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Seasonal and Interannual Variability of Wet and Dry Spells over Two Urban Regions in the Western Maritime Continent

PRADEEP V. MANDAPAKA, XIAOSHENG QIN, AND EDMOND YAT-MAN LO
School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

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ABSTRACT

Daily rainfall data from two urban regions in Southeast Asia are analyzed to study seasonal and interannual variability of wet and dry spells. The analysis is carried out using 35 years of data from Singapore and 23 years of data from Jakarta. The frequency distribution of wet (dry) spells and their relative contribution to the total number of wet (dry) days and to the total rainfall are studied using 15 statistical indicators. At the annual scale, Singapore has a greater number of wet spells and a larger mean wet spell length compared to Jakarta. However, both cities have equal probability of extreme wet spells. Seasonal-scale analysis shows that Singapore is drier (wetter) than Jakarta during boreal winter (summer). The probability of extreme wet spells is lower (higher) for Singapore than Jakarta during boreal winter (summer). The results show a stronger contrast between Singapore and Jakarta during boreal summer. The study also examined the time series of Singapore wet and dry spell indicators for the presence of interannual trends. The results indicate statistically significant upward trends for a majority of wet spell indicators. The wet day percentage and mean wet spell length are increasing at 2.0% decade$^{-1}$ and 0.18 days decade$^{-1}$, respectively. Analysis of dynamic and thermodynamic variables from ERA-Interim during the study period indicates a strengthening of low-level convergence and vertical motion and an increase in specific humidity and atmospheric instability (convective available potential energy), which explain the increasing trends observed in Singapore wet spell indicators.

1. Introduction

The Maritime Continent is known for high convective activity, warm and shallow seas, abundant rainfall, and significant latent heat release (e.g., Ramage 1968; Chang et al. 2005). These characteristics make this region one of the main drivers of global atmospheric circulation (e.g., Neale and Slingo 2003). In addition, complex land–sea organization and island topography of the region result in high variability in precipitation characteristics (e.g., Qian 2008; Hamada et al. 2008). In recent years, the western Maritime Continent (WMC) has experienced a number of extreme rainfall events, which led to severe impacts on society and environment. The December 2006 and November 2012 floods in the southern Peninsular Malaysia and February 2007 and January 2013 floods in Jakarta, Indonesia, resulted in extensive property and infrastructure damage along with some fatalities (e.g., Tangang et al. 2008; Chatterjea 2011; Chang 2011; Trilaksono et al. 2012; Wu et al. 2013; Budiyono et al. 2015). At the other end of the spectrum is the February 2014 prolonged dry spell in Singapore and Peninsular Malaysia, which compelled Malaysian states like Johor and Selengor to implement water rationing (e.g., Ziegler et al. 2014). These recent extreme events call for an improved understanding of different rainfall regimes in this region.

There have been many studies that have analyzed various aspects of precipitation variability in the WMC region at local to regional scales and from subdaily to annual time scales (e.g., Sivakumar et al. 1999; Manton et al. 2001; Aldrian and Susanto 2003; Wu et al. 2009; Suhaila et al. 2010; Varikoden et al. 2010, 2011; Mandapaka and Qin 2013, 2015). Rain-rate probabilities, diurnal behavior, spatial correlations,
scale invariance, and interannual variability are some of the features that received particular attention. Besides these characteristics of rainfall, it is also important to understand the distribution of wet and dry periods at seasonal and annual scales. An extreme rainfall event embedded in an already long wet period would result in more damage because of antecedent wet conditions (e.g., Chatterjea 2011). The wet and dry spell structure is also an important input to the weather generators.

Recent studies investigated the characteristics of wet and dry spells over Peninsular Malaysia and Singapore (Deni et al. 2008; Deni and Jemain 2009; Deni et al. 2010a,b; Zin and Jemain 2010; Chatterjea 2011). However, a majority of these studies focused on identifying parametric probability distributions that best fit the wet and dry spell occurrences. For example, Deni et al. (2008) assessed the performance of various theoretical probability models in representing the wet (dry) spell distributions and provided a summary of basic statistics such as the mean, standard deviation, and maximum wet (dry) spell lengths. Deni et al. (2010b) focused on the spatial variability of the trends in dry spell characteristics over Peninsular Malaysia. Zin and Jemain (2010) analyzed return periods of extreme dry spells using annual maximum and partial duration approaches.

The above studies improved our understanding of the wet and dry spell distributions, especially regarding the best-fitting probability models and basic characteristics such as mean and maximum wet (dry) spell lengths. However, there is a need to explore wet (dry) spell structure from the perspective of their contribution to the total wet (dry) days and total rainfall accumulation. The extreme wet (dry) spells also need to be defined in an objective manner and studied in a more rigorous framework. Furthermore, the linkages between local-scale wet (dry) spell distributions of the WMC region and the large-scale variables such as wind patterns, vertical motion, and moisture availability need to be better understood. The purpose of this study is to address these research gaps by carrying out a comprehensive analysis of point rainfall data from rain gauges in Singapore and Jakarta. These two selected cities have undergone a rapid rate of urbanization and are home to about 15 million people. Jakarta is particularly vulnerable to coastal and riverine flooding because of its flat and low terrain and closeness to the sea (e.g., Firman et al. 2011). The selected cities are representative to some extent of other cities in the WMC region. In addition, good-quality rainfall data are available for these cities. The goals of the present work are as follows:

1) to characterize and compare the frequency distributions of wet and dry spells in Singapore and Jakarta by using various statistical indicators;
2) to assess the relative contribution of wet (dry) spells to the total number of wet (dry) days and to the total rainfall accumulation;
3) to study the seasonal behavior in wet and dry spells with a particular focus on extreme spells;
4) to evaluate and quantify the trends in wet and dry spell characteristics using nonparametric statistical techniques; and
5) to examine if the seasonal and interannual variability in wet and dry spells can be explained by the behavior of large-scale dynamic and thermodynamic variables.

The study area and data characteristics are described in the next section. Section 3 provides a description of wet and dry spell indicators used in this study. The results are discussed in section 4, followed by concluding remarks in section 5.

