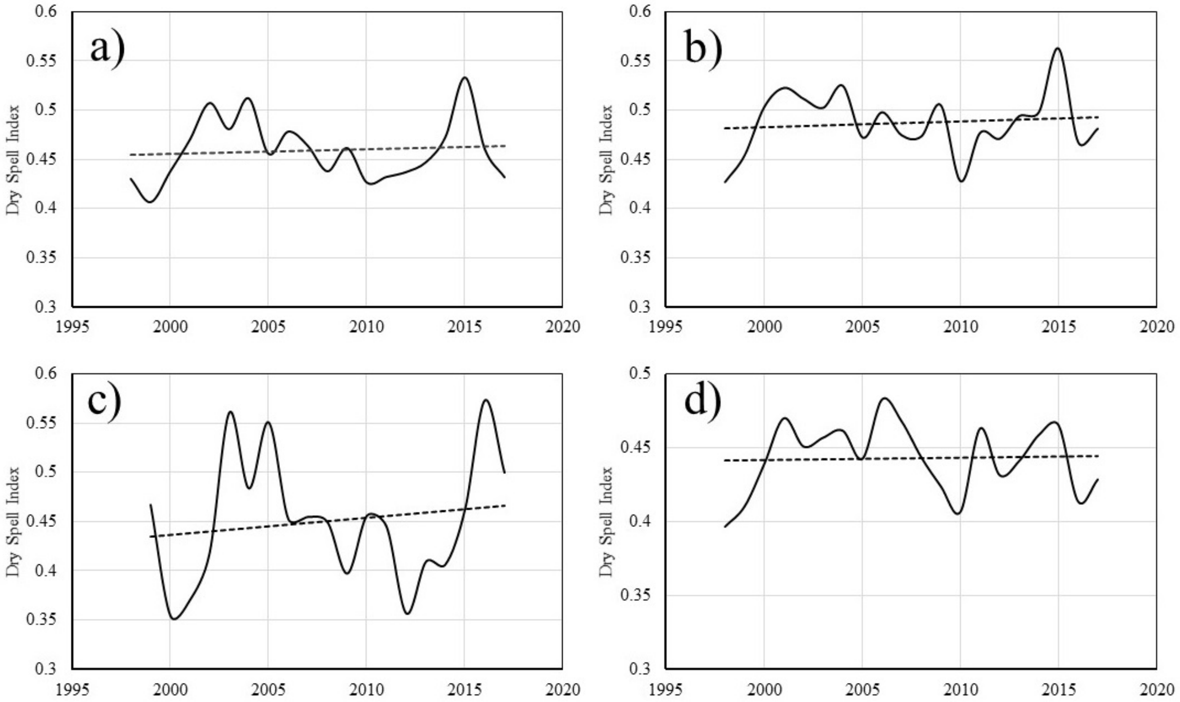


Figure 4.6 Temporal changes in rainy season Dry Spell Index over (a) the whole region of Indonesian Maritime Continent, (b) Monsoon, (c) Anti-monsoon, and (d) Semi-annual regimes.

4.5 Discussion

In this study, we applied a dry spell index that makes use of both evaporation and dry spells to estimate the severity of dryness. We used satellite-based data for both precipitation and actual evaporation, capturing the diversity of precipitation regimes over the Indonesian Maritime Continent. The onsets of the rainy season confirm striking differences in precipitation characteristics within the IMC region as described by Aldrian and Dwi Susanto (2003). The precipitation data showed that the rainy season onset occurred within period of mid-June to October, August to November and April to August for monsoon, semi-annual and anti-monsoon regimes, respectively. However, this result is not consistent with that of Marjuki et al. (2016) and Moron et al. (2010). The inconsistency is likely due to the differences in data and method used. Marjuki et al. (2016) applied the same onset definition to a precipitation station dataset while Moron et al. (2010) used satellite data but adopted different onset definition. A difference in the onsets up to 3 months was also shown by Wati et al. (2019) who adopted multiple thresholds of precipitation in determination of onset in this region.

The average total rainy season precipitation over the IMC has not changed over the last two decades. However, increasing and decreasing trends were found within the precipitation regimes, although they were not significant. These results are very much in line with a previous study (Murray-Tortarolo et al. 2017) who found no significant changes in rainy season precipitation at global scale but on the smaller scales there are tendencies of increasing or decreasing trends. This is also a strong indication of the smoothing out effect when the result is averaged over a large region. The impact of regional oscillation, particularly ENSO, is also evident in the total precipitation at regional and precipitation regime scales. The total precipitation dropped significantly during the very strong El Nino year 2015/2016. These findings were consistent with Supari et al. (2018) who that decreasing total seasonal precipitation is due to El Nino/La Nina.

The map of total precipitation suggested that the southern part of the IMC has a lower rainy season total precipitation while, northern part of the IMC, particularly Kalimantan and northern Sumatera received more precipitation. The results were caused by the longer rainy season duration found for the northern part the IMC. More than 60% of the northern IMC is classified as belonging to the semi-annual regime, which has two peaks of precipitation. However, during the time between these two peaks, precipitation does not completely cease, resulting in a continuous increase in anomaly accumulation, which eventually causes the rainy season to last longer than the single peak regimes. Significant increasing total precipitation was spatially coherent with the increasing length of rainy season. Although it has lower total precipitation, the southern IMC exhibits more increasing trends and some of those were significant. Significant increasing trends were also found in middle Kalimantan, which received more precipitation. Both southern IMC and Kalimantan are within the monsoon regime. Meanwhile, northern Sumatera (semi-annual) and middle Irian Jaya (anti-monsoon regime) are dominated by significant decreasing trends. The increasing trends found in the southern part of the IMC are opposite to the result of Murray-Tortarolo et al. (2017) who found decreasing trends. The primary cause of the discrepancy is the definition of rainy season used in their study. The threshold of 100 mm monthly precipitation used to define their wet/dry season may have resulted in overestimating the wet period. The map of total precipitation shows high spatial variability in this region, which hardly can be observed in rain gauge data set.

