Characteristics and mechanisms of the diurnal variation of winter precipitation in Taiwan

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Using gridded precipitation data remapping from rain-gauge observations of the time period of 2001–2015 winter months (December, January and February), this study examines the spatio-temporal characteristics of the climatological diurnal winter precipitation in Taiwan. Our results show that the timings of the maximum values of the diurnal precipitation in Taiwan exhibit clear east–west regional differences, with night-time maxima over eastern Taiwan but early morning maxima over western Taiwan. Analyses also show that the climatological characteristics of diurnal winter precipitation documented in this study are not controlled by some unusual, heavy precipitation events and can be seen as the common features. By examining the changes in meteorological variables (including winds, relative humidity and temperature) extracted from the in situ observations and the MERRA (Modern-Era Retrospective Analysis for Research and Applications) reanalysis, this study further suggests that (a) the radiative cooling effect and (b) the surface wind convergence induced by the interaction between the local orography, the local land–sea breeze and the large-scale diurnal circulation changes over the East Asian–western North Pacific (EAWNP) region are two of the possible formation mechanisms responsible for the spatio-temporal differences of the climatological diurnal winter precipitation in Taiwan. This finding sheds light on the importance of understanding the role of the large-scale diurnal circulation changes over the EAWNP region in modulating local diurnal precipitation properties during the winter months.

KEYWORDS
climatology, diurnal circulation, diurnal precipitation, East Asia, winter

1 | INTRODUCTION

Taiwan, an island located in the East Asian–western North Pacific (EAWNP), exhibits a clear diurnal variation in the surface winds and precipitation during both the warm and cold seasons (Chen et al., 1983; Johnson and Bresch, 1991; Kerns et al., 2010). In general, the formation of diurnal variations in the warm season precipitation over Taiwan has been recognized as the result of local forcings involving solar thermal heating and island-scale land–sea breezes (LSB) interacting with orography (e.g., Johnson and Bresch, 1991). The importance of understanding the role of topography and local LSB in modulating the warm season diurnal cycle of precipitation over various areas of EAWNP is also noted by many other studies (e.g., Fujinami et al., 2005; Hirose et al., 2008; Takahashi et al., 2010a; 2010b; Huang et al., 2015; Takahashi, 2016). For example, Fujinami et al. (2005) have noted that the formation and development of the summer diurnal cycle of convection over the southern Tibetan Plateau were strongly affected by the topography of the Tibetan Plateau. Studying the warm season diurnal cycle of precipitation around the Indochina Peninsula, Takahashi...
et al. (2010a) and Takahashi et al. (2010b) have noted that the timing of the occurrence of the diurnal precipitation maximum is geostrophic-dependent and is greatly affected by the local land use and land cover changes. For information on the role of topography and local LSB in affecting the diurnal precipitation variation over contiguous China, one can refer to the detailed review in the earlier literature by Hsu et al. (2014) and Yu et al. (2014).

More recently, studies have noted that in addition to the local circulations, the large-scale circulations covering the EAWNP region also exhibit marked diurnal variations (e.g., Yu et al., 2009; Huang et al., 2010). In Huang et al. (2010). In Huang et al. (2010), the researchers found that the LSB circulation over much of the East Asian coastal areas is coupled with the global-scale atmospheric pressure tide; this produces a large-scale LSB with a spatial scale of ~1,000 km over the EAWNP region (hereafter EAWNP-LSB). Later, Huang and Wang (2014) demonstrated that the interactions between the island-scale LSB and the EAWNP-LSB can lead to timing differences in the occurrences of the maximum values of the diurnal precipitations over different subregions of Taiwan during May and June. As the EAWNP-LSB also exhibits such variations in the winter months (Huang et al., 2010), it is possible that EAWNP-LSB also plays a role in modulating the characteristics of diurnal winter precipitation in Taiwan.