2. Study area and data description
2a. Description of the study area

Figure 1 shows a map of the WMC region and the location of Singapore and Jakarta. Singapore lies near the southern tip of Peninsular Malaysia, between 1.2° and 1.5°N and 103.5° and 104.1°E. Most of the island nation is at about 15 m above mean sea level. The special capital region of Jakarta [Daerah Khusus Ibukota Jakarta (Jakarta DKI)] lies in the northwestern part of the island of Java, between 6.0° and 6.4°S and 106.6° and 107.1°E. The region is part of a delta formed by as many as 13 rivers and is mainly below sea level (e.g., Firman et al. 2011).

The average annual rainfall in Singapore is about 2430 mm with 51% rainy days (e.g., Mandapaka and Qin 2013), and the annual rainfall in Jakarta is about 2000 mm with 40% rainy days. Singapore is characterized by a tropical rain forest climate (according to the Köppen climate classification) with high humidity, heavy rainfall, and uniformly warm temperatures throughout the year (e.g., Fong 2012). Jakarta has a tropical monsoon climate and shows significant seasonality in rainfall (e.g., Hendon 2003; Hamada et al. 2012). The months of November and December are the rainiest for Singapore, whereas the months of January and February are the rainiest for Jakarta (Fig. 2). The seasonality of Jakarta rainfall is clearly evident in Fig. 2, with August and September receiving lower rainfall (e.g., Hendon 2003; Hamada et al. 2012).

The WMC region experiences two monsoons: the northeast monsoon from late November to March, and
the southwest monsoon from June to September. Figure 3 illustrates the variation in mean sea level pressure and 850-hPa horizontal winds obtained from ERA-Interim (Dee et al. 2011). During the boreal winter, an intense high pressure system sits over the Asian landmass and a low pressure system is present south of the equator (Fig. 3a). The pressure gradient results in northeasterly winds over the South China Sea. The northeasterly winds are deflected eastward by the topography and the Coriolis effect as they cross the equator (Fig. 3c). Although widely referred to as a northeast monsoon, the direction of the low-level winds is quite variable at the local scales. For example, the winds are north-northeasterly in Singapore and west-northwesterly over Jakarta. Hereafter, we refer to this period as the December–March (DJFM) monsoon.

During the boreal summer, the position of maximum solar heating is well north of the equator. The winter high over the Asian landmass is replaced by a low pressure system, and a high pressure system develops over the Australian landmass. The pressure gradient leads to southeasterly winds, which are deflected eastward as they cross the equator (Figs. 3b,d). The winds are easterly over Jakarta and south-southwesterly over Singapore during this time period. Hereafter, we refer to this monsoon as the June–September (JJAS) monsoon.

The first half of the DJFM monsoon (December and January) in Singapore is the wettest period of the year, and the second half (February in particular) is relatively dry (e.g., Fong 2012; Mandapaka and Qin 2013). Jakarta has a distinct wet season during the months of December–February, and the months of June–September are dry. The precipitation seasonality is mainly determined by the proximity of the study region to the intertropical
convergence zone (ITCZ), which is a region of convergence of northeast and southeast trade winds. The seasonality in rainfall over Singapore and Jakarta, and the role of the ITCZ, are explored in detail later in section 4c.

b. Data

We used 35 years (1980–2014) of daily rainfall observations at 28 stations in Singapore and 23 years (1984–2006) of daily observations at five stations in Jakarta (Fig. 1). The Singapore dataset is obtained from the National Environment Agency (NEA), Singapore, and the Jakarta dataset is obtained from Meteorology, Climatology, and Geophysics (BMKG), Indonesia. There are gridded rainfall datasets such as Asian Precipitation–Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE; Yatagai et al. 2012), which are available for longer time periods. Because of the gridded nature of these datasets, and the interpolation involved, these datasets are sensitive to the gauge network density. This is a major concern over the Maritime Continent with complex land–sea organization. Therefore, we employed gauge rainfall observations in this study.

The missing time periods are filled using data from the nearest neighbor gauge. However, the neighboring gauge data are used only if the gauge is within a radius of 3 km. Given that the spatial decorrelation distance (distance at which the spatial correlation drops to 1/e) of daily rainfall in Singapore is about 33 km (Mandapaka and Qin 2013), it is reasonable to fill the missing time periods using data from a gauge within a 3-km radius. Using this procedure, the missing data percentage is reduced from 1.6% to 0.3%. Because of the sparse nature of Jakarta gauge network, the nearest neighbor
approach is not employed, and the data are used as they are. As a result, the Jakarta data have a higher percentage (6.9%) of missing data.

In addition to the rain gauge data, we employed ERA-Interim (Dee et al. 2011) to understand linkages between rain gauge statistics and large-scale variables. The reanalysis data were obtained from the ECMWF data portal (http://apps.ecmwf.int/datasets/data/interim-full-daily) at three pressure levels (850, 500, and 250 hPa) and at the surface.

3. Methodology

a. Extracting wet and dry spells

In this study, a wet spell is defined as the number of consecutive days with precipitation greater than or equal to a particular threshold. A dry spell is defined as the number of consecutive days with precipitation less than a threshold value. We used two thresholds in this study: 0.1 mm day\(^{-1}\) and 1.0 mm day\(^{-1}\). The threshold of 0.1 mm day\(^{-1}\) is the lowest value observed in the dataset. Given the uncertainties in measuring weak rainfall intensities, we also included a threshold of 1.0 mm day\(^{-1}\) in this study. The daily rainfall time series at each station was converted into a binary series by applying a rain threshold. Specifically, all values less than the threshold were set to zero and the values greater than or equal to the threshold were set to 1. The length (days) of a particular wet (dry) spell was determined by the number of consecutive ones (zeros) in the binary series. For the wet spells, we also extracted the rainfall accumulation (mm). The process was repeated for each station, but the corresponding wet/dry spell lengths were appended to a single unidimensional array, ignoring spatial variability. Since most of the gauge pairs (375 out of 378 for the Singapore dataset) had intergauge distances within the spatial decorrelation distance of 33 km, it is reasonable to pool the wet/dry spells extracted at all gauges together. We adopted the same pooling methodology also for the Jakarta dataset. Once the wet/dry spell lengths are determined, the frequency of a wet spell of length \(l\) was obtained as

\[
PWS(l) = \frac{n_{WS}(l)}{WS_{max}} \times 100, \quad (1)
\]