The spatial variation in rainy season precipitation was spatially opposite to the variations in DSI. The area that received more precipitation during the rainy season generally has low DSI. Based on trend tests, significant trends were found in the western and central part of the IMC. The significant increasing trends were found mostly in southern Sumatera, northern Kalimantan and Lesser Sunda islands. However, more than 40% of the IMC area have increasing trends in both total precipitation and DSI but only less than 2% of that area has significant trends for both parameters. Increasing trends in those parameters indicate more dry spells occurred during the rainy season along with the possibility of increases in extreme precipitation, which eventually cause increases in total precipitation. These findings were in line with the study by Supari et al. (2017) who found a significant increase in regional precipitation extremes during Dec-Mar and a significant increase in dry spells frequency in the monsoon regime particularly in Java.

The temporal variation of DSI shows consistent positive change at both regional and precipitation regime scales. The change indicates a uniform progression of an increase in dryness severity due to dry spells across the IMC region. This study also found that the most significant increase in rainy season total precipitation occurred in the monsoon regime leading to the strong impression of "getting wetter". However, the DSI revealed that nearly 75% of the area with an increasing dryness is part of the monsoon area. Hence, the impression based on accumulated precipitation only may cause a false interpretation of ongoing drought development. This finding is in accordance with the increasing dry spells frequency found in monsoon regimes (Supari et al, 2017). Decreasing trends in DSI were found generally around the equator area, which covers the area of Sumatera, Kalimantan, Sulawesi and Irian Jaya. However, significant trends were only found mostly in Sumatera and Kalimantan.

Studies have observed and modelled the potential changes in precipitation characteristics, such as intensities, frequencies, and spatial distribution (Donat et al., 2016), which are interrelated with the changes in distribution of wet and dry spells. However, the total precipitation in general may not change significantly (Trenberth 2011), thereby underestimating the drought severity, which is generally assessed based on the accumulated precipitation. Future warmer air temperature will cause more water to evaporate which, also potentially elevate the drought severity (Dai and Zhao 2017). This research provides an alternative characterization of the dryness severity by combining the dry spell and evaporation rate. The proposed method is not only able to capture variation in dryness severity at finer spatial scale but is also time independent, hence it can be applied in at any time scale.

With an increasing need for the drought monitoring, it is also important to have a method that is globally applicable. DSI has shown to be able to capture the dryness severity in the IMC, hence future research needs to calibrate and standardize the dryness severity resulting from the DSI.

4.6 Conclusion

Overall, the dry spell analysis suggested that the dryness severity has increased in the southern part of the IMC over the last 20 years. Meanwhile, decreasing dryness severity was mostly found near the equator. The same pattern was also observed in total precipitation indicating the change in precipitation frequency and intensity toward more extreme conditions. Increasing dryness severity may have important consequences for agricultural activities and water resources management. Increasing dry spell frequency or duration may harm crop development during the growing period, which eventually has impact on total crop production. Important for the IMC is that increasing rainy season dryness was generally found in Java, which is a very important area for agriculture. Hence, water resources and agricultural management need to take the increasing rainy season dryness into account to ensure that no loss in crop productivity will occur.

Chapter 5

Conclusions

5.1 Summary of findings

This thesis investigated the dryness during the rainy season by utilizing frequency and duration of dry spells. This analysis involved the procedure to determine the onset and cessation of the rainy season by using a more flexible approach that can handle high spatial and temporal variations in precipitation. The Indonesian Maritime Continent (IMC) was selected as study area because it is the largest rainy area on the earth and also has high spatial and temporal variability in precipitation. The general results support the findings of previous studies (Damberg and AghaKouchak 2014), showing a general tendency that southern hemisphere regions are experiencing an increase in dryness while northern regions seem to have a decreasing dryness severity. This study also strengthens the prediction of consequences of changing precipitation frequency and intensity (Murray-Totarolo et al. 2017; Trenberth, 2011). Those changes would have no significant impact on total seasonal and annual precipitation but potentially generate more and longer dry spells, which will be the main factor that changes dryness severity (Huang et al., 2015). The four major conclusions of this thesis are:

1. The flexible corresponding year is defined based on the driest period in the year. The driest period of a corresponding year is defined as the longest period of at least 14 consecutive days with the lowest accumulated precipitation. An important advantage of this approach is that it prevents the occurrence of premature cessation of the rainy season and keeps the cessation within the corresponding year. Comparing onset and cessation of the rainy season based on a corresponding year and a traditional calendric year, showed that successfully estimated onsets and cessations for both type of years, were similar. The gap between the first day of the driest period and the onset has significant linear relationship with the onset at most stations over the region.
2. A dry spell index (DSI) primarily based on frequency and duration of dry spells was introduced to characterise the dryness severity during the rainy season. The DSI has the

capability to capture variabilities and changes in both total precipitation and dry days. Drought indications produced by DSI were significantly different from results based on the Standardised Precipitation Index (SPI), suggesting that DSI is not replicating SPI.

3. Integrating evaporation data into DSI by modifying the weight of mean evaporation rate for each dry day in dry spell suggested that the weight increases from the first day to the last day in dry spell. Based on the average of DSI, the dryness severity has increased in the southern part of IMC during the last 20 years. Meanwhile, spatial variation shows that decreasing dryness severities were mostly found near the equator.

4. The Mann-Kendall (MK) trend test for both ground-based and satellite data implied that the southern hemisphere region is dominated by increasing dryness severity. On the other hand, the increasing rainy season total precipitation indicates more extreme but less frequent precipitation. This change has caused increasing number of dry days, an increasing contribution of long dry spells, and an increasing duration of extreme dry spells, which are the main factors in the increasing drought severity over the IMC region.

