Diurnal cycle of rainfall in amount, frequency, intensity, duration, and the seasonality over the UK

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The diurnal variation of the rainfall amount, frequency and intensity, and the rainfall with different durations, as well as their seasonality, were analysed by using the hourly rainfall data at 90 stations in the UK during 1998–2015. The rainfall amount averaged in the entire UK presented two comparable peaks in the early morning and the late afternoon, which contributed by the frequency (the early morning) and the intensity (the late afternoon), separately. The rainfall peaks were closely related with the location and the duration of the rainfall. For the rainfall amount, the early morning peaks were more prevailing in the rainfall events lasting more than 6 hr and at the stations along the western coast of the British Isles; however, the rainfall events lasting 1–6 hr usually reached the hourly maximum in the late afternoon. For the seasonal variability, more nocturnal rainfall peaks of rainfall amount and intensity were found over the southern plains in winter. In spring to autumn, only the rainfall at some coastal stations or the stations on islands got the maximum during midnight to the early morning. For the rainfall frequency, the regional differences were more apparent in spring and summer, and the hourly rainfall frequency in the UK mainly peaked around 0600 GMT (Greenwich mean time) in autumn and in 1100–1300 GMT in winter. The results enriched the knowledge of the hourly rainfall features over the UK.

KEYWORDS
diurnal cycle, durations, rainfall, seasonality, UK

1 | INTRODUCTION

The most fundamental modes of variability of the climate system are the diurnal and seasonal variations, which are associated with the variations in the solar forcing. The seasonal cycle in precipitation has been extensively studied for several decades (Klein and Hartmann, 1993; Lau and Yang, 1996; Yanai and Li, 1996), while the diurnal cycle in the precipitation was mostly confined in limited regions because of the scarcity of the observational data. However, the diurnal cycle of rainfall is closely related to surface temperature, moist convection, the formation of clouds, and boundary-layer development (Yang and Slingo, 2001; Sorooshian et al., 2002). Meanwhile, it is also connected with both regional and synoptic-scale dynamical and thermal conditions (Dai and Trenberth, 2004). The study of diurnal cycle in the precipitation is not only important in helping to understand the relationship between the rainfall processes and the above factors, but a key test of many aspects of the physical parametrizations in a climate model.

Earlier studies about diurnal cycle in the rainfall mainly used the surface observations and showed that the convective or summer precipitation maximum tended to occur in the late afternoon or the early evening over most land area and at midnight or in the early morning in plain areas in the downstream of the elevated regions (Wallace, 1975; Gray and Jacobson, 1977). Recent advances in the availability of the high spatial and temporal resolution satellite data greatly
enriched the analysis of the diurnal cycle in the precipitation worldwide, especially in the oceans and the land area with complex topography (e.g., Chang et al., 1995; Chen and Houze, 1997; Garreaud and Wallace, 1997; Yang and Smith, 2006; Dai et al., 2007). For example, the propagating diurnal phases were found along the coastlines and mountains and its downstream (Yang and Slingo, 2001; Carbone et al., 2002; He and Zhang, 2010; Yuan et al., 2012). The diurnal variation in precipitation presented seasonal variations and summer precipitation usually had the most notable diurnal variation than the rainfall in other seasons (Oki and Musiake, 1994; Li et al., 2008). Rainfall over lands in the cold season mainly occurred in the early morning contrasted to the primary late afternoon peaks in the warm season.

Using the hourly rainfall data, other detailed characteristics of the rainfall were revealed in addition to the diurnal cycle. Yu et al. (2007) defined the duration of rainfall events by the hours between the start and end. They found that the rainfall events with different durations presented different diurnal features and were involved in different forming mechanisms. The long-duration rainfall was usually linked to the large-scale circulation and reached the peak in the early morning, while most of the rainfall events lasting 1–6 hr reached the hourly maximum in the late afternoon to the early evening, and were mainly associated with the thermal instability triggered by the solar heating. Chen et al. (2009), following Yu et al. (2007), got similar results over the U.S. Great Plains.