Unlike the widely examined warm season diurnal precipitation variations, the characteristics and formation mechanisms of the diurnal winter precipitation in Taiwan have been less well studied. In addition, of the studies touching the issue of the diurnal winter precipitation in Taiwan (e.g., Chen et al., 1980; Chen and Liu, 1981; Chen et al., 1983), most have mainly focused on the changes of precipitation over northern Taiwan, but not those over other subregions. For example, Chen et al. (1983) examined the temporal evolution of several heavy precipitation events affecting northern Taiwan in the winter months; they noted that the amount of precipitation generally reaches a maximum value during the day in the early morning. This change in precipitation was suggested to be mainly attributed to the interaction between the island-scale LSB and the prevailing wintertime northeasterly monsoonal flow (Chen et al., 1983). However, (a) whether the EAWNP-LSB has an impact on the diurnal winter precipitation in Taiwan and (b) whether the diurnal winter precipitation shows regional differences are two scientific questions that were not examined by Chen et al. (1983) or other studies but are examined herein.

The objective of this study is to document the spatio-temporal characteristics of the diurnal winter precipitation in Taiwan and understand its formation mechanisms with a focus on the possible impacts of changes in EAWNP-LSB. The importance of understanding the diurnal winter precipitation over the EAWNP region has also been noted by another study (e.g., Takahashi, 2012). The remainder of the article is organized as follows. The data sets used for the analyses are introduced in section 2. The results of characteristics of diurnal winter precipitation in Taiwan are shown in section 3. Possible causes for the regional differences in the diurnal winter precipitation in Taiwan are examined in section 4. A discussion of the possible impact of unusual, extreme precipitation events to the documented characteristics of diurnal winter precipitation in Taiwan is provided in section 5. A summary and conclusion are provided in section 6.

2 | DATA AND METHODOLOGY

The analysis of this article focuses on the winter months (December, January and February [DJF]) of the time period from 2001 to 2015. The hourly precipitation data from the studied time period are obtained from a data set with a 5-km resolution uniform grid provided by the Taiwan Climate Change Projection and Information Platform (TCCIP, http://tccip.ncdr.nat.gov.tw/v2/index.aspx). This gridded product, which has been used to show details of the spatio-temporal variations of the precipitation in Taiwan (e.g., Huang et al., 2016a; 2016b), is created by remapping data from the Central Weather Bureau rain-gauge observations in Taiwan. The global atmospheric variables (including wind, relative humidity and temperature) are extracted from the 3-hourly MERRA (Modern-Era Retrospective Analysis for Research and Applications) reanalysis (Rienecker et al., 2011), with a spatial resolution of 0.667° lon. × 0.5° lat. The temporal and spatial resolutions of the MERRA reanalysis represent a leap forward when compared to the commonly used 6-hourly, 2.5° resolutions of older reanalyses (Huang et al., 2010).

Despite the gridded data productions, our analysis also uses the hourly temperature, relative humidity and precipitation provided by the 21 standard weather stations in Taiwan (see Figure 5a), and the surface wind observations provided by selected weather stations (see Figure S2, Supporting information), following Huang and Wang (2014). Hereafter, unless otherwise stated, the analysed variables are the climatological values averaged over the winter months of 2001–2015. All presented results refer to the local standard time (LST) in Taiwan, which is universal time UTC + 8, for example, 0800 LST is 0000 UTC, and so forth. Following Huang et al. (2010), the anomalies of a given variable from the MERRA reanalysis and surface stations at a specific synoptic time step (e.g., 0800 LST) are obtained by subtracting the daily means from their 3- and 24-hourly observations, respectively. The diurnal harmonic of the anomalies of variables is obtained from the Fourier analysis and adopted to construct Figures 6, 7 and S1–S3 (discussed later). For details on how to obtain the harmonic
components of an examined variable from the Fourier analysis, please refer to von Storch and Zwiers (1999).

The empirical orthogonal function (EOF) analysis used to construct Figure 3 (discussed later) was based on a singular value decomposition (SVD) approach following Huang and Wang (2017). The SVD approach, which avoids having to compute the covariance matrix directly, provides an optimal way for data sets with a large spatial dimension (Hannachi et al., 2007). Any missing spaces or time data were removed before applying the SVD approach. In addition, it is a formal requirement of EOF analysis that the data array has columns with a zero mean (von Storch and Zwiers, 1999). The EOF solvers will automatically attempt to subtract the mean from each column. In other words, the output of the EOF analysis reveals mainly the spatio-temporal features of the anomalies of variables. For the detailed review of the EOF analysis (including historical background, formulation and computation, application, etc.), please refer to Hannachi et al. (2007).