5.2 Limitations and Future work

Early detection of drought development is becoming more and more important and also requires a more detailed dryness progression at finer spatial and temporal scales. Especially during the rainy season, where the appearance of dry spells can elevate the dryness severity. The dryness is difficult to detect with the commonly used indices because they depend on the accumulation of rainfall in a fixed and uniform period. This thesis showed the use of a dry spell index to characterize the dryness severity based on dry spell frequency and duration. The index is unique and important because it is capable of capturing the dryness development at finer time scale than other drought indices. However, there are some limitations in this study:

1. The driest period, which was used to define the corresponding year as well as the start of onset and cessation of the rainy season, is hard to be identified during the year. Because the driest period is defined as the longest occurrence of at least 14 consecutive days with the lowest cumulative precipitation in the year, it would be difficult to identify the driest period in real-time. Hence, more analysis focussing on the determination of the driest period and how to update the driest period in real time as well as its relationship with the onsets is an

important topic for future study. Since the strong relationship between the occurrence of driest period and the onset of rainy season and the need to have a reliable method that can predict the onset in the real time basis, the definition of driest period then can be modified to be the first n-consecutive days receiving a precipitation less than the 5th percentile of long-term n-days accumulated precipitation. This definition makes it possible to use the driest period for onset prediction in real time. However, the correlation between this revised driest period definition with onset dates need to be carefully evaluated prior to be used for rainy season onset prediction.

2. The dryness severity resulting from the DSI has not been calibrated in this study. Absolute calibration is not possible as there is no true measure of dryness severity. However, comparison to other approaches of dryness severity is crucial to understand the differences and reliability of the DSI to estimate the dryness severity. Since DSI is integrated with evaporation rate, hydrological parameters such as runoff and soil water content or crop production parameters might be potential references for calibration. This evaluation can be used as a method to investigate the added value of DSI against other drought indices, particularly SPI.

3. In order to get a better drought severity, supporting data such as soil type and land cover can be integrated in determining the actual evaporation characteristics. It should also be noted that the level of accuracy of these data should be taken into account by validating them with field recorded data or validation results from previous studies.

4. It is also important to have an index that is globally applicable, hence standardization of DSI should also be considered for further study. Standardization methods and drought classification can be adopted from SPI. It involves fitting to DSI a distribution and transforming to the normal standard distribution. This will make it possible to combine drought severities based on SPI (climatology) and DSI (hydrology), which is very useful in determining actions in dealing with drought mitigation. For example, there might be a year which is classified as wet by SPI but dry by DSI, which can be interpreted as a condition where there is ample of rainfall but hydrologically and agronomically useless because the water cannot be stored and used by vegetation for longer periods of time.

5. The potential impact of El Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) on the drought modulation have not been addressed in this study. As IMC climate is strongly affected by ESNO and IOD through the changes in precipitation characteristic, it is expected that ENSO would also have impact not only on total precipitation but also on daily precipitation rate and the number of dry spell. Therefore, the use of DSI to quantify the impact of ENSO and IOD on the drought development is an interesting subject for future study.

Appendix A

Variation in the onset of the rainy season over the Indonesian Maritime Continent

Abstract for the 9^{th} Edition of the STAHY International Workshop, 2018

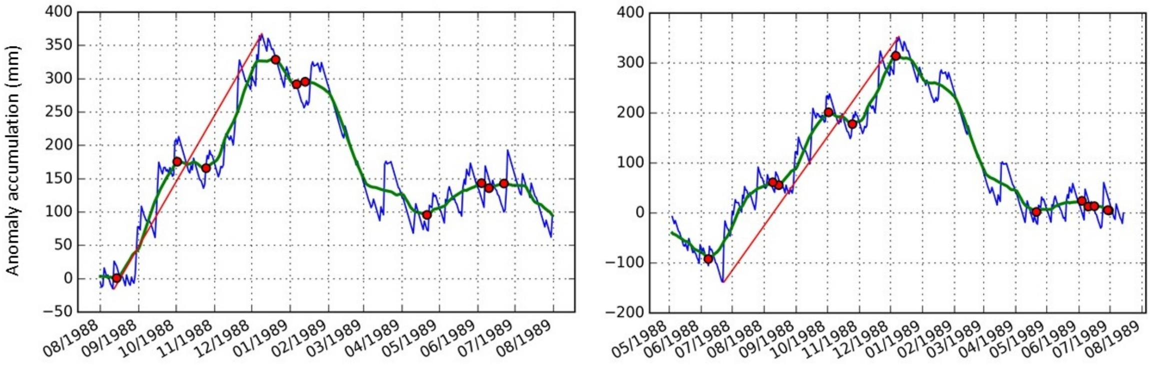
Teuku Ferijal, Okke Batelaan, Margaret Shanafield
College of Science and Engineering, Flinders University, Adelaide, Australia

Indonesian agriculture is highly dependent on the availability and timing of sufficient rainfall. Determination of the onset of the wet season is therefore very important for setting the planting date and ensuring adequate water during plant growth. Currently, the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) method requires at least three consecutive 10-day periods with each at least 50 mm rainfall to determine the beginning of the rainy season. Previous research has concluded that based on rainfall characteristics, Indonesia can be classified into three regions. This study investigates the variation in the onset of the rainy season using the BMKG method and three other methods, including Agronomy, Anomalous Accumulation and modified BMKG, for different regions in Indonesia. With the exception of the BMKG that sets September 1 as the beginning of calculation, other definitions calculate the onset of the wet season from the first day of the driest 14 days in the year. The results show that the onset progression is very similar to the beginning of the driest period, starting from the north of Sumatra down to the south and then to the eastern part of Indonesia. All definitions produce significantly different onsets. However, the Agronomic definition has a very good correlation with modified BMKG ($r \geq 0.7$). This is understandable because both use the rainfall accumulation approach. High correlation is found in all stations in Sumatera and Java Islands except in Banda Aceh ($r = 0.27$). Based on the correlation to the duration from the driest period to the onset day, the occurrences of the driest period can be used to predict the Agronomics' onset days for stations with annual rainfall less than 3,000 mm ($r > 0.6$). The BMKG method has a high probability of ignoring true onset days particularly for stations in northern Sumatera Island. Spatial and temporal variations reveal that the Agronomic definition predicts the most spatially coherent onset day.