About the UK, the mean states and long-term rainfall characteristics have been thoroughly studied using daily rainfall data. Wigley et al. (1984), using the daily rainfall data on 55 stations during 1861–1970, first divided the England and Wales into five subregions according to their inter-annual variability. After that, a series of research further confirmed their methods and found an increasing trend in winter rainfall and a decreasing one in summer rainfall (Wigley and Jones, 1987; Gregory et al., 1991; Jones and Conway, 1997; Alexander and Jones, 2000), as well as pointing out that the intensity of rainfall became more intense in winter and less intense in summer (Osborn et al., 2000). In spring and autumn, increases in extreme rainfall over the period 1961–2000 for short-duration events around the UK were identified (Fowler and Kilsby, 2003; Biggs and Atkinson, 2011; Jones et al., 2013). Using the hourly rainfall data, the relationships between the extremes and the temperatures in the UK were also analysed (Blenkinsop et al., 2015).

For the UK, there has been considerable research into the climatology of daily precipitation but relatively little on sub-daily timescales (Blenkinsop et al., 2017). Svensson and Jakob (2002) analysed the seasonal variations of diurnal cycle in precipitation with different intensity on one station in the western Scotland. They found two comparable peaks in the morning and the afternoon of the weak rainfall and a dominant afternoon peak in the summer heavier rainfall, and they pointed out the relationship between the topography and rainfall diurnal features. Similar diurnal features were found in Blenkinsop et al. (2017) using more stations, and they pointed out that the diurnal amplitudes were small in winter and strong in summer. But previous studies on the diurnal feature of rainfall over the UK were mainly confined in rainfall amount, limited regions, or limited seasons. The purpose of this study was to investigate the diurnal variability of rainfall amount, frequency and intensity, and its seasonality in the entire UK. In addition, the rainfall events with the long and short durations were also analysed over the UK, which have not been studied before. These results will enrich the understanding of the rainfall in the UK.

The data and methods are described in section 2 of the paper. Results are presented in section 3, followed by conclusions and discussions in section 4.

2 | DATA AND METHODOLOGY

The hourly data set was from the UK Met Office Integrated Data Archive System (Met Office, 2012), which can be downloaded from the Centre for Environmental Data Analysis. It contained the land surface and marine surface observations from the UK Met Office station network and other worldwide stations. The data set has been subjected to basic quality controls. For example, data range and self-consistency checks were performed to ensure that the meteorological values did not lie outside long-term climatological extremes. The detailed information can be gotten at http://artefacts.ceda.ac.uk/badc_datadocs/ukmo-midas/ukmo_guide.html and in Met Office (2012). We selected those observation stations within the Synoptic Rainfall Europe West Station Network, and never moved their observation site during 1998–2015. Locations of the 90 observation stations selected in this study are shown in Figure 2.
The rainy hour was defined as the one with more than or equal to 0.1 mm precipitation accumulated during an hour. The hourly mean rainfall amount (the mean rate of accumulated rainfall in all observational hours), frequency (the ratio of observational hours having measurable precipitation), and intensity (the mean rate of accumulated rainfall in rainy hours) were calculated at each hour averaged in 1998–2015. The time of diurnal peak was represented by the hour when the maximum of the mean precipitation amount, frequency, or intensity occurred. The amplitudes were calculated as the ratio of the rainfall amount, frequency, or intensity at the peak hour and those of 24-hr mean. The hourly rainfall event was further classified according to its continuous durations, which meant that the rainfall after an intermittence was

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**FIGURE 2** Spatial distributions of the peaks of diurnal cycles of the hourly precipitation amount (a), frequency (b), and intensity (c) averaged during 1998 to 2015 and the topography (shaded, units: m). The vectors denote GMT of the maximum precipitation occurrences (the phase clock) [Colour figure can be viewed at wileyonlinelibrary.com]
considered to belong to a new event, if a dry period lasted for 2 hr or longer (Yu et al., 2007). The number of hours between the start and the end of an event was defined as the duration. The calculation of the diurnal cycles of rainfall events with different duration was based on each single event. If a rainfall event lasted from 1300 to 1500 GMT (Greenwich mean time), the rainfall amount, frequency, and intensity at 1300, 1400, and 1500 GMT was accumulated at each hour separately for events with duration of 3 hr. Finally, the average was made for events with the same durations. To be noticed, the hourly rainfall amounts of events with different duration were averaged by all observational hours at each hour (the same as total rainfall amount and the same values used for all durations), and the intensity was by only the rainy hours of the specific duration. The hourly rainfall amount, frequency, and intensity were normalized with the daily mean for a better comparison among rainfall events with different duration times.