where \(n_{WS}(l)\) is the number of wet spells of length \(l\) and \(WS_{max}\) is the maximum wet spell length (days). In this study, we also focus on the relative contribution of wet (dry) spells of specific length to the total number of wet (dry) days and to the total rainfall accumulation. The fractional contribution of wet (dry) spells to the total wet (dry) days and total rainfall accumulation has been a subject of interest in recent studies (e.g., Ratan and Venugopal 2013; Zolina et al. 2010, 2013). The frequency distributions of the wet spell contribution to the total number of wet days and total rainfall accumulation are obtained as follows:

\[
PWS_{d}(l) = \frac{n_{WS}(l) \times l}{\sum_{l=1}^{WS_{max}} [n_{WS}(l) \times l]} \times 100 \quad \text{and} \quad (2)
\]

\[
PWS_{R}(l) = \frac{R(l)}{WS_{max}} \times 100, \quad (3)
\]

\[
\sum_{l=1}^{WS_{max}} R(l)
\]

where \(R(l)\) is the rainfall accumulation from wet spells of length \(l\). Similarly, we obtain the frequency of dry spells of specific length \([PDS(l)]\) and their relative contribution to the total dry days \([PDS_{d}]\) using equations similar to Eqs. (1) and (2). Note that there is no dry spell counterpart for Eq. (3) as there is no rainfall involved.

The frequency distributions were obtained for wet and dry spells extracted under following three scenarios: 1) using continuous rainfall series for the entire study period, 2) using time series for each year separately, and 3) using rainfall time series from each year’s DJFM monsoon and JJAS monsoon separately. While the first scenario gave a general view of the wet and dry spell frequencies, the second and third scenarios allowed us to investigate interannual and seasonal variability. For all the three scenarios, as mentioned earlier, we combined wet (dry) spells at all gauges together before obtaining frequency distributions. We characterized the frequency distributions using various statistical indicators, which are discussed in the following section.

b. Statistical indicators

We employed 15 indicators, which include 10 for wet spells and 5 for dry spells to analyze wet and dry spells in the study region. Table 1 provides a short description of each indicator. The indicators such as mean (\(WS_{mean}\)), 95th percentile (\(WS_{95}\)), and the maximum (\(WS_{max}\)) of the wet spell lengths were calculated directly from the empirical frequency distribution \(PWS\) [Eq. (1)]. We followed the empirical approach as it was straightforward and did not introduce fitting errors into the estimated indicators.

The indicator \(WS_{95}\) denotes the wet spell length that corresponds to the 95th percentile of the wet spell contribution to the total wet days and is obtained from the frequency distribution \(PWS_{d}\) [Eq. (2)]. Similarly, the indicator \(WS_{95}\) denotes the wet spell length that corresponds to the 95th percentile of the wet spell contribution
Dry spells and rainfall accumulations. It should be noted that $R_{95}$ is obtained from the empirical distribution of wet spell rainfall accumulation during a spell. Specifically, extreme wet spells are at least WSN5 days long with a rainfall of at least R65 mm. The indicators PXWS and PACX denote the percentage of extreme wet spells and percentage of total rainfall accumulation from the extreme wet spells, respectively. Since each wet spell is followed by a dry spell by definition, we do not require an indicator to quantify the number of dry spells. Similarly, the percentage of dry days in a year need not be represented using a separate indicator. In addition, rainfall accumulation related indicators are absent for dry spells. As a result, we have five indicators to characterize dry spells (Table 1). These indicators are defined similar to their wet spell counterparts and are obtained using frequency distributions (PDS and PDSd).

c. Analysis of trends

The indicators described above were obtained for the entire data record as well as for each year. This allowed us to look for any increasing or decreasing trends in indicators. The trends were evaluated by applying the nonparametric Mann–Kendall (MK) test (e.g., Mann 1945; Kendall 1975; McCuen 2002) on the standardized anomalies of indicators. The standardization was carried out as

$$x'_t = \frac{x_t - \bar{x}}{s_x} \times 100,$$

where $\bar{x}$ and $s_x$ represent mean and standard deviation of the indicator $x$, respectively, and $x'_t$ is the standardized anomaly at time $t$.

The MK test is a distribution-free test, where the test statistic is computed based on the sign of the differences of the elements rather than the values. The null hypothesis is that there is no trend, and the alternative hypothesis is a positive or a negative trend (two-tailed test). A significance level of 5% was chosen in this study to determine if the trends are statistically significant. Regardless of the outcome of the MK test (i.e., significant or not), we obtained the magnitude of trend in standardized anomalies following Sen’s nonparametric regression, which is known to be more robust to the presence of outliers (Sen 1968). The slope of the regression line, referred to as Sen’s slope, is estimated as the median of pairwise slopes between elements of the anomaly series (e.g., Yue et al. 2002; Shifteh Some’e et al. 2012). In this work, the trends are quantified in the form of percentage change $\Delta x$ with respect to the mean value as

$$\Delta x = \beta_{x'} \times \frac{x'_t}{\bar{x}} \times 100,$$

where $\beta_{x'}$ is Sen’s slope for the standardized anomaly $x'$.

Both the MK test and Sen’s slope are widely used in Earth sciences for assessing trends (e.g., Gan 1995, 1998; Yue et al. 2002; Zhai et al. 2005; Villarini et al. 2011; Shifteh Some’e et al. 2012; Yang et al. 2013). Therefore, we do not provide their full description here. For more details, please refer to McCuen (2002) and Yue et al. (2002).

4. Results and discussion

Wet and dry spells are extracted from each dataset (35 years for Singapore and 23 years for Jakarta) for the two rain thresholds. First, we describe the wet spell characteristics, and then we proceed to the description of dry spells.

a. Wet spell characteristics

The wet spells extracted from each gauge series are pooled together as described in section 3a. Given that the interannual variability in wet spells is more significant than the spatial variability (please refer to Table S1 in the supplemental material), it is reasonable to ignore the latter and pool the wet spells observed at each gauge.
into a single series. The frequency distribution of wet spells (i.e., PWS) is then obtained using Eq. (1). The fractional contribution of a wet spell of a specific length to the total wet days (i.e., $P_{WS_d}$) and total rainfall (i.e., $P_{WS_R}$) are obtained using Eqs. (2) and (3), respectively. Figure 4 shows PWS, $P_{WS_d}$, and $P_{WS_R}$ for Singapore and Jakarta for two different rain thresholds. The duration axis in Fig. 4 is curtailed to 14 days for better clarity. As expected, the wet spell distribution is right skewed with a large number of short-duration spells. For example, the 1–2-day wet spells account for $\sim$65% of total wet spells in Singapore and contribute 33% of total wet days and 31% of total rainfall (Fig. 4a). Similarly, the 1–2-day wet spells form $\sim$70% of total wet spells in Jakarta and contribute 37% of total wet days and 34% of total rainfall (Fig. 4b). As the threshold increases to 1 mm day$^{-1}$, the skewness of the wet spell distribution increases (from 2.2 to 2.5), which is due to the breaking of longer wet spells into short wet spells (Figs. 4c,d).