Appendix B

Variations in the onset and cessation dates of anomalous accumulation resulting from the application of flexible and fixed corresponding years

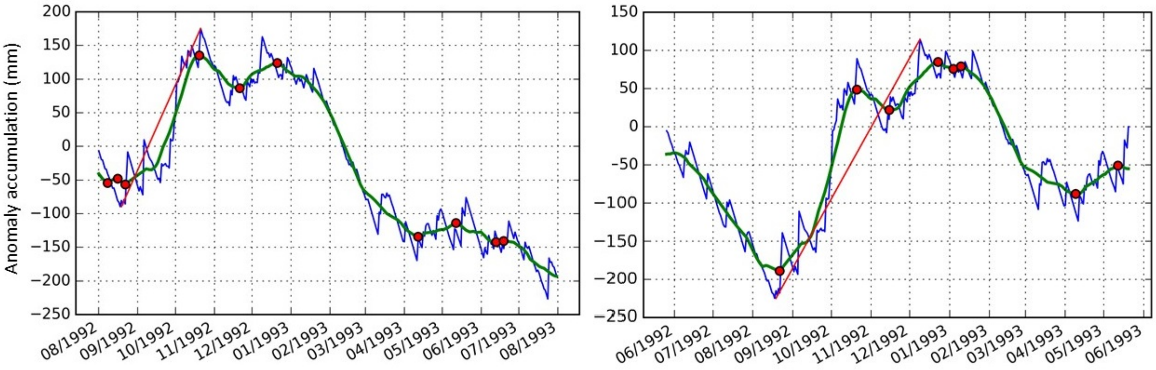
It is expected that the anomaly curve should fall to the minimum point (onset) and then rise to the maximum (cessation). However, the Anomaly accumulation (Aa) curve is often not well established, especially for the IMC, where precipitation occurs almost all year long. The curve sometimes immediately rises or falls continuously because the calculation did not start at the driest period. Here, a comparison is made of the Aa curve resulting from fixed and flexible corresponding years at Medan station for 1988 (Figure B1). It is clear that the flexible corresponding Aa curve produces a better curve that starts with a decline to a minimum point and then rises to a maximum point. The decline indicates the period with no precipitation or precipitation less than the average daily precipitation. The increase indicates a period in which precipitation occurs more frequent at a rate greater than daily average. Meanwhile the fixed corresponding year starts with no increase or decrease in the anomaly curve (horizontal line) and then rises to a maximum point. The horizontal line indicates that the precipitation during that period has a similar rate to the average daily precipitation.



a b

Figure B1. The comparison of the Aa curve resulting from the fixed and flexible method for the Medan station in 1988. The fixed year curve (a) starts with a horizontal green line and then increases indicating that the calculation started in the middle rainy period. The flexible year curve (b) starts with a declining green line (a period when daily precipitation is zero or less than the daily average) and increasing green line (a period when the daily precipitation is greater than the daily average).

Traditionally, Aa uses a fixed mean daily precipitation for whole period of observation. Consequently, the value is sometimes too high for dry years or too low for wet years, which eventually result in incorrect cessation dates. The average daily precipitation of the fixed corresponding year (Figure B2.a) is greater than the flexible corresponding year (Figure B2.b). Although both approaches produce the same onset dates, those methods produce different cessation dates because of differences in average daily precipitation. In this example, the higher average daily precipitation of fixed year approach caused the cessation date (maximum point of anomaly accumulation) to occur earlier. Similarly, the maximum point will be found earlier in case of a lower than average daily precipitation. The cessation date of the flexible year approach is considered to be more a more appropriate cessation date because it takes into account the intense precipitation period after the cessation dates of the fixed year approach.



a b

Figure B2. The comparison of onset and cessation dates resulting from the fixed and flexible method for the Medan station in 1992. Both methods start during a period without precipitation, shown by declining lines at the beginning. The fixed method produces earlier cessation dates than the flexible method because it has greater average daily precipitation. The lower/upper end of red line is the onset/cessation date.

References

Adler, R. F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P.-P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J., Arkin, P. & Nelkin, E. 2003. The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). *Journal of Hydrometeorology,* 4, 1147-1167.

Aldrian, E. 2006. Decreasing trends in annual rainfalls over Indonesia: A threat for the national water resource? *Jurnal Meteorologi dan Geofisika,* 7, 40 - 49.

Aldrian, E. & Djamil, Y. S. 2008. Spatio-temporal climatic change of rainfall in East Java Indonesia. *International Journal of Climatology,* 28, 435-448.

Aldrian, E. & Dwi Susanto, R. 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology,* 23, 1435-1452.

Allan, R. P., Soden, B. J., John, V. O., Ingram, W. & Good, P. 2010. Current changes in tropical precipitation. *Environmental Research Letters,* 5, 025205.

Anagnostopoulou, C., Maheras, P., Karacostas, T. & Vafiadis, M. 2003. Spatial and temporal analysis of dry spells in Greece. *Theoretical and Applied Climatology,* 74, 77-91.

As-Syakur, A. R., Osawa, T., Miura, F., Nuarsa, I. W., Ekayanti, N. W., Dharma, I. G. B. S., Adnyana, I. W. S., Arthana, I. W. & Tanaka, T. 2016. Maritime Continent rainfall variability during the TRMM era: The role of monsoon, topography and El Niño Modoki. *Dynamics of Atmospheres and Oceans,* 75, 58-77.

As-Syakur, A. R., Tanaka, T., Osawa, T. & Mahendra, M. S. 2013. Indonesian rainfall variability observation using TRMM multi-satellite data. *International Journal of Remote Sensing,* 34, 7723-7738.