3 | RESULTS

3.1 | Diurnal cycles of annual rainfall amount, frequency, and intensity

Diurnal variations of the rainfall amount, frequency, and intensity averaged during 1998–2015 of the entire UK are
presented in Figure 1. The rainfall amount (the red line) showed two comparable diurnal peaks in the early morning (0600 GMT) and the late afternoon (1700 GMT). The late-afternoon rainfall peak was slightly stronger than that in the early morning. The two peaks of rainfall amount were contributed by the frequency (the green line) and intensity (the black line), separately. The rainfall frequency presented a primary early morning peak and a much weaker peak in the late afternoon, and a single late afternoon peak was found in the diurnal cycle of the rainfall intensity. The rainfall of the UK occurred more frequently in the early morning, but was stronger in the late afternoon.

FIGURE 5  Standardized diurnal cycles (by the daily mean) of the precipitation amount (first column), frequency (second column), and intensity (third column) of the events with different durations averaged over UK (first row), daytime stations (second row), and night-time stations (third row) [Colour figure can be viewed at wileyonlinelibrary.com]
Except the spatially averaged state over the entire UK, the diurnal cycles of the rainfall also had regional features. Figure 2 shows the peak time of the rainfall amount (Figure 2a), frequency (Figure 2b), and intensity (Figure 2c) at the 90 stations in the UK. The early morning peaks of rainfall amount were mainly found along the western coastlines of the British Isles, and the rest of the island and the Northern Ireland were controlled by the rainfall peaks from the afternoon to the evening. Fifty-five out of ninety stations reached the hourly maximum during 1300–1900 GMT, and 32 stations reached the maximum in 0400–0800 GMT. Two stations on the isolated islands had rainfall peaks at 0200 GMT. For the rainfall frequency, the early morning peaks dominated along both the western and eastern coastlines and the late afternoon peaks were only found in the inland areas and the peak time was generally earlier than that of the rainfall amount. For the rainfall intensity, the diurnal peaks mainly appeared in the afternoon over the UK and only six stations along the coastlines reached the maximum during midnight to the morning. The diurnal amplitudes of the rainfall intensity (Figure 3c) were relatively larger than that of the frequency (Figure 3b) and smaller than the amount (Figure 3a). For the rainfall frequency, the stations with larger diurnal amplitudes mostly located along the western and southern coastlines of the British Isles and corresponded to the early morning peaks, while the counterpart in rainfall intensity was more popular in the southeastern part of the British Isles with late afternoon peaks. The spatial distributions of diurnal amplitudes of rainfall amount were more complex, and stations with large amplitudes were on both the coastlines and southeastern part of England, as well as the Northern Island.

According to the peak time of the rainfall amount, the stations were divided into two groups. The stations with diurnal peaks in 0900–2000 GMT were daytime stations and those in 2100–0800 GMT were night-time ones. According to Figure 2, most night-time stations were located along the western coastlines and isolated islands and the daytime stations were relatively widespread. Figure 4 illustrates the mean diurnal variations of rainfall amount (red lines), frequency (green lines), and intensity (black lines) of the two groups of stations. The rainfall amount and frequency of night-time stations (dashed lines) were about 1.2 times of that of daytime ones (solid lines). The mean rainfall amount was 0.095 and 0.121 mm/hr for daytime and night-time stations, and 0.119 and 0.141 times per hour for the rainfall frequency. The rainfall intensity was relatively close for the two groups, especially in the afternoon.

Compared with the comparable double peaks of rainfall amount over the entire UK (Figure 1), the secondary peaks were less apparent in the rainfall amount of the two groups of stations (Figure 4). For the rainfall frequency, the night-time stations only showed an early morning peak and two comparable peaks in the early morning and the late afternoon were found at the daytime stations. For rainfall intensity, the late afternoon peaks were found in both groups. The intensity at the night-time stations was stronger, but the diurnal amplitude at the daytime stations was larger.