3 | CHARACTERISTICS OF WINTER DIURNAL PRECIPITATION IN TAIWAN

Figure 1a shows the winter mean of the low-level wind circulation at 925 hPa over the EAWNP region. Climatologically, the prevailing northeasterly monsoon flows (Figure 1a) interacting with the local orography (Figure 1b) can lead to larger amounts of precipitation appearing over northern Taiwan than over other subregions (Figure 1c) (Kerns et al., 2010; Chen et al., 2012). In examining the heavy precipitation events affecting northern Taiwan in the winter seasons, Chen et al. (1983) noted that the precipitation of those events tended to reach maximum amounts during the day at 0500 LST. Here, by examining the evolution of the climatological winter mean of hourly precipitation area-averaged over the whole of Taiwan (Figure 2a), it is noted that the temporal variations of precipitation exhibit two peaks during the day: one at 0600 LST and another at 2200 LST. Apparently, the features revealed in Figure 2a for the whole of Taiwan are different from those revealed in Chen et al. (1983, fig. 5) for northern Taiwan. This finding implies that the temporal evolutions of the climatological hourly winter precipitation in Taiwan may be location dependent.

To clarify the above inference, we produced a phase diagram to illustrate the timing of the appearance of a maximum value for the climatological winter precipitation during a day over Taiwan (Figure 2b). Here, the timing of the diurnal peak presented in Figure 2b is picked from the evolution of the climatological winter mean of hourly precipitation (e.g., Figure 2a) for each grid with a sample number of 1,350 days (=15 years × 90 days) over the winter months of the time period of 2001–2015. As seen in Figure 2b, most of western Taiwan has a maximum value of precipitation in the early morning. In contrast, most of eastern Taiwan experienced maximum values of precipitation at night. Late morning to early afternoon precipitation maxima are revealed only in a few of the central mountain ranges. These results confirm that the temporal evolution of the climatological hourly winter precipitation in Taiwan is location-dependent.

Statistically, the changes in the variables during the day can be separated into the changes related to its diurnal component, semi-diurnal component and others (e.g., Huang and Chan, 2011). Studying the cause of the early morning precipitation over southeast China (an area nearby Taiwan) during the warm seasons, Huang and Chan (2011) suggested that this feature is mostly controlled by the changes of its semi-diurnal component rather than by the changes of its diurnal component. In addition, Huang and Chan (2011) noted that the formation mechanisms of the changes of the diurnal component of the warm season precipitation over southeast China are different from the formation mechanisms of the changes of its semi-diurnal component. As inferred from Huang and Chan (2011), it is necessary and important to clarify the component (diurnal or semi-diurnal) that dominates the spatio-temporal distribution of the hourly winter precipitation over Taiwan prior to examining its possible causes.

In view of earlier studies, EOF analysis has been widely adopted to identify the dominant components of the precipitation changes during the day (e.g., Huang and Wang, 2017). Here, the EOF analysis is applied to the anomalies of gridded hourly winter precipitation and averaged over the 2001–2015 winter months to help identify the major features of the spatio-temporal distribution of the

**FIGURE 1** (a) The winter (DJF) mean of the low-level atmospheric circulation at 925 hPa over East Asia. (b) The topography of Taiwan. (c) The climatological mean of the winter precipitation over Taiwan [Colour figure can be viewed at wileyonlinelibrary.com]
climatological hourly winter precipitation over Taiwan (Figure 3). For the definition of “anomalies” as well as the details of the EOF analysis, please refer to information provided in section 2.

As shown in the temporal variations of Figure 3, the first two principle modes of the EOF analysis in the anomalies of hourly winter precipitation are mainly featured with one maximum peak and one minimum peak over 24 hr, suggesting that these two modes are related to the changes in the diurnal component. In contrast, the third principle mode, which is featured with two maximum peaks and two minimum peaks over 24 hr, can be categorized as the mode related to the changes in the semi-diurnal component. Among the three principle modes, only the spatial patterns of the first EOF mode (explaining approximately 43.2% of the total variability) shows a clear east–west contrast. By examining the spatial and temporal patterns of the first EOF mode, one can infer that most of eastern Taiwan exhibits a maximum precipitation amount at night, while most of western Taiwan experiences precipitation maxima in the early morning. This observed east–west contrast is consistent with what was found in Figure 2b. In addition, one can also infer from Figure 3 that the spatio-temporal patterns of the second EOF mode (explaining approximately 37.2% of the total variability) capture the aforementioned noon to early afternoon precipitation maxima over a few of the
central mountain ranges. The third EOF mode (explaining only approximately 8.12% of total variability) does not show an east-west contrast or mountain-plain contrast spatial pattern similar to those revealed in Figure 2b. The results shown in Figure 3 imply that the changes in the diurnal component are the major control on the spatio-temporal distribution of the anomalies of hourly winter precipitation over Taiwan.