Asadi Zarch, M. A., Sivakumar, B. & Sharma, A. 2015. Droughts in a warming climate: A global assessment of Standardized precipitation index (SPI) and Reconnaissance drought index (RDI). *Journal of Hydrology,* 526, 183-195.

Ati, O. F., Stigter, C. J. & Oladipo, E. O. 2002. A comparison of methods to determine the onset of the growing season in northern Nigeria. *International Journal of Climatology,* 22, 731-742.

Bombardi, R. J., Moron, V. & Goodnight, J. S. 2020. Detection, variability, and predictability of monsoon onset and withdrawal dates: A review. *International Journal of Climatology,* 40, 641-667.

Bordi, I., Fraedrich, K., Gerstengarbe, F.-W., Werner, P. C. & Sutera, A. 2004. Potential predictability of dry and wet periods: Sicily and Elbe-Basin (Germany). *Theoretical and Applied Climatology,* 77, 125-138.

Boyard-Micheau, J., Camberlin, P., Philippon, N. & Moron, V. 2013. Regional-Scale Rainy Season Onset Detection: A New Approach Based on Multivariate Analysis. *Journal of Climate,* 26, 8916-8928.

Byakatonda, J., Parida, B. P., Kenabatho, P. K. & Moalafhi, D. B. 2018. Prediction of onset and cessation of austral summer rainfall and dry spell frequency analysis in semiarid Botswana. *Theoretical and Applied Climatology,* 135, 101-117.

Byun, H.-R. & Wilhite, D. A. 1999. Objective Quantification of Drought Severity and Duration. *Journal of Climate,* 12, 2747-2756.

Chang, C.-P., Wang, Z., Ju, J. & Li, T. 2004. On the Relationship between Western Maritime Continent Monsoon Rainfall and ENSO during Northern Winter. *Journal of Climate,* 17, 665-672.

Chou, C., Chiang, J. C. H., Lan, C.-W., Chung, C.-H., Liao, Y.-C. & Lee, C.-J. 2013. Increase in the range between wet and dry season precipitation. *Nature Geoscience,* 6, 263-267.

Cindrić, K., Pasarić, Z. & Gajić-Čapka, M. 2010. Spatial and temporal analysis of dry spells in Croatia. *Theoretical and Applied Climatology,* 102, 171-184.

Cook, B. I. & Buckley, B. M. 2009. Objective determination of monsoon season onset, withdrawal, and length. *Journal of Geophysical Research: Atmospheres,* 114, D23109.

Dabanli, I. 2019. Temperature difference relationship among precipitation, dry days, and spells in Turkey. *Theoretical and Applied Climatology,* 135, 765-772.

Dai, A. 2011. Drought under global warming: a review. *Wiley Interdisciplinary Reviews: Climate Change,* 2, 45-65.

Dai, A. & Zhao, T. 2017. Uncertainties in historical changes and future projections of drought. Part I: estimates of historical drought changes. *Climatic Change,* 144, 519-533.

Damberg, L. & Aghakouchak, A. 2014. Global trends and patterns of drought from space. *Theoretical and Applied Climatology,* 117, 441-448.

Dash, S. K., Kulkarni, M. A., Mohanty, U. C. & Prasad, K. 2009. Changes in the characteristics of rain events in India. *Journal of Geophysical Research: Atmospheres,* 114, D10109.

Deni, S. M., Suhaila, J., Wan Zin, W. Z. & Jemain, A. A. 2009a. Spatial trends of dry spells over Peninsular Malaysia during monsoon seasons. *Theoretical and Applied Climatology,* 99, 357-371.

Deni, S. M., Suhaila, J., Wan Zin, W. Z. & Jemain, A. A. 2009b. Spatial trends of dry spells over Peninsular Malaysia during monsoon seasons. *Theoretical and Applied Climatology,* 99, 357.

Deni, S. M., Suhaila, J., Zin, W. Z. W. & Jemain, A. A. 2010. Spatial trends of dry spells over Peninsular Malaysia during monsoon seasons. *Theoretical and applied climatology,* 99, 357.

Dodd, D. E. S. & Jolliffe, I. T. 2001. Early detection of the start of the wet season in semiarid tropical climates of western Africa. *International Journal of Climatology,* 21, 1251-1262.

Donat, M. G., Lowry, A. L., Alexander, L. V., O'gorman, P. A. & Maher, N. 2016. More extreme precipitation in the world's dry and wet regions. *Nature Climate Change,* 6, 508-513.

Dore, M. H. I. 2005. Climate change and changes in global precipitation patterns: What do we know? *Environment International,* 31, 1167-1181.

Dunning, C. M., Black, E. C. L. & Allan, R. P. 2016. The onset and cessation of seasonal rainfall over Africa. *Journal of Geophysical Research: Atmospheres,* 121, 11405-11424.

Fasullo, J. & Webster, P. J. 2003. A Hydrological Definition of Indian Monsoon Onset and Withdrawal. *Journal of Climate,* 16, 3200-3211.

Fischer, E. M. & Knutti, R. 2016. Observed heavy precipitation increase confirms theory and early models. *Nature Climate Change,* 6, 986-991.

Fischer, T., Gemmer, M., Lüliu, L. & Buda, S. 2011. Temperature and precipitation trends and dryness/wetness pattern in the Zhujiang River Basin, South China, 1961–2007. *Quaternary International,* 244, 138-148.

Fitzpatrick, R. G. J., Bain, C. L., Knippertz, P., Marsham, J. H. & Parker, D. J. 2015. The West African Monsoon Onset: A Concise Comparison of Definitions. *Journal of Climate,* 28, 8673-8694.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D. W., Haywood, J., Lean, J., Lowe, D. C. & Myhre, G. 2007. Changes in atmospheric constituents and in radiative forcing. Chapter 2. *Climate Change 2007. The Physical Science Basis.*

Fu, R., Yin, L., Li, W., Arias, P. A., Dickinson, R. E., Huang, L., Chakraborty, S., Fernandes, K., Liebmann, B., Fisher, R. & Myneni, R. B. 2013. Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences,* 110, 18110–18115.

