Discontinuity of diurnal temperature range along elevated regions

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Abstract

Low clouds and fog trap outgoing longwave radiation, thus reducing the radiative cooling effect at night, and block downward solar radiation, thus reducing the warming effect during the day; these two effects moderate the diurnal temperature range (DTR). Consequently, frequent foggy events make montane cloud forests (MCFs) stable and unique. However, long-term observations of the microclimate in the understory of the forest are rare. To investigate various diurnal cycles in different forest ecosystems, we surveyed the area where the Central Cross-Island Highway in Taiwan transects with MCFs. The results revealed that the DTR increases significantly with altitude in open fields but not in the understory of the forest. Furthermore, the DTR decreases in both the open field and understory of MCFs. The DTR discontinuity highlights the value and indispensability of MCF for the mountain ecosystem. Understanding the spatial variation of the climate and further simulating the integrative effect exerted by the climate and changes in land use on fog are crucial for determining the mechanism through which such alterations affect the ecosystem and climate in mountainous regions.

Key word: Diurnal temperature range, Montane Cloud forest, Microclimate

1. Introduction

Mountains provide diverse habitats and elevational gradients that critically enable species to respond to the climate change. The diurnal temperature range (DTR), which is a relatively short temporal variation, can greatly influence species distribution (Chan et al., 2016). The DTR is defined as the range enclosed by the daily maximum and minimum temperatures (Tmax and Tmin, respectively), a key indicator that provides more information than the mean temperature in determining the effect of climate change (Braganza et al., 2004; Easterling et al., 1997). Forests cover about a quarter of the global mountain area and is the most diverse terrestrial system, but in the meantime, the most threatened ecosystem worldwide (Körner, 2004). The canopy and topography create a unique microclimate and exert moderating effects on terrestrial species (De Frenne et al., 2013; Zellweger et al., 2019). However, traditional weather stations are located on flat and uniform grassland, and observational data from mountainous regions are rare (Nick Pepin et al., 2019; Nicolas Pepin et al., 2015). Therefore, high-resolution, in situ observations under the canopy and in open fields of mountainous regions are crucial.

Most previous studies have focused on how the DTR varies over time (Easterling et al., 1997; Jaagus et al., 2014; Kumar et al., 1994; Nick Pepin et al., 2019; Shekhar et al., 2018; Shen et al., 2014; Vose et al., 2005; Zhang et al., 2021). Comparatively, the trends of DTR at an altitude were not consistent both in the open field. (Gheyret et al., 2020; Rapp & Silman, 2012) and understory (Wang et al., 2017; Xue et al., 2020) Variations in the DTR along the elevated region play a crucial role in macroecology and biogeography. The occurrence of dynamic clouds, fog, and rainfall might narrow DTR significantly. (Dai et al., 1999; Hansen et al., 1995; Jackson & Forster, 2010; Karl et al., 1993; Rapp & Silman, 2012, 2012). Nevertheless, previous studies usually focused on either single-point in-situ observations or reginal data with coarse resolution. Thus, this study set paired weather stations in open fields and the understory in the meantime along the continuous mountain range with high-resolution to explore the altitudinal gradient of diurnal variation across normal forests and montane cloud forests (MCFs) in Taiwan.

2. Study Sites and Method

We selected the Chi-Lan flux tower (1650 m a.s.l., 24°35'N, 121°25'E) in northeastern Taiwan as MCF study site from 2008 to 2011. The third quantile of the duration of foggy conditions in no-rain days is approximately 6.5 hours. To compare the effect of fog on the DTR in open fields and the understory, we paired sites in Chi-Lan within 300 m horizontally. The understory and open field sites in Chi-Lan were installed at 1.5 m above the ground on the flux tower and on a flat grassland without canopy cover (1711 m a.s.l., 24°35'N, 121°24'E), respectively. Another study site was selected to determine changes in the microclimate over the east-facing slope of the Central Cross-Island Highway (CCH) with an elevation interval of approximately 250 m, from 100 to 3250 m a.s.l. (Fig. 2A) during 2018 to 2019. To demonstrate the contrast in the microclimates of the understory and open fields without the effect of any synoptic weather conditions and landscapes, paired meteorological stations were installed on the opposite sides of the road. All sites were placed around 1m to 2 m away from the road to constrain the edge effect. We also conducted an observation over an Intensive Observation

Periods (IOP, 2017/4/25- 5/12 and 5/26- 6/7) in the open fields at 1500 m a.s.l. of the east-facing slope of the CCH from April 25, 2017, to June 7, 2017. In addition to air temperature, visibility data and time-lapse photos were recorded during the IOP.