To further clarify whether it is common to see the diurnal signal in the hourly winter precipitation in Taiwan, we examined the contribution of the diurnal harmonic component (denoted as D1(P)) to the total variability of the anomalies of hourly precipitation (denoted as ΔP) for each precipitation day (defined as a day with an accumulated daily precipitation larger than zero) during the 2001–2015 winter months based on following Equation (1):

\[ \text{Contribution of D1(P)} = \left( \frac{\text{Variability of D1(P) for an examined day}}{\text{Variability of P for an examined day}} \right) \times 100\%. \] (1)

The value of the contribution of D1(P) for each precipitation day during the 2001–2015 winter months is given in Figure 4a. When the value of contribution of D1(P) in Figure 4a is larger than 50% (indicated by a solid line in Figure 4a), we then counted this day as one that is greatly modulated by the signal of the diurnal cycle. By doing this, it is noted that among the 1,188 precipitation days over the focus period of the 2001–2015 winter months, 927 days (approximately 78%) can be recognized as days that are greatly modulated by the diurnal cycle. The related distribution of the total number of precipitation days (filled bars) and the total number of precipitation days with a clear diurnal cycle (outlined bars) for each winter season of 2001–2015 is shown in Figure 4b. Based on these results in Figures 3 and 4, it is clarified that the diurnal component is the predominant pattern for the hourly winter precipitation in Taiwan for most situations. Next, we focus on the causes of the changes in the diurnal component for the winter precipitation over Taiwan.

4 POSSIBLE CAUSES FOR THE REGIONAL DIFFERENCES IN THE DIURNAL PRECIPITATION IN TAIWAN

Examining the causes of the nocturnal precipitation of the warm season of Taiwan and its nearby areas (e.g., Hong Kong), previous studies have indicated that nocturnal instabilities can be initiated by (a) radiative cooling (e.g., Gray and Jacobson, 1977; Chen et al., 2010; Huang and Chan, 2012), (b) the convergence of surface winds (e.g., Wai et al., 1996; Chen et al., 1999) and many others (such as gravity waves, the transportation of unstable condition, squall lines, cold air flow from previous precipitation system, moving precipitation systems, etc.) (e.g., Chen et al., 1983; Ichikawa and Yasunari, 2006; Kerns et al., 2010; Yokoi et al., 2017). In the present study, we focus on understanding the possible roles of (a) the radiative cooling effect and (b) the surface wind convergence in modulating the formation of winter nocturnal precipitation over Taiwan, while further examinations of the other possibilities of formation mechanisms are planned for the near future.

To clarify the possible role of the radiative cooling effect, first we examine the relationship between the changes of the hourly precipitation, temperature and relative humidity extracted from in situ observations over three subregions: western Taiwan (Figure 5b), the central mountain range of Taiwan.
Taiwan (Figure 5c) and eastern Taiwan (Figure 5d). The classification of the stations, as shown in Figure 5a, follows that of Huang and Wang (2014). For all three subregions, a common feature is that a clear negative relationship exists between the temporal evolutions of the relative humidity and the temperature (Figure 5b–d). When the radiative cooling effect, which can induce increases in relative humidity, is the main or only cause of the formation of nocturnal precipitation over Taiwan, all three subregions should exhibit maximum precipitations at the times when the lowest temperature, coupled with the highest relative humidity, appears. However, this does not agree with observations, which show that the stations located over eastern Taiwan record precipitation maxima before the temperature reaches its lowest value during the day (Figure 5d). In contrast, for stations located over other subregions of Taiwan, the precipitation maxima tend to occur around the time of the lowest temperatures (Figure 5b,c), suggesting that the radiative cooling effect might be one of the major formation mechanisms.