Fubao, S., L., R. M., D., F. G., Ho, L. W., Yongqiang, Z., Neil, B. & H., R. S. 2010. Partitioning the variance between space and time. *Geophysical Research Letters,* 37.

Goswami, B. N. & Xavier, P. K. 2005. ENSO control on the south Asian monsoon through the length of the rainy season. *Geophysical Research Letters,* 32, L18717.

Groisman, P. Y., Knight, R. W., Easterling, D. R., Karl, T. R., Hegerl, G. C. & Razuvaev, V. N. 2005. Trends in Intense Precipitation in the Climate Record. *Journal of Climate,* 18, 1326-1350.

Hamada, J.-I., Yamanaka, M. D., Matsumoto, J., Fukao, S., Winarso, P. A. & Sribimawati, T. 2002. Spatial and Temporal Variations of the Rainy Season over Indonesia and their Link to ENSO. *Journal of the Meteorological Society of Japan. Ser. II,* 80, 285-310.

Hamed, K. H. & Ramachandra Rao, A. 1998. A modified Mann-Kendall trend test for autocorrelated data. *Journal of Hydrology,* 204, 182-196.

Hao, Z. & Singh, V. P. 2015. Drought characterization from a multivariate perspective: A review. *Journal of Hydrology,* 527, 668-678.

Huang, J., Liu, F., Xue, Y. & Sun, S. 2015. The spatial and temporal analysis of precipitation concentration and dry spell in Qinghai, northwest China. *Stochastic Environmental Research and Risk Assessment,* 29, 1403-1411.

Ibrahim, B., Polcher, J., Karambiri, H. & Rockel, B. 2012. Characterization of the rainy season in Burkina Faso and it's representation by regional climate models. *Climate Dynamics,* 39, 1287-1302.

Juneng, L. & Tangang, F. T. 2010. Long-term trends of winter monsoon synoptic circulations over the maritime continent: 1962–2007. *Atmospheric Science Letters,* 11, 199-203.

Karl, T. R. & Trenberth, K. E. 2003. Modern Global Climate Change. *Science,* 302, 1719-1723.

Kebede, A., Diekkrüger, B. & Edossa, D. C. 2017. Dry spell, onset and cessation of the wet season rainfall in the Upper Baro-Akobo Basin, Ethiopia. *Theoretical and Applied Climatology,* 129, 849-858.

Kendall, K. 1975. Thin-film peeling-the elastic term. *Journal of Physics D: Applied Physics,* 8, 1449-1452.

Kirono, D. G. C., Butler, J. R. A., Mcgregor, J. L., Ripaldi, A., Katzfey, J. & Nguyen, K. 2016. Historical and future seasonal rainfall variability in Nusa Tenggara Barat Province, Indonesia: Implications for the agriculture and water sectors. *Climate Risk Management,* 12, 45-58.

Kostopoulou, E. & Jones, P. D. 2005. Assessment of climate extremes in the Eastern Mediterranean. *Meteorology and Atmospheric Physics,* 89, 69-85.

Lana, X., Martínez, M. D., Burgueño, A., Serra, C., Martín-Vide, J. & Gómez, L. 2008. Spatial and temporal patterns of dry spell lengths in the Iberian Peninsula for the second half of the twentieth century. *Theoretical and Applied Climatology,* 91, 99-116.

Latif, M. & Syed, F. S. 2016. Determination of summer monsoon onset and its related large-scale circulation characteristics over Pakistan. *Theoretical and Applied Climatology,* 125, 509-520.

Laux, P., Wagner, S., Wagner, A., Jacobeit, J., Bárdossy, A. & Kunstmann, H. 2009. Modelling daily precipitation features in the Volta Basin of West Africa. *International Journal of Climatology,* 29, 937-954.

Lestari, S., Hamada, J.-I., Syamsudin, F., Sunaryo, Matsumoto, J. & Yamanaka, M. D. 2016. ENSO Influences on Rainfall Extremes around Sulawesi and Maluku Islands in the Eastern Indonesian Maritime Continent. *SOLA,* 12, 37-41.

Li, X., Meshgi, A. & Babovic, V. 2016. Spatio-temporal variation of wet and dry spell characteristics of tropical precipitation in Singapore and its association with ENSO. *International Journal of Climatology,* 36, 4831-4846.

Li, Z., Li, Y., Shi, X. & Li, J. 2017. The characteristics of wet and dry spells for the diverse climate in China. *Global and Planetary Change,* 149, 14-19.

Liebmann, B., Camargo, S. J., Seth, A., Marengo, J. A., Carvalho, L. M. V., Allured, D., Fu, R. & Vera, C. S. 2007. Onset and End of the Rainy Season in South America in Observations and the ECHAM 4.5 Atmospheric General Circulation Model. *Journal of Climate,* 20, 2037-2050.

Liebmann, B. & Marengo, J. 2001. Interannual Variability of the Rainy Season and Rainfall in the Brazilian Amazon Basin. *Journal of Climate,* 14, 4308-4318.

Mandapaka, P. V., Qin, X. & Lo, E. Y.-M. 2016. Seasonal and Interannual Variability of Wet and Dry Spells over Two Urban Regions in the Western Maritime Continent. *Journal of Hydrometeorology,* 17, 1579-1600.

Mann, H. B. 1945. Nonparametric Tests Against Trend. *Econometrica,* 13, 245-259.

Marjuki, Schrier, G. V. D., Tank, A. M. G. K., Besselaar, E. J. M. V. D., Nurhayati & Swarinoto, Y. S. 2016. Observed Trends and Variability in Climate Indices Relevant for Crop Yields in Southeast Asia. *Journal of Climate,* 29, 2651-2669.

Mathugama, S. & Peiris, T. 2011. Critical evaluation of dry spell research. *Int. J. Basic Appl. Sci,* 11, 153-160.