### 3.2 Diurnal cycles of annual rainfall with different durations

Yu et al. (2007) pointed out that the diurnal peaks were greatly affected by the rainfall duration in China. Short-duration rainfall usually reached the maximum in the late afternoon and the long-duration rainfall primarily had nocturnal diurnal peaks. In the UK, the diurnal cycles of rainfall were also related with the durations. Figure 5 presented the normalized diurnal
variations (x axis) of the rainfall events with different durations (y axis) in rainfall amount, frequency, and intensity.

For the rainfall amount over the UK (Figure 5a), the ratio of rainfall occurring in 1200–1900 GMT gradually decreased when the rainfall duration increased. The rainfall lasting less than or equal to 6 hr primarily got the peak in the late afternoon, but a secondary peak in the early morning was found in the rainfall lasting more than 6 hr. For the rainfall lasting more than 6 hr, the early morning peak dominated, and a secondary peak between 2200–2400 GMT were found in the rainfall lasting more than 12 hr. The rainfall frequency (Figure 5b) with different durations presented similar diurnal variations to that of the rainfall amount, but the rainfall events lasting 1 hr mainly happened in the early morning. The late afternoon peaks were found in the intensity of both the events lasting less than 6 hr and more than 12 hr (Figure 5c). Only the intensity of rainfall events with the duration of 6–12 hr got the maximum during 0400–1200 GMT, and the peaks were later than that of the rainfall amount and frequency.

**FIGURE 7** Spatial distributions of the diurnal peaks of the hourly precipitation amount averaged in spring (a), summer (b), autumn (c), and winter (d). The vectors denote GMT of the maximum precipitation occurrences (the phase clock) [Colour figure can be viewed at wileyonlinelibrary.com]
For the daytime (Figure 5d,f) and night-time stations (Figure 5g,i), the rainfall with different durations also showed different diurnal variations. Generally, the diurnal variations of rainfall amount (Figure 5d), frequency (Figure 5e), and intensity (Figure 5f) of daytime stations were similar to that of the total rainfall, but the morning rainfall amount and frequency of rainfall events lasting 4–6 hours were weak. However, for the night-time stations, the rainfall frequency of the events with most durations got the hourly maximum in 0500–0600 GMT, and no obvious late afternoon peak was found (Figure 5h). The peak of rainfall amount with 1-hour duration appeared in the morning (Figure 5g) and the diurnal variations of the rainfall intensity in night-time stations (Figure 5i) resembled those in daytime ones and the whole UK.

3.3 | Diurnal variations of the rainfall in four seasons
The diurnal cycles of rainfall presented seasonal variations. Generally, more rainfall occurred in the late afternoon in the warm season due to the stronger instability caused by the solar heating and more rainfall appeared in nocturnal period in the cold season (Li et al., 2008). The mean seasonal variations of diurnal cycles of rainfall amount, frequency, and intensity were shown in Figure 6. The diurnal amplitudes were the strongest in summer and weakest in winter, and the amplitudes in spring and autumn were closed. For rainfall amount (Figure 6a), comparable diurnal peaks in the early morning and late afternoon were found in all seasons but summer. For the frequency (intensity, Figure 6b,c), the early morning (late afternoon) peaks dominated from spring to autumn, and the rainfall occurred more frequently around noon (morning) in winter. The spatial distributions of diurnal peaks of the rainfall amount were similar in spring, summer and autumn (Figure 7a,c) and the number of stations with peaks in 2200–0900 GMT was slightly smaller in summer (30) than that in in spring and autumn (32 and 36). But the diurnal amplitudes in summer were the strongest in four seasons at most stations (Figure 8). In winter, the peaks at
stations south to 52°N shifted a few hours earlier to the morning (Figure 7d), when compared with the diurnal peaks in autumn (in the late afternoon). Although the rainfall amount was larger in winter (Jenkins et al., 2008), the diurnal peaks of annual rainfall amount (Figure 2a) were similar to those in the warm season, because the diurnal amplitude of rainfall in winter was weak (Figure 8). Seasonal variations were evident in the diurnal variations of the rainfall frequency (Figure 9) and intensity (Figure 10). In the southern inland areas and northern highlands, the late afternoon peaks of rainfall frequency prevailed in spring and summer and the other areas were dominated by the morning rainfall peaks around 0800 GMT (Figure 9). But for rainfall frequency in autumn and winter, the peaks around 0500–0800 GMT and at 1100 GMT dominated most of the UK, separately (Figure 9). The rainfall intensity was mainly dominated by the late-afternoon peaks (Figure 10). The peaks occurring during midnight to the morning all year were only found in some coastal stations and night-time peaks were found at inland stations in winter (Figure 10d). The seasonal variation
of the diurnal amplitudes was small in rainfall frequency and the variations in rainfall intensity were similar to that in rainfall amount (figure omitted).