Notably, the observed differences between Figure 5d and Figure 5b,c imply that there should be other factors in addition to the radiative cooling effect that help speed up the process of precipitation formation over eastern Taiwan. To clarify whether the variations of EAWNP-LSB are one of the possible factors that could speed up precipitation formation, we examined the horizontal distribution of the diurnal component of the 3-hourly surface wind, temperature, and relative humidity records over the EAWNP region (Figure 6). Here, prior to the detailed discussions, we would like to clarify that the diurnal variation of wind circulation change revealed in Figure 6 is consistent with the results of Huang et al. (2010). According to Huang et al. (2010), the large-scale LSB-like circulation over the EAWNP region is mainly driven by the diurnal variation of the “global pressure tide,” which cannot be simply inferred from the local land–sea temperature changes. Following Huang et al. (2010), we have noted from the spatio-temporal evolution of the diurnal harmonic component of the sea level pressure change averaged over the 2001–2015 winter months (i.e., Figure S1) that the EAWNP-sea breeze at 2300 LST, shown in Figure 6, is formed in response to the related change in the pressure gradient forcing of the global pressure tide. Furthermore, we have noted that because land cooling occurs earlier than the sea level pressure increases for southeast China and nearby regions at 2300 LST (see Figure S1), the large-scale wind direction shown in Figure 6 is blowing from the land to the ocean at 2300 LST, when the temperature is cooler over the land than over the ocean. For more details on the formation mechanisms of EAWNP-LSB and the verification of the existence of EAWNP-LSB using the in situ observations, please refer to Huang et al. (2010).

**FIGURE 5** (a) The topography of Taiwan (shaded) and the locations of the stations in western Taiwan (marked by the plus signs), central Taiwan (marked by the open circle) and eastern Taiwan (marked by the closed square). (b) The winter means of the hourly precipitation (denoted as bars), hourly temperature (denoted by the dashed line) and hourly relative humidity (denoted by the solid line), averaged from the observations from the western stations. (c), (d) Similar to (b), but for the variations averaged from the observations at the central and eastern stations, respectively [Colour figure can be viewed at wileyonlinelibrary.com]
Also, it should be noted that this study is not the first study using the MERRA reanalysis for examining the local surface wind features in Taiwan. In Huang and Wang (2014), they have provided evidence to demonstrate that the MERRA reanalysis is capable of representing the in situ observations of diurnal cycle of surface wind convergence over Taiwan. Here, by comparing the diurnal harmonic of the wind circulation features in Figure 6 and that from the in situ observations (see Figure S2), we clarify that the MERRA reanalysis can represent the climatological wintertime LSB features over Taiwan similar to those revealed in the in situ observations.

Focusing on 2000–2300 LST (i.e., the period with more precipitation over eastern Taiwan), the circulation of Figure 6 is characterized by a large-scale sea-breeze-like pattern extending westwards from the western North Pacific to southeast China (Huang et al., 2010). At this time, the precipitation in Taiwan is modulated by the interaction between the EAWNP-sea breeze and the local orography (see vectors in Figure 6). By examining the associated changes of the low-level upwards motion (Figure 7a) and the changes of the east–west vertical circulation (Figure 7b) at 2000 LST, it is further noted that the interactions between the EAWNP-sea breeze and the local orography can lead to active upwards motion over eastern Taiwan, but not over western Taiwan. This observed strengthening of the active upwards motion (Figure 7a,b) together with an increase in relative humidity (see Figures 6 and 7c) can help precipitation form over eastern Taiwan at night, before the appearance of the lowest temperature in the early morning (see Figure 5d). This can be seen as evidence of the EAWNP-LSB’s modulation on the characteristics of the diurnal winter precipitation in Taiwan.

Also shown in Figures 6 and 7, eastern Taiwan is under the modulation of the island-scale land breeze (Figure 6).
coupled with downwards motion in the early morning (Figure 7d,e). This circulation change is unfavourable for precipitation formation over eastern Taiwan at 0500 LST, even though the relative humidity over eastern Taiwan at 0500 LST (Figure 7f) is comparable to that at 2000 LST (Figure 7c). Based on these findings (Figures 6 and 7) and the fact that eastern Taiwan tends to experience more precipitation at night than in the early morning (Figure 5d), it is suggested that the surface wind convergence plays a more important role than the radiative cooling effect in determining the timings of the appearances of the maximum diurnal winter precipitation over eastern Taiwan.