Mckee, T. B., Doesken, N. J. & Kliest, J. 1993. The relationship of drought frequency and duration to time scales. Proceedings of the Eighth Conference on Applied Climatology, 17–22 January 1993 1993 Anaheim, California. 179-184.

Mishra, A. K. & Singh, V. P. 2010. A review of drought concepts. *Journal of Hydrology,* 391, 202-216.

Misra, V. & Dinapoli, S. 2014. The variability of the Southeast Asian summer monsoon. *International Journal of Climatology,* 34, 893-901.

Misra, V. & Dinapoli, S. M. 2013. Understanding the wet season variations over Florida. *Climate Dynamics,* 40, 1361-1372.

Mori, S., Jun-Ichi, H., Tauhid, Y. I., Yamanaka, M. D., Okamoto, N., Murata, F., Sakurai, N., Hashiguchi, H. & Sribimawati, T. 2004. Diurnal Land–Sea Rainfall Peak Migration over Sumatera Island, Indonesian Maritime Continent, Observed by TRMM Satellite and Intensive Rawinsonde Soundings. *Monthly Weather Review,* 132, 2021-2039.

Moron, V., Lucero, A., Hilario, F., Lyon, B., Robertson, A. W. & Dewitt, D. 2009a. Spatio-temporal variability and predictability of summer monsoon onset over the Philippines. *Climate Dynamics,* 33, 1159.

Moron, V., Robertson, A. W. & Boer, R. 2009b. Spatial Coherence and Seasonal Predictability of Monsoon Onset over Indonesia. *Journal of Climate,* 22, 840-850.

Moron, V., Robertson, A. W. & Qian, J.-H. 2010. Local versus regional-scale characteristics of monsoon onset and post-onset rainfall over Indonesia. *Climate Dynamics,* 34, 281-299.

Muhammad, T. U. & Reason, C. J. C. 2004. Dry spell frequencies and their variability over southern Africa. *Climate Research,* 26, 199-211.

Mupangwa, W., Walker, S. & Twomlow, S. 2011. Start, end and dry spells of the growing season in semi-arid southern Zimbabwe. *Journal of Arid Environments,* 75, 1097-1104.

Murray-Tortarolo, G., Jaramillo, V. J., Maass, M., Friedlingstein, P. & Sitch, S. 2017. The decreasing range between dry- and wet- season precipitation over land and its effect on vegetation primary productivity. *PLOS ONE,* 12, e0190304.

Neale, R. & Slingo, J. 2003. The Maritime Continent and Its Role in the Global Climate: A GCM Study. *Journal of Climate,* 16, 834-848.

Ngetich, K. F., Mucheru-Muna, M., Mugwe, J. N., Shisanya, C. A., Diels, J. & Mugendi, D. N. 2014. Length of growing season, rainfall temporal distribution, onset and cessation dates in the Kenyan highlands. *Agricultural and Forest Meteorology,* 188, 24-32.

Omotosho, J. B., Balogun, A. A. & Ogunjobi, K. 2000. Predicting monthly and seasonal rainfall, onset and cessation of the rainy season in West Africa using only surface data. *International Journal of Climatology,* 20, 865-880.

Pérez-Sánchez, J. & Senent-Aparicio, J. 2017. Analysis of meteorological droughts and dry spells in semiarid regions: a comparative analysis of probability distribution functions in the Segura Basin (SE Spain). *Theoretical and Applied Climatology,* 133, 1061–1074.

Pierre, C. & Mbaye, D. 2003. Application of daily rainfall principal component analysis to the assessment of the rainy season characteristics in Senegal. *Climate Research,* 23, 159-169.

Polade, S. D., Pierce, D. W., Cayan, D. R., Gershunov, A. & Dettinger, M. D. 2014. The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports,* 4, 4364.

Qian, J.-H. 2008. Why Precipitation Is Mostly Concentrated over Islands in the Maritime Continent. *Journal of the Atmospheric Sciences,* 65, 1428-1441.

Qian, J.-H., Robertson, A. W. & Moron, V. 2010. Interactions among ENSO, the Monsoon, and Diurnal Cycle in Rainfall Variability over Java, Indonesia. *Journal of the Atmospheric Sciences,* 67, 3509-3524.

Qian, W., Fu, J. & Yan, Z. 2007. Decrease of light rain events in summer associated with a warming environment in China during 1961–2005. *Geophysical Research Letters,* 34, L11705.1– L11705.5.

Ramage, C. S. 1968. Role of a tropical "maritime continent" in the atmospheric circulation. *Mon. Wea. Rev,* 96, 365-370.

Ratan, R. & Venugopal, V. 2013. Wet and dry spell characteristics of global tropical rainfall. *Water Resources Research,* 49, 3830-3841.

Raymond, F., Ullmann, A., Camberlin, P., Drobinski, P. & Smith, C. C. 2016. Extreme dry spell detection and climatology over the Mediterranean Basin during the wet season. *Geophysical Research Letters,* 43, 7196-7204.

Richard, S. & Walsh, K. J. E. 2017. The influence of El Niño–Southern Oscillation on boreal winter rainfall over Peninsular Malaysia. *Theoretical and Applied Climatology,* 134, 121-138.

Robertson, A. W., Moron, V. & Swarinoto, Y. 2009. Seasonal predictability of daily rainfall statistics over Indramayu district, Indonesia. *International Journal of Climatology,* 29, 1449-1462.

S. Debortoli, N., Dubreuil, V., Funatsu, B., Delahaye, F., De Oliveira, C. H., Rodrigues-Filho, S., Saito, C. H. & Fetter, R. 2015. Rainfall patterns in the Southern Amazon: a chronological perspective (1971–2010). *Climatic Change,* 132, 251-264.

Sahoo, A. K., Sheffield, J., Pan, M. & Wood, E. F. 2015. Evaluation of the Tropical Rainfall Measuring Mission Multi-Satellite Precipitation Analysis (TMPA) for assessment of large-scale meteorological drought. *Remote Sensing of Environment,* 159, 181-193.