The wet spell distributions are then analyzed using the indicators described in section 3b. In the first two columns of Table 2, we compare the values of wet spell indicators for Singapore and Jakarta for the threshold of 0.1 mm day$^{-1}$. Singapore has a higher number of wet days, wet spells, and larger mean wet spell length compared to Jakarta. The 95th percentile of the wet spell lengths (i.e., $W_{95}$) is the same for both Singapore and Jakarta. However, if we focus on the fractional contribution of wet spells to the total wet days and total rainfall accumulation, the corresponding 95th percentiles (i.e., $W_{95d}$ and $W_{95R}$) are lower for Singapore. From the values of $W_{95d}$, it can be said that 95% of the wet days in Singapore are due to wet spells of up to 13 days in length, while in Jakarta this value increases to 16 days. Similarly, 95% of total rainfall in Singapore is due to wet spells of up to 14 days in length, while in Jakarta this value increases to 17 days. The indicators $W_{max}$ and $R_{95}$ are also lower for Singapore than Jakarta. Although the extreme wet spell percentage (as defined in section 3b) is the same for both cities, their contribution to the total rainfall is lower for Singapore (Table 2, first two columns). In general, Fig. 4 and Table 2 show that Singapore is rainier, but Jakarta has a few very long wet spells, which result in high values for indicators ($W_{95d}$, $W_{95R}$, $R_{95}$, and PACX) that quantify the upper tail of the frequency distribution.
1) **SEASONAL VARIABILITY**

To further understand the differences in wet spell statistics between the two cities, we calculated the frequency distributions $P_{WS}$, $P_{WS^d}$, and $P_{WS^R}$ separately for the DJFM and JJAS seasons. Figure 5 displays the seasonal wet spell frequency distributions of Singapore and Jakarta for the threshold of 0.1 mm day$^{-1}$. Unlike the annual scenario, the 1–4-day wet spells in Singapore contribute almost equally (~12.5% each) to the total duration of wet spells during the DJFM season (Figs. 4a, 5a). In addition, the fractional contribution of wet spells to the total rainfall in Singapore reaches a maximum (12.4%) for the spell length of 4 days. For Jakarta, 1–3-day wet spells contribute equally (~12.1% each) to the total number of rainy days, and the 3-day wet spells contribute the most (11.6%) to the total rainfall (Fig. 5b). The frequency distributions are characterized using 10 wet spell indicators listed in Table 1. Compared to the annual value, the percentage of rainy days ($P_{WD}$) is slightly lower for Singapore during the DJFM season (Table 2). All other indicators (except NWS) have higher values during the DJFM season compared to annual statistics for both the cities. Although Singapore and Jakarta have the same number of wet spells during the DJFM season, the former has lower values for all other indicators, including those that characterize the percentage of extreme wet spells (i.e., $P_{XWS}$) and the percentage of rainfall from extreme wet spells (Table 2).

The wet spell frequencies drop rapidly during the JJAS monsoon (Figs. 5c,d) compared to the DJFM monsoon. The 1–2-day spells comprise 74% of total wet spells in Singapore during this season and account for

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<th>Full year</th>
<th>DJFM</th>
<th>JJAS</th>
</tr>
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<tr>
<td>$P_{WD}$ (%)</td>
<td>52.05</td>
<td>40.03</td>
<td>51.67</td>
</tr>
<tr>
<td>NWS</td>
<td>72</td>
<td>55</td>
<td>21</td>
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<tr>
<td>$WS_{mean}$ (days)</td>
<td>2.62</td>
<td>2.48</td>
<td>3.01</td>
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<tr>
<td>$WS_0.05$ (days)</td>
<td>7</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>$WS_{2.5}$ (days)</td>
<td>13</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>$WS_{95}$ (days)</td>
<td>14</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>$WS_{max}$ (days)</td>
<td>32</td>
<td>43</td>
<td>32</td>
</tr>
<tr>
<td>$R_{95}$ (mm)</td>
<td>126.60</td>
<td>136.50</td>
<td>158.40</td>
</tr>
<tr>
<td>$P_{XWS}$ (%)</td>
<td>3.24</td>
<td>3.22</td>
<td>5.43</td>
</tr>
<tr>
<td>PACX (%)</td>
<td>19.58</td>
<td>22.28</td>
<td>30.22</td>
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</table>

FIG. 5. Frequency distributions of wet spells and contribution of wet spells to total number of wet days and total rainfall for Singapore and Jakarta for DJFM and JJAS monsoons. Rainfall threshold used is 0.1 mm day$^{-1}$. 

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**TABLE 2.** Wet spell indicator statistics for Singapore (SG) and Jakarta (JK) for the rain threshold of 0.1 mm day$^{-1}$. 

---
almost half the total number of wet days (Fig. 5c). The rapid drop in frequencies is more evident for Jakarta, with 1–2-day spells forming 83% of total wet spells and contributing 62% of wet days and 60% of total rainfall (Fig. 5d). The pattern observed in the wet spell indicators of the DJFM monsoon is reversed during the JJAS monsoon. All indicators have significantly higher values for Singapore than Jakarta. Singapore has 46% rainy days compared to 20.5% of Jakarta. During this season, Singapore also receives more than twice the number of wet spells compared to Jakarta. The maximum wet spell length observed during the study period was 25 days for Singapore and 18 days for Jakarta.

It is thus concluded that Jakarta is wetter than Singapore during the DJFM season, with a higher percentage of rainy days, longer wet spells, and higher probability of extreme wet spells, whereas Singapore is significantly wetter than Jakarta during the JJAS season. However, the contrast between the two cities is more marked during the JJAS season. It will be shown later in section 4c that the differences in statistics between Singapore and Jakarta at seasonal scales are mainly due to the relative position of the ITCZ.