3. Results

We preliminarily applied observational data from Chi-Lan (24°35'N, 121°25'E), located at 1650 m a.s.l. in northeastern Taiwan to determine the diurnal cycle of radiative forcing in a typical MCF ecosystem (Fig. 1A). In Chi-Lan, the DTR was narrower during foggy days both in the open field and understory sites during the observational period of 2011 (Fig. 1B). During foggy days, low solar radiation penetration (Fig. 1C) limited the increase in daytime temperature, and downward longwave radiation (Fig. 1D) caused an increased nighttime temperature. Figure 1 suggests that the fog might efficiently narrow the DTR of MCFs, resulting in a unique and stable elevational region in the mountain forest ecosystem.

3.1 Canopy Shade Moderates Spatial Variance in the Understory

To comprehend the difference in microclimates between the traditional meteorological observation and realistic habitat, we found that the DTR was positively correlated with the elevation in open sites (Fig. 2B). Nevertheless, no significant elevational trends of the DTR were observed in the understory. In the open field, the Tmax increased more substantially than the Tmin at higher altitudes, which contributed to an increase in the. In the understory, the decreasing rate of the Tmax and Tmin at elevated regions were similar, resulting in no significant trend of the DTR at elevated regions.
Solar radiation is usually the dominant factor affecting the Tmax, which is competently reduced by canopy cover. Therefore, the canopy cover effect could smoothen the elevational heterogeneity of the DTR, reducing climatic variability with altitude even in the understory. Because of such a dampening effect from the canopy cover, the difference of the DTR between the understory and open field is greater at a higher altitude. The variation of the DTR at an altitude between two sites demonstrates that moderation by the canopy is more substantial at a high altitude. That is, the forests are conducive for ensuring a stable and comfortable habitat for various species at high altitudes.

3.2 Discontinuous Trend of DTR at High Altitudes

Our result further suggested a discontinuous feature of the DTR along the elevation in both the open field and understory (Fig. 2A). We observed that fog could significantly reduce the DTR through altering the radiation budget (Fig. 1). The characteristic features of MCFs in Taiwan are distributed from 1500 to 2000 m a.s.l., whereas in some monsoon-affected areas, the MCFs might extend down to 1000 m a.s.l. (Schulz et al., 2017). During rainless days in IOP, the chance of >1 hour of foggy events was approximately 30% (Fig. 2B). The visibility (Fig. 2C) and DTR (Fig. 2D) were markedly lower on a foggy day than on a fogless day. Accordingly, fog might be a primary reason explaining the discontinuity in the DTR at high altitudes of the CCH.
On the basis of the MCF map stated by Schulz et al. (2017), we extracted 4 study sites, located from 1250 to 2000 m a.s.l., in the MCF region (Fig. 2A) to represent the microclimate of MCF in CCH. After eliminating the elevational trend, whether in the open field or understory, we observed that the DTR in the MCF was significantly smaller than that in the elevated regions (Fig. 4A, B). Furthermore, in the MCFs, the Tmax was significantly lower than in other elevated regions at both sites, which might be remarkably affected by the fog (Fig. 4C, D). However, the Tmin in the MCFs was similar with low elevations at both sites, and its variations diverged. In the open fields, the Tmin in the MCFs was warmer compared with that in high altitude regions, probably due to the warming effect of the downward longwave radiation by fog. In the understory, the Tmax in the MCFs was much lower, and even if a nighttime warming effect of fog existed in the MCFs, the Tmin was seldom warmer than that at a high altitude. Thus, a significant discontinuity of the DTR along the altitude was most likely due to a smaller Tmax in the MCFs of the CCH.

4. Discussion

Along the continuous mountain range across normal forest and MCFs, our result indicates that the DTR becomes narrower meaningfully in the MCFs in both the understory and open field. Furthermore, a significant elevational trend of the DTR is apparent over open fields but not in the understory. Species at the mid-elevational range necessarily encounter greater climate variability if they shift to a higher altitude for cooler habitats during the warmer climate. The discontinuity of the DTR at higher altitudes makes mid-elevational habitats particularly crucial because species cannot find such an environment with a small DTR along the elevation. If environmental changes along the elevation are assumed to be linear or if the weather conditions of open fields are used to explore the forest ecosystem, the distribution or behavior of species might be misinterpreted.
In addition to the aforementioned abiotic factors, biotic factors severely influence the microclimate in mountainous regions. The different altitudinal gradients of the DTR in the understory and open fields demonstrate that the modulation due to the forest is essential for the microclimate (Fig. 4). The canopy could moderate the spatial variation of the DTR in the understory due to the reduction of solar radiation and heat storage of the crown. Within such a short distance between the understory and open field in our in situ experiments, the results differed with respect to DTR, particularly at high elevations. As the elevation increased, the DTR significantly increased in the absence of forest cover. This considerable difference underscores the importance of observing the understory, which is vital for forest ecosystems. Furthermore, in mountainous

regions, the elevation provides a continuous altitudinal gradient of mean temperature and regulates deforestation-induced warming (Zeng et al., 2021). Even in MCFs, changes in land use could irretrievably affect the functions of the local ecosystem (Hamilton, 1995; Ledo et al., 2009).