Segele, Z. T. & Lamb, P. J. 2005. Characterization and variability of Kiremt rainy season over Ethiopia. *Meteorology and Atmospheric Physics,* 89, 153-180.

Seleshi, Y. & Camberlin, P. 2006. Recent changes in dry spell and extreme rainfall events in Ethiopia. *Theoretical and Applied Climatology,* 83, 181-191.

Seregina, L. S., Fink, A. H., Van Der Linden, R., Elagib, N. A. & Pinto, J. G. 2019. A new and flexible rainy season definition: Validation for the Greater Horn of Africa and application to rainfall trends. *International Journal of Climatology,* 39, 989-1012.

Serra, C., Martínez, M. D., Lana, X. & Burgueño, A. 2013. European dry spell length distributions, years 1951–2000. *Theoretical and Applied Climatology,* 114, 531-551.

She, D. & Xia, J. 2013. The spatial and temporal analysis of dry spells in the Yellow River basin, China. *Stochastic Environmental Research and Risk Assessment,* 27, 29-42.

Simpson, J., Keenan, T. D., Ferrier, B., Simpson, R. H. & Holland, G. J. 1993. Cumulus mergers in the maritime continent region. *Meteorology and Atmospheric Physics,* 51, 73-99.

Singh, D., Tsiang, M., Rajaratnam, B. & Diffenbaugh, N. S. 2014. Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. *Nature Climate Change,* 4, 456-461.

Singh, N. & Ranade, A. 2010. The Wet and Dry Spells across India during 1951–2007. *Journal of Hydrometeorology,* 11, 26-45.

Siswanto, S., Van Oldenborgh, G. J., Van Der Schrier, G., Jilderda, R. & Van Den Hurk, B. 2016. Temperature, extreme precipitation, and diurnal rainfall changes in the urbanized Jakarta city during the past 130 years. *International Journal of Climatology,* 36, 3207-3225.

Supari, Tangang, F., Juneng, L. & Aldrian, E. 2017. Observed changes in extreme temperature and precipitation over Indonesia. *International Journal of Climatology,* 37, 1979-1997.

Supari, Tangang, F., Salimun, E., Aldrian, E., Sopaheluwakan, A. & Juneng, L. 2018. ENSO modulation of seasonal rainfall and extremes in Indonesia. *Climate Dynamics,* 51, 2559-2580.

Sushama, L., Ben Said, S., Khaliq, M. N., Nagesh Kumar, D. & Laprise, R. 2014. Dry spell characteristics over India based on IMD and APHRODITE datasets. *Climate Dynamics,* 43, 3419-3437.

Tolika, K. & Maheras, P. 2005. Spatial and temporal characteristics of wet spells in Greece. *Theoretical and Applied Climatology,* 81, 71-85.

Trenberth, K. E. 2011. Changes in precipitation with climate change. *Climate Research,* 47, 123-138.

Trenberth, K. E., Dai, A., Van Der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R. & Sheffield, J. 2013. Global warming and changes in drought. *Nature Climate Change,* 4, 17-22.

Tsakiris, G. 2017. Drought Risk Assessment and Management. *Water Resources Management,* 31, 3083-3095.

Tsakiris, G., Nalbantis, I., Vangelis, H., Verbeiren, B., Huysmans, M., Tychon, B., Jacquemin, I., Canters, F., Vanderhaegen, S., Engelen, G., Poelmans, L., De Becker, P. & Batelaan, O. 2013. A System-based Paradigm of Drought Analysis for Operational Management. *Water Resources Management,* 27, 5281-5297.

Van Loon, A. F. 2015. Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water,* 2, 359-392.

Vicente-Serrano, S. M. & López-Moreno, J. I. 2005. Hydrological response to different time scales of climatological drought: an evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin. *Hydrology and Earth System Sciences Discussions,* 9, 523-533.

Wati, T., Kusumaningtyas, S. D. A. & Aldrian, E. 2019. Study of season onset based on water requirement assessment. *IOP Conference Series: Earth and Environmental Science,* 299, 012042.

Wilby, R. L., Noone, S., Murphy, C., Matthews, T., Harrigan, S. & Broderick, C. 2016. An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network. *International Journal of Climatology,* 36, 2854-2865.

Wilhite, D. A. & Glantz, M. H. 1985. Understanding: the Drought Phenomenon: The Role of Definitions. *Water International,* 10, 111-120.

Yamanaka, M. D. 2016. Physical climatology of Indonesian maritime continent: An outline to comprehend observational studies. *Atmospheric Research,* 178-179, 231-259.

Yanto, Rajagopalan, B. & Zagona, E. 2016. Space–time variability of Indonesian rainfall at inter-annual and multi-decadal time scales. *Climate Dynamics,* 47, 2975-2989.

Ye, H. & Fetzer, E. J. 2019. Asymmetrical Shift Toward Longer Dry Spells Associated with Warming Temperatures During Russian Summers. *Geophysical Research Letters,* 46, 11455-11462.

Yue, S., Pilon, P. & Cavadias, G. 2002. Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology,* 259, 254-271.

Zhang, T., Yang, S., Jiang, X. & Zhao, P. 2016. Seasonal–Interannual Variation and Prediction of Wet and Dry Season Rainfall over the Maritime Continent: Roles of ENSO and Monsoon Circulation. *Journal of Climate,* 29, 3675-3695.

Zhang, X., Alexander, L., Hegerl, G. C., Jones, P., Tank, A. K., Peterson, T. C., Trewin, B. & Zwiers, F. W. 2011. Indices for monitoring changes in extremes based on daily temperature and precipitation data. *WIREs Climate Change,* 2, 851-870.

Zhang, Y., Li, T., Wang, B. & Wu, G. 2002. Onset of the Summer Monsoon over the Indochina Peninsula: Climatology and Interannual Variations. *Journal of Climate,* 15, 3206-3221.