2) INTERANNUAL VARIABILITY AND TRENDS

The wet spell results presented to this point were obtained by analyzing a continuous record of data. To study year-to-year changes, we extracted wet spells for each year separately and obtained frequency distributions $P_{WS}$, $P_{WS_{d}}$, and $P_{WS_{R}}$ using Eqs. (1)–(3). The procedure was repeated for the DJFM and JJAS seasons to analyze temporal changes at seasonal scales. The mean and standard deviation of the indicators for annual and seasonal scales are given in Table 3. The mean values of indicators are consistent with those observed for the “all year” continuous record except for $WS_{\text{mean}}$ (Tables 2, 3). The smaller mean values of $WS_{\text{max}}$ in Table 3 are because of breaking of a few very long wet spells when we extract spells for each year separately. The standard deviation values in Table 3 suggest significant interannual variability with standard deviation values over 10% of the mean value for majority of indicators.

The interannual variability is further examined in the context of temporal trends. The time series of each indicator is transformed into standardized anomalies using Eq. (4). The null hypothesis of no trend in anomalies is then tested using the MK test for a significance level of 5%. It should be noted that trend analysis is limited to the Singapore dataset. We did not perform trend analysis for Jakarta because of the limited size of the dataset. The time series of standardized anomalies of each indicator is shown in Fig. 6 along with the regression line fitted using Sen’s method. The fitted regression line is displayed as a thick solid line if the trend is statistically significant at the 95% confidence level. The trends are quantified in the form of percentage change per decade using Sen’s slope with respect to the mean value [Eq. (5)] and shown in Fig. 6.

It is observed from Fig. 6 that all indicators except $NWS$ have an increasing trend, and all indicators except $WS_{\text{max}}$ show statistically significant trends at the 95% confidence level. A trend of 3.98% decade$^{-1}$ for $PWD$ implies that wet day percentage is increasing at a rate of $0.0398 \times 52 = 2.08\%$ decade$^{-1}$ (mean annual $PWD = 52\%$, Table 3). Similarly, a trend of $-2.78\%$ decade$^{-1}$ for $NWS$ indicates a decrease of two wet spells per decade. The decadal trends in $WS_{\text{mean}}$ and $WS_{\text{95}}$ are 6.9% ($0.18$ days) and 9.19% ($0.64$ days), respectively. The indicator representing the fractional contribution of wet spells to the total wet days (i.e., $WS_{\text{95}}$) is found to increase at 8.24% decade$^{-1}$. The maximum length of a wet spell (i.e., $WS_{\text{max}}$) is increasing at 5.94% decade$^{-1}$ (1.2 days decade$^{-1}$), but the trend is not significant at the 95% confidence level.

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<th>DJFM</th>
<th>JJAS</th>
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<tbody>
<tr>
<td></td>
<td>SG</td>
<td>JK</td>
<td>SG</td>
</tr>
<tr>
<td>PWD (%)</td>
<td>52.0 (4.7)</td>
<td>39.9 (3.6)</td>
<td>51.6 (8.7)</td>
</tr>
<tr>
<td>NWS</td>
<td>73 (5)</td>
<td>55 (10)</td>
<td>21 (3)</td>
</tr>
<tr>
<td>$WS_{\text{mean}}$ (days)</td>
<td>2.6 (0.3)</td>
<td>2.5 (0.2)</td>
<td>3.0 (0.5)</td>
</tr>
<tr>
<td>$WS_{\text{95}}$ (days)</td>
<td>7 (1)</td>
<td>7 (1)</td>
<td>9 (2)</td>
</tr>
<tr>
<td>$WS_{\text{d95}}$ (days)</td>
<td>13 (3)</td>
<td>17 (10)</td>
<td>13 (4)</td>
</tr>
<tr>
<td>$WS_{\text{R95}}$ (days)</td>
<td>13 (3)</td>
<td>18 (10)</td>
<td>13 (4)</td>
</tr>
<tr>
<td>$WS_{\text{max}}$ (days)</td>
<td>21 (4)</td>
<td>21 (9)</td>
<td>18 (5)</td>
</tr>
<tr>
<td>$R_{\text{95}}$ (mm)</td>
<td>126.9 (25.8)</td>
<td>137.8 (27.8)</td>
<td>170.5 (74.7)</td>
</tr>
<tr>
<td>PXWS (%)</td>
<td>3.2 (1.6)</td>
<td>3.3 (1.6)</td>
<td>5.5 (3.7)</td>
</tr>
<tr>
<td>PACX (%)</td>
<td>18.4 (8.7)</td>
<td>21.6 (10.0)</td>
<td>27.1 (15.9)</td>
</tr>
</tbody>
</table>
(though significant at 90%). The 95th percentile of wet spell accumulation (i.e., $R_{95}$) is found to increase at 9.44% decade$^{-1}$ (12 mm decade$^{-1}$). Strong positive trends are observed for the extreme wet spell indicators PXWS and PACX, with a percent change of 21.9% decade$^{-1}$ and 15.4% decade$^{-1}$, respectively. It is inferred from Fig. 6 that Singapore is getting wetter, with an increase in the number of wet days, mean wet spell length, and number of extreme wet spells.

The seasonal-scale trend analysis results for the DJFM and JJAS monsoons are shown in Figs. 7 and 8, respectively. The upward trends are observed in all indicators (except $WS_{95}$) during the DJFM monsoon, but the trend is statistically significant only for $WS_{max}$ (Fig. 7). The indicator $WS_{max}$ shows an increase of 11.38% decade$^{-1}$ (2 days decade$^{-1}$). For the JJAS monsoon, all indicators except PWD and NWS show statistically significant upward trends.
The decadal trends in $W_S^{\text{mean}}$, $W_S^{95}$, and $W_S^{\max}$ are 6.35% ($\pm 0.13$ days), 7.12% ($\pm 0.36$ days), and 9.93% ($\pm 1.2$ days), respectively. The 95th percentile of wet spell accumulation (i.e., $R^{95}$) is found to increase at 8.1% decade$^{-1}$ (7.7 mm decade$^{-1}$). Strong positive trends are observed for the extreme wet spell indicators PXWS and PACX with a percent change of 32.0% decade$^{-1}$ and 28.8% decade$^{-1}$, respectively. In general, it is concluded that the seasonal trends replicate the patterns observed for annual scales, but the percentage changes are significant for the JJAS monsoon compared to the DJFM monsoon.