Notably, western Taiwan also experiences the modulation of island-scale land breezes coupled with downwards motion at 0500 LST (Figure 7d,e). Because these circulation conditions are unfavourable for local precipitation formation (e.g., Huang and Wang, 2014), it is less likely that the aforementioned early morning precipitation maxima over western Taiwan (Figure 5b) are dominated by the surface wind changes alone. Instead, according to results of Figures 5–7, it is more likely that the radiative cooling effect plays a more important role than the surface wind changes in determining the timings of the appearances of the maxima of the diurnal winter precipitation over western Taiwan. This phenomenon can also explain the formation of the early morning precipitation maxima over much of the central mountain range of Taiwan (see Figure 5c). As for the formation of the noon to early afternoon precipitation over a few of the central mountain ranges of Taiwan (see Figure 2b), it is likely related to local forcings involving daytime thermal heating and island-scale sea breezes interacting with orography, as shown in Figure 6.

One might question how the cooling-induced increases in relative humidity can lead to the formation of early morning precipitation. To clarify this issue, we referred to the earlier works of Dai (2001) and Huang and Chan (2012). Huang and Chan (2012) noted that the seasonal transition of predominant precipitation type from showery precipitation

**FIGURE 7** The changes in the diurnal harmonic components of the various atmospheric variables at 2000 LST: (a) 925-hPa omega (sign reversed; $-\omega$), (b) east–west vertical cross section of the circulation (streamline) superimposed with $-\omega$ (shaded) averaged over 22°–25°N, (c) east–west vertical cross section of relative humidity averaged over 22°–25°N. (d)–(f) Similar to (a)–(c), respectively, but for the variations at 0500 LST. [Colour figure can be viewed at wileyonlinelibrary.com]
in the summer to non-showery precipitation in the winter is one of the main causes of the seasonal phase change of the diurnal precipitation from a peak in the late afternoon to one in the early morning over southeast China (a region close to Taiwan). Dai (2001) has suggested that the non-showery precipitation often occurs when the environment has high relative humidity. Based on the suggestion of Dai (2001), Huang and Chan (2012) further demonstrated that the formation mechanism of the diurnal variation of non-showery precipitation over southeast China is linked to the diurnal variation of the local middle-level relative humidity, as well as the surface relative humidity. In association with the characteristics of the diurnal variation of non-showery precipitation, it is therefore common to see the early morning precipitation maximum formed over southeast China with decreases in surface temperature and increases in surface relative humidity (Huang and Chan, 2012).

Because Taiwan is close to southeast China, it is likely that the suggestion of Huang and Chan (2012) for the high relative humidity-induced, early morning precipitation in southeast China can also be applied to explain the similar features revealed in Taiwan. In fact, by adopting the same analysis method and data of Huang and Chan (2012), we have examined the predominant winter precipitation type in Taiwan and found that the non-showery precipitation is the most frequently observed precipitation type in Taiwan (see Figure S3a). Furthermore, we have noted that the temporal evolution of the diurnal harmonic component of the climatological hourly, non-showery precipitation in the winter in Taiwan tends to reach its maximum in the early morning at 0500 LST (see Figure S3b), when the cooling-induced increases in relative humidity are revealed in both the low levels (see Figures 5 and 6) and middle levels (see Figure 7c,f). As a result, it is reasonable to observe early morning precipitation (which is dominated mainly by the non-showery precipitation) forming over Taiwan with decreases in surface temperature and increases in surface relative humidity. For more details on the explanations of high relative humidity-induced, early-morning precipitation and its relationship with the middle-level cloud formation over southeast China and nearby regions (including Taiwan), please refer to Huang and Chan (2012).

5 | POSSIBLE IMPACT OF UNUSUAL, HEAVY PRECIPITATION EVENTS ON THE RESULTS

It should be clarified that we do not exclude any heavy precipitation events for all analysis presented in sections 3 and 4. Thus, one might question whether some unusual heavy precipitation events control the spatio-temporal features of hourly winter precipitation identified in Figures 2 and 3. To clarify this issue, additional testing was performed to examine the possible impact of the unusual, heavy precipitation events for the results presented in Figures 2 and 3. The details are discussed as follows.