Our findings indirectly infer the role of frequent foggy events in elevational discontinuity in the DTR. However, with the increasing temperature caused by global warming and urbanization, the altitude and frequency of fog occurrence and cloud base might be altered due to the lack of water vapor condensation (Foster, 2001; Still et al., 1999). Therefore, only with a clear understanding of how the integrative mechanism influences the location of fog and cloud band in montane areas can we further explore how such alterations affect climatic variability and what their impact on species in the MCF ecosystems is.

5. Reference

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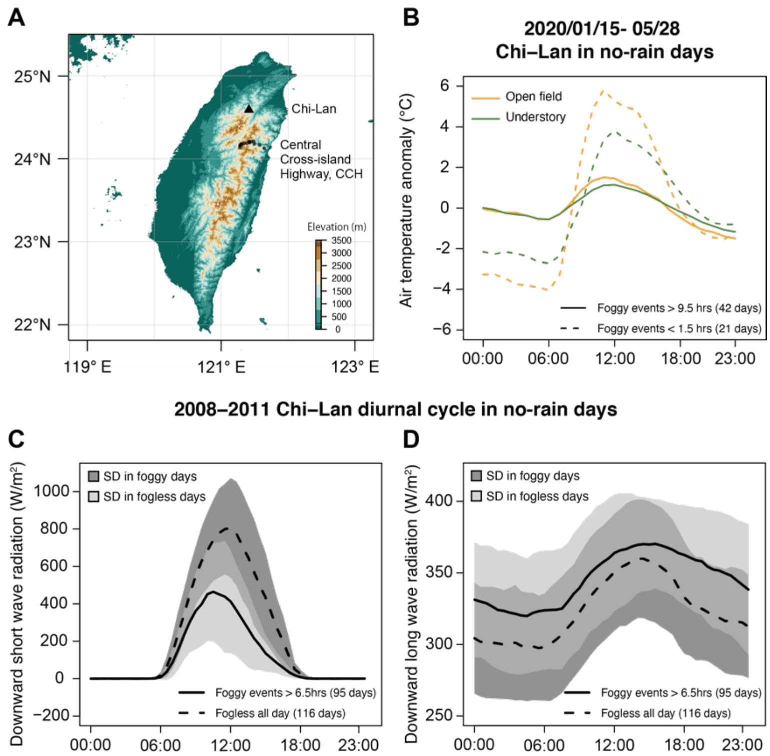

Figure 1. (A) Map of observational sites in Taiwan. (B–D) Diurnal cycle in no-rain days in Chi-Lan Solid lines represent the mean of the observational data every half hour in the foggy days as fog events span >9.5 hours and 6.5 hours (third quantile of daily total duration). The grey shaded areas represent the mean ± 1 standard deviation.

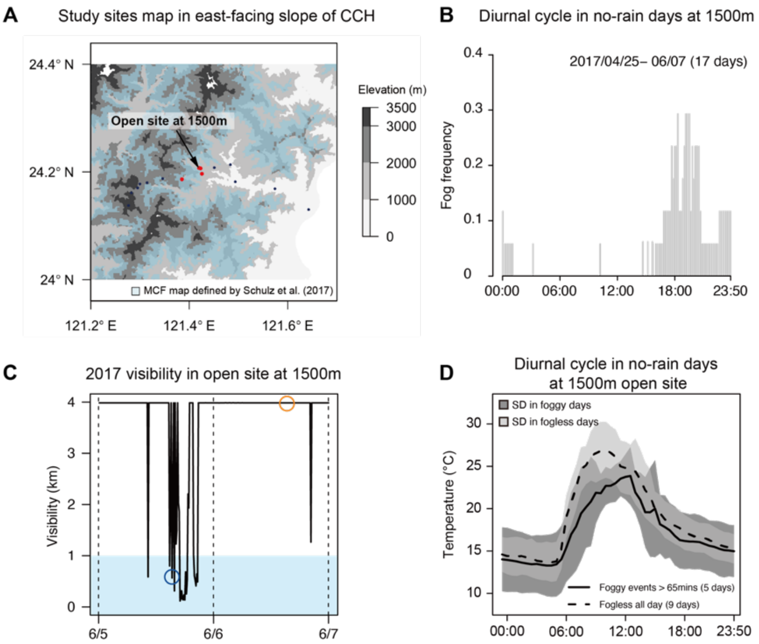

Figure 2. (A) Maps of study sites along the CCH in Taiwan. Light blue shaded map is the MCF map defined by Schulz et al. (2017), and contours represent the altitude. (B) The diurnal cycle of fog frequency at CCH 1500 m in IOP. The gray bars represent the probability of fog occurrence for each hour. (C–D) Diurnal cycle of visibility and air temperature during two IOP days. Blue shaded areas represent fog events.