b. Dry spell characteristics

The frequency distribution of dry spells (i.e., PDS) and the fractional contribution of dry spells of a specific length to the total dry days (i.e., $P_{\text{DS}d}$) are shown in Fig. 9 for the rain thresholds of 0.1 and 1.0 mm day$^{-1}$. Similar to the wet spell distribution, PDS is right skewed with a large number of short-duration dry spells. As the threshold increases, the distributions get flatter, which
is a reflection of the adding up of shorter dry spells into longer ones (Figs. 9c,d). A 2-day mode is seen in the distribution PDSD for the rain threshold of 1.0 mm day\(^{-1}\). The dry spell distributions are characterized using five indicators described in Table 1. The values of indicators for Singapore and Jakarta, and for the threshold of 0.1 mm day\(^{-1}\), are listed in Table 4. As mentioned in section 3b, it is not required to have separate indicators for percentage of dry days and the number of dry spells, as they can be deduced from their wet spell counterparts (PWD and NWS). Singapore has a higher number of dry spells per year but a lower percentage of dry days. The indicators related to dry spell length such as DSmean, DS95, WSd95, and DSmax are all lower for Singapore compared to Jakarta. From the values of WSd95, it can be said that 95% of the dry days in Singapore are due to dry spells of up to 14 days in length, while in Jakarta this value is significantly higher at 43 days. However, the extreme dry spell (\(l \geq DS95\)) percentage is slightly higher for Singapore. The higher percentage of dry days and the higher values for most dry spell indicators suggest that Jakarta is drier compared to Singapore at annual time scales.

**Fig. 8.** As in Fig. 6, but for the JJAS season.
1) SEASONAL VARIABILITY

To further understand the differences in dry spell distributions between Singapore and Jakarta, we extracted dry spells at seasonal scales for the DJFM and JJAS seasons. The short-duration (1–2 day) dry spells have almost equal contribution to the total number of dry days during the DJFM season (Figs. 10a,b). All indicators have higher values for Singapore compared to Jakarta during the DJFM season (Table 4). Therefore, it can be said that Singapore is drier than Jakarta during the DJFM season. It will be shown later in section 4c that the ITCZ position in the second half of the DJFM season is one of the main reasons for Singapore being drier than Jakarta. The regional differences in dry spell distributions are more striking during the JJAS season compared to that of the DJFM season. The frequencies drop more rapidly for Singapore than for Jakarta during the JJAS season (Figs. 10c,d) compared to the DJFM season (Figs. 10a,b). In addition, the dry spells of length 1–7 have almost equal contribution to total dry days in Jakarta during the JJAS season. All indicators are lower for Singapore compared to Jakarta (Table 4). Therefore, it is inferred that Jakarta is significantly drier compared to Singapore during the JJAS season.

2) INTERANNUAL VARIABILITY AND TRENDS

To study year-to-year changes, the dry spell frequency distributions PDS and PDS_{95} are obtained for each year separately. The mean and standard deviation of the indicators for annual and seasonal scales are given in Table 5. The mean values of indicators are consistent with those observed for the all-year scenario, except indicators such as WS_{95} and DS_{max} that quantify the upper tail behavior of frequency distributions (Tables 4, 5). Table 5 indicates considerable interannual variability in dry spells with the standard deviation values over 10% of mean value for a majority of indicators. We further analyzed the interannual variability by carrying

![Fig. 9. Frequency distributions of dry spells and contribution of dry spells to the total number of dry days for Singapore and Jakarta for two rain thresholds.](image-url)
out trend analysis on standardized anomalies of each indicator. The null hypothesis of no trend is tested using a nonparametric Mann–Kendall test at a significance level of 5%. Although DSmean showed a decreasing trend at annual scale and during the DJFM season, the trends are not statistically significant. In fact, none of the dry spell indicators has shown statistically significant trends, either at annual or seasonal scales (please refer to Figs. S1–S3 in the supplemental material).

c. Role of large-scale meteorology

To provide physical interpretation of annual and interannual variability in wet and dry spells, we analyzed ERA-Interim data at different pressure levels. Specifically, we examined the patterns of horizontal and vertical winds, divergence, and specific humidity at 850, 500, and 250 hPa. The three pressure surfaces were selected to roughly represent lower, middle, and upper atmosphere, respectively. We also analyzed the behavior of convective available potential energy (CAPE) and total column water vapor. We present these results in the subsequent two subsections.

1) ANNUAL CYCLE

It was observed in sections 4a and 4b that Singapore is drier (wetter) compared to Jakarta during the DJFM (JJAS) season. In addition, the contrast between Singapore and Jakarta was found to be stronger during the

![Figure 10. Frequency distributions of dry spells and the contribution of dry spells to the total number of dry days for Singapore and Jakarta for the DJFM and JJAS monsoons.](image)

| Table 5. Mean and standard deviation (shown in parentheses) of dry spell indicators for Singapore (SG) and Jakarta (JK) for the rain threshold of 0.1 mm day⁻¹. |
|-----------------|-------|-------|-------|-----------------|-------|
| Indicator       | Full year |        |        |        |        | DJFM |        |        |        |        |        | JJAS |        |        |
|                 | SG   | JK   | SG   | JK   | SG   | JK   | SG   | JK   | SG   | JK   |
| DSmean (days)   | 2.4 (0.3) | 3.8 (0.7) | 2.9 (0.8) | 2.3 (0.3) | 2.5 (0.6) | 8.2 (5.1) |
| DS95 (days)     | 7 (1) | 14 (5) | 9 (4) | 7 (2) | 7 (3) | 29 (20) |
| WSd95 (days)    | 14 (6) | 37 (22) | 16 (8) | 15 (8) | 10 (4) | 39 (21) |
| DSmax (days)    | 23 (9) | 42 (20) | 21 (9) | 16 (8) | 14 (5) | 39 (21) |
| PXDS (%)        | 5.6 (2.5) | 5.4 (2.6) | 9.1 (5.5) | 0.9 (1.2) | 6.4 (5.2) | 18.9 (15.4) |
JJAS season than the DJFM season. To further understand this contrast, we obtained monthly climatologies of percentage (ratio of the number of spells in a month to the annual total number of spells) of wet/dry spells and extreme wet and dry spells for the rain threshold of 0.1 mm day$^{-1}$ (Fig. 11). It should be noted that the percentage of wet spells per month is the same as that of dry spells, as each wet spell is followed by a dry spell, by definition. However, the percentages of extreme wet and dry spells are different, as evident in Fig. 11. For Singapore, the number of wet spells is lower in January and February, increases during March and April, and is uniformly distributed (at ~9%) from April to October, particularly during the JJAS season. The probability of extreme wet spells is high during the first half of the DJFM season, drops rapidly in February, and is lowest during the JJAS season (Fig. 11a). The distribution of extreme dry spells in Singapore has a bimodal shape, with peaks in February and July and low values during the intermonsoonal months of April and November. For Jakarta, the annual cycle of wet and dry spells is more distinct, with about 11% of wet spells in March and April and only 5% in August (Fig. 11b). The extreme wet spell percentage is highest during January and negligible during the JJAS season.