4 | CONCLUSIONS AND DISCUSSIONS

Using the hourly rainfall data at 90 stations in the UK during 1998–2015, the diurnal variations of the rainfall amount, frequency and intensity of rainfall events and the rainfall with different durations, as well as their seasonality, were analysed. The major conclusions were summarized below.

1. The rainfall amount averaged in the UK presented two comparable peaks in the early morning and the late afternoon, which was contributed by the early morning peak in the frequency and the late afternoon peak in the intensity.
2. The diurnal rainfall peaks were closely related with the location of stations and the durations of events. The
early morning rainfall peaks were more prevailing in the rainfall with durations more than 6 hr and at stations along the western coasts of the British Isles, however, the rainfall events lasting 1–6 hr usually reached the hourly maximum in the late afternoon.

3. For the rainfall amount and intensity, more nocturnal rainfall peaks were found over the southern plains in winter. In spring to autumn, only the rainfall at the coastal stations or the stations on islands got the maximum at midnight or in the early morning. For the rainfall frequency, the regional differences were more apparent in spring and summer, and the afternoon peaks were found in inland southern plains and northern highland areas and the morning rainfall peaks at the coastal stations. The hourly rainfall frequency in the UK mainly peaked around 0600 GMT in autumn and in 1100–1300 GMT in winter, but the amplitudes were weak. The stations showing rare seasonal shifts of the diurnal phases were mostly located along the coastal.

Results in the present analyses further confirmed conclusions in previous studies. For example, the rainfall mainly reached the maximum in the early morning in the coastal regions and the different diurnal variations were found in warm and cold seasons. These findings suggest that an early morning maximum was linked to the moisture source (Landin and Bosart, 1989; Oki and Musiakc, 1994), to the interactions between the topography and wind directions (Svensson and Jakob, 2002) and to the land–sea interactions (Mayes and Wheeler, 1997). When the temperature decreased in response to the radiational cooling during the night, the relative humidity of moist maritime air in coastal locations increased and the fog, stratus or other low clouds formed or increased in depth at night (Mass, 1982). Because low-level stratus clouds often produce light precipitation, this mechanism may also explain the morning maximum of the rainfall frequency and the relatively stronger intensity in the afternoon. Over the areas covered by the deep continental stratus cloud, the cloud hinders the solar radiation from reaching the ground and results in a relatively stable instability in the daytime. However, during night-time, longwave radiative cooling at the cloud top leads to instability and is favourable to the nocturnal precipitation (Yu et al., 2004; Li et al., 2005; 2008). The seasonal changes of the diurnal peaks also reflected the alternate importance of the orographic effects and thermal forcing and the orographic enhancement is most pronounced in winter (Harrison, 1997). In our future work, the physical mechanism behind will be further studied by the atmospheric circulation data sets.

Meanwhile, the comprehensive sub-daily rainfall features could be used in the numerical weather prediction model evaluations (Blenkinsop et al., 2017). The current advanced numerical models still showed large biases when simulating the diurnal variations of rainfall, not only in climate models (Yuan, 2013) but also in numerical prediction models (Du et al., 2015). Even for the convection-permitting model, which showed improvements in the simulation of the diurnal cycle of precipitation and the representation of convection (Guichard et al., 2004; Pearson et al., 2013; Ban et al., 2014), the nocturnal rainfall over land area was still a limitation (P. Li et al., submitted, 2018). To improve the long-lasting errors in the rainfall simulations, more detailed metrics based on a complete understanding of the observed hourly rainfall features are needed. The diurnal features of rainfall frequency and intensity, the diurnal variations of the rainfall with different durations and the seasonal variations of rainfall diurnal over the UK could be further used in the model evaluations.

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