According to the information provided in the official website of the Central Weather Bureau (CWB) in Taiwan (http://www.cwb.gov.tw/V7/observe/rainfall/define.htm), a local heavy precipitation event is defined as (a) when the accumulated precipitation over past 24 hr is larger than 80 mm or (b) when the hourly precipitation is larger than 40 mm. An extremely heavy precipitation event in Taiwan is defined as (a) when the accumulated precipitation over past 24 hr is larger than 200 mm or (b) when the 3 hr accumulated precipitation is larger than 100 mm. When using above criteria to check through all the days of the 2001–2015 winter months, we found that only 2 days (December 3, 2004 to December 4, 2004) can be counted as days with heavy precipitation, while none of the days can be counted as extremely heavy precipitation days. By removing these 2 days, which were affected by a typhoon event (Figure S4), we conducted the examinations similar to Figures 2 and 3 but without the influence of unusual heavy precipitation events. The results are provided in Figures S5 and S6.

It is noted that the features revealed in Figures S5 and S6 are consistent with those revealed in Figures 2 and 3, again suggesting that the timing of the maximum values of the diurnal precipitation in Taiwan exhibits clear east–west regional differences, with night-time maxima over eastern Taiwan and early morning maxima over western Taiwan. In addition to Figures S5 and S6, we also tested the results in Figures S7 and S8 by removing the days with daily accumulated precipitation amount ranked in the top 1% of all days of the 2001–2015 winter months (i.e., passing the criteria of 99% percentiles). Despite the differences in the magnitude, the overall spatio-temporal characteristics revealed in Figures S7 and S8 are also consistent with those revealed in Figures 2 and 3. These results confirmed that the climatological characteristics of diurnal winter precipitation documented in the current study are not controlled by some unusual, heavy precipitation events, and can be seen as the common features.

6 | CONCLUSIONS

This study examines the spatio-temporal characteristics and related formation mechanisms of the diurnal winter precipitation over Taiwan. The analyses of this study show that the temporal evolution of the hourly precipitation area-averaged over Taiwan exhibits a bimodal pattern, with one peak at 0600 LST and another at 2200 LST; the former peak is found to be mainly attributed to the precipitation formation over western Taiwan, while the latter peak is found to be mainly dominated by the precipitation formation over eastern Taiwan. The analyses of the formation mechanisms focus on the possible roles of (a) radiative cooling effect...
and (b) the surface wind convergence in modulating the winter diurnal precipitation formation in Taiwan. Our results suggest that the cooling induced increase in relative humidity is an important factor in modulating the early morning precipitation formation over western Taiwan and much of the central mountain ranges of Taiwan. In contrast, the results show that the interactions between the EAWNP-sea breeze and the local orography are very important for the modulation of the night-time precipitation formation over eastern Taiwan, while the cooling-induced increase in relative humidity plays a minor role in this formation process. As for the formation of the noon to early afternoon precipitation revealed over a few of the central mountain ranges of Taiwan, it is related to the local forcings involving daytime thermal heating and island-scale sea breezes interacting with orography.

In summary, this study finds that the temporal variations of the winter diurnal precipitation in Taiwan is location-dependent and demonstrates that the EAWNP-LSB plays a crucial role in modulating the diurnal winter precipitation over eastern Taiwan. These findings shed light on the importance of understanding the possible role of EAWNP-LSB in modulating the diurnal winter precipitation over other subregions of EAWNP. However, it should be noted that the mechanism of diurnal cycle in precipitation is complicated and our analysis only suggests two (i.e., radiative cooling effect and the surface wind convergence), but not all, of the possible mechanisms. Also, the two proposed formation mechanisms in this study might not independent to other possibilities of formation mechanisms (such as gravity waves, the transportation of unstable condition, squall lines, cold air flow from previous precipitation system, moving precipitation systems, etc.). Further examinations of the other possibilities of maintenance mechanisms of winter diurnal precipitation in Taiwan and the seasonal differences in the characteristics of diurnal precipitation in Taiwan are planned for the near future.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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