The annual cycle in wet and dry spells and their extremes can be better understood by examining the relative position of the ITCZ, which migrates north (south) during boreal summer (winter), following the zone of maximum solar heating. However, regional differences exist in its seasonal movement. For example, over the central Atlantic and Pacific oceans, the ITCZ migrates between 9° and 2°N, whereas over the Indian Ocean, it moves between 20°N and 8°S (e.g., Schneider et al. 2014). The position of the ITCZ over Southeast Asia can be illustrated using the monthly climatology maps of 500-hPa vertical motion (omega, Fig. 12). Note that the negative (positive) values of omega imply ascending (descending) air. In December, the ITCZ is broadly centered just south of the equator, with both Singapore and Jakarta in the region of strong ascending air (Fig. 12a). As the DJFM monsoon progresses, the ITCZ moves farther south of the equator and is centered around 7°S by February (Fig. 12b). During this period, the vertical motion over Singapore is weak, which partly explains low frequency of extreme wet spells. Similarly, the high probability of extreme wet spells in Jakarta during January and February is due to its proximity to the ITCZ. The ITCZ then moves northward toward the equator and lies in the Northern Hemisphere by June (Fig. 12c). The contrast between Singapore and Jakarta omega values is particularly evident during the months of July–September (Figs. 12f–h), which explains the large contrast in wet and dry spell statistics that was observed (Tables 2, 4) during the JJAS season.

We computed areal averages of various ERA-Interim variables for a 3° × 3° box over Singapore and Jakarta. Figure 13 shows the monthly time series of areal averages over Singapore (0°–3°N, 102°–105°E) and Jakarta (4.5°–7.5°S, 105°–108°E) at three pressure levels of 850, 500, and 250 hPa. The negative (positive) values in Figs. 13a and 13b imply convergence (divergence). Divergence, omega, and specific humidity exhibit a weaker annual cycle over Singapore compared to Jakarta. The time series of divergence for Singapore shows low-level convergence and upper-level divergence throughout the year, except for March, when a low-level divergence is observed (Fig. 13a). The low (high) percentage of
FIG. 12. (a)–(h) Monthly climatology of vertical motion at 500 hPa during DJFM and JJAS seasons. The locations of Singapore (SG) and Jakarta (JK) are shown in (a).
extreme wet (dry) spells during the month of February for Singapore can be attributed to the weak low-level convergence, weak vertical motion (omega closer to zero), low specific humidity, and low CAPE (Fig. 13, left). Over Jakarta, the conditions in January are favorable (strong low-level convergence, upward motion, and high specific humidity and CAPE) for the occurrence of extreme wet spells, which explains the high probability of extremes seen in Fig. 11b.

During the intermonsoon months of April and May, although the low-level convergence over Singapore is weak, other variables such as omega, specific humidity, and CAPE are gaining strength (Fig. 13, left). In particular, high CAPE values indicate greater instability and higher potential for thunderstorms. During these months, Singapore has a high percentage of wet spells, but only a small percentage fall into the extreme category (Fig. 11a), which can be attributed to the

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**Fig. 13.** Monthly time series of (a),(b) area-averaged divergence at three different pressure levels; (c),(d) vertical motion at three different pressure levels; (e),(f) specific humidity at three different pressure levels; and (g),(h) CAPE for Singapore and Jakarta. The specific humidity values at each pressure level are normalized with the corresponding annual mean.
thunderstorm activity and the associated short-duration convective rainfall events (we remind the reader that extreme wet spells are defined based on both duration and rainfall accumulation). Short-duration convective showers are also dominant in Singapore during the JJAS season, as suggested by higher CAPE values (Fig. 13g). Furthermore, a typical feature of the JJAS monsoon is the Sumatra squall, which is a line of thunderstorms that develops over the Strait of Malacca and reaches Singapore around the predawn hours. The Sumatra squalls are characterized by strong wind gusts, and therefore the associated rainfall lasts over Singapore only for a few hours (e.g., Fong 2012). The JJAS season is thus dominated by short-duration wet spells. About 50% of the total number of wet days in this season is contributed by 1- and 2-day wet spells (Fig. 5c).

For Jakarta, the values of low-level convergence, 500-hPa omega, specific humidity at all three pressure levels, and CAPE indicate least favorable conditions for wet spells (Fig. 13, right). In other words, the probability of extreme dry spells is high during the JJAS season, which is consistent with the results presented in Fig. 11b. By November, the low-level convergence and vertical motion have gained strength, and specific humidity has also increased, resulting in an increase in extreme wet spells. We quantified the relationship between the annual cycles of extreme wet/dry spells (Fig. 11) and the annual cycles of climate variables (Fig. 13) using Spearman’s correlation. The analysis showed that about 78% of the variability in the annual cycle of Jakarta extreme wet spells can be explained by the annual cycle of low-level divergence. Similar correlations were observed between the annual cycles of extreme wet spells over Jakarta and those of 500-hPa omega and specific humidity.

2) TRENDS

We also examined if the interannual trends observed in wet spells over Singapore (Fig. 6) can be explained by the areal averages of ERA-Interim variables. First, we carried out the trend analysis for time series at each grid point in the ERA-Interim data over a larger region of Southeast Asia to obtain a large-scale assessment of trends. Figure 14 shows decadal trends in specific humidity and omega at two pressure levels of 500 and 850 hPa. The hatched pattern indicates statistically significant trends at the 95% confidence level.
850 hPa. Significant upward trends in specific humidity and vertical motion were observed over Peninsular Malaysia and Borneo for 500-hPa fields. The pattern is similar for 850 hPa fields but less significant (Figs. 14b,d). To focus on local scales, the trend analysis was performed on areal averages of ERA-Interim variables over Singapore (0°–3°N, 102°–105°E) using the MK test. The null hypothesis of no trend is tested at a significance level of 5%. The results show significant strengthening of the low-level convergence (decreasing divergence), enhanced vertical motion, and an increase in 500-hPa specific humidity during the study period (Fig. 15). We also examined if the strengthening of low-level convergence is associated with a strengthening of upper-level (250 hPa) divergence. The time series of area-averaged divergence over Singapore does show an upward trend, but the trend is not significant at the 95% confidence level (Fig. S4). The p value was found to be 0.08, which indicates that the trend is still significant at 90%. Upward trends are also observed in the values of CAPE and the total column water vapor over Singapore (Fig. S5). The analysis of ERA-Interim variables shows that the upward trends in wet spells over Singapore are due to the increasing low-level convergence, strengthening of vertical motion, increasing instability, and greater availability of moisture.

5. Concluding remarks

We characterized wet and dry spell structure in Singapore and Jakarta using rain gauge datasets. These study areas were selected because of their vulnerability to extreme wet and dry spells. Besides estimating the frequency of wet (dry) spells, the study also focused on their fractional contribution to the total number of wet (dry) days and to the total rainfall accumulation. The frequency distributions were characterized using 15 indicators, out of which 10 represent wet spells and 5 were for dry spells. An indicator for extreme wet spells was proposed that is based on spell length and the rainfall amount during the spell. In addition to characterizing
frequency distributions, another goal was to study the interannual variability and trends in wet (dry) spells. The trends were quantified for the Singapore dataset using Sen’s regression, and their statistical significance was assessed using the nonparametric Mann–Kendall test. The study also analyzed data from ERA–Interim to see if the regional contrasts in the annual cycle of wet spells, and the temporal changes in wet spell statistics, can be associated with the regional and temporal patterns in dynamic and thermodynamic variables. Following are the main conclusions from this work.

1) A higher percentage of wet days, greater number of wet spells per year, and a larger mean wet spell length were observed for Singapore compared to Jakarta at the annual scale. Although the probability of extreme wet spells was found to be the same for both cities, the relative contribution of extreme wet spells to the total rainfall is higher for Jakarta. Furthermore, the mean, the 95th percentile, and the maximum of dry spell lengths were found to be significantly smaller for Singapore compared to Jakarta at annual scales.

2) The results from the seasonal-scale analysis indicate that Singapore is drier (wetter) compared to Jakarta during boreal winter (summer) seasons. The wet spell probability distributions are flatter during boreal winter, with 1–3-day wet spells having an almost equal contribution to the total number of wet days. In addition, 4-day (3-day) wet spells were found to contribute the most to the total rainfall in Singapore (Jakarta) during boreal winter. The contrast between Singapore and Jakarta statistics was found to be stronger in boreal summer.

3) The monthly climatology of extreme wet spells in Singapore is characterized by two peaks: a primary one in December and a secondary one in March–April. The probability of extreme dry spells also displayed a bimodal pattern for Singapore with a primary peak in February and a secondary peak in July. On the other hand, the probability of extreme wet spells in Jakarta has a distinct maximum in January, which explains a high frequency of flood events during this month. The results further show that the boreal summer months of June–August have a high probability of extreme dry spells for Jakarta.

4) Our analysis of ERA-Interim data suggests that the annual cycles of convergence, vertical motion, and specific humidity over Jakarta have higher amplitudes compared to those over Singapore, which explains the stronger annual cycle in Jakarta wet spell statistics. The results also indicated that higher probability of extreme dry spells in Singapore during February can be associated to weaker low-level convergence and vertical motion and lower moisture availability and CAPE. Furthermore, during the JJAS season, Jakarta lies in the region of low-level divergence, with negligible upward motion, low moisture availability, and low CAPE leading to a rapid drop in the number of wet spells and almost zero probability of extreme wet spells. However, during the same period, Singapore is in the region of mild low-level convergence and ascent and high CAPE, which maintain a more uniform wet spell count. The net result is a marked contrast in wet spell statistics between Jakarta and Singapore during the JJAS season.

5) Time series analysis for the Singapore dataset showed significant interannual trends in wet spell characteristics. The percentage of wet days showed an upward trend of 2% decade$^{-1}$. The mean, the 95th percentile, and the maximum of wet spell length were found to increase at a rate of 0.18, 0.64, and 1.2 days decade$^{-1}$, respectively. The 95th percentile of wet spell accumulation was found to increase at 12 mm decade$^{-1}$. Strong upward trends were observed in other indicators such as percentage of extreme wet spells and rainfall amount from extreme wet spells. It can therefore be concluded that Singapore has been getting wetter during the study period of 1980–2014. No significant trends were observed in dry spell indicators.

6) A trend analysis of ERA-Interim data indicated significant strengthening of the low-level convergence and vertical motion, and an increase in moisture availability and instability during the study period, which explain the upward trends observed in wet spells over Singapore.

The study, besides characterizing wet and dry spell distributions and their temporal trends, provides insights on their linkages with large-scale atmospheric conditions. Regarding the trend analysis, we note that long-term oscillations such as Pacific decadal oscillation may also have a role in interannual fluctuations of precipitation. Thus, the results presented here will benefit from a further robust assessment of trends using longer datasets (e.g., duration 70–80 years) to minimize interference from such long-term oscillations.

The results from this study would serve as a useful reference for an extended evaluation of regional climate models over the study area. The wet and dry spell frequency distributions are key components of stochastic rainfall generators, and therefore the results would also be helpful in parameter estimation of rainfall generators for this region. A natural extension of this work would be to create a catalog of extreme wet and dry spells and conduct an event-scale analysis for identifying
atmospheric conditions responsible for the onset, maintenance, and dissipation of extremes. Our future work also aims to characterize spatial variability in wet and dry spells over a larger region of Southeast Asia using gridded precipitation products. The large-scale phenomena such as El Niño–Southern Oscillation, the Madden–Julian oscillation, and the Indian Ocean dipole are known to influence rainfall in the WMC region (e.g., Haylock and McBride 2001; Hendon 2003; Juneng and Tangang 2005). Further research is required to understand the relative roles of the above phenomena in wet and dry spell distributions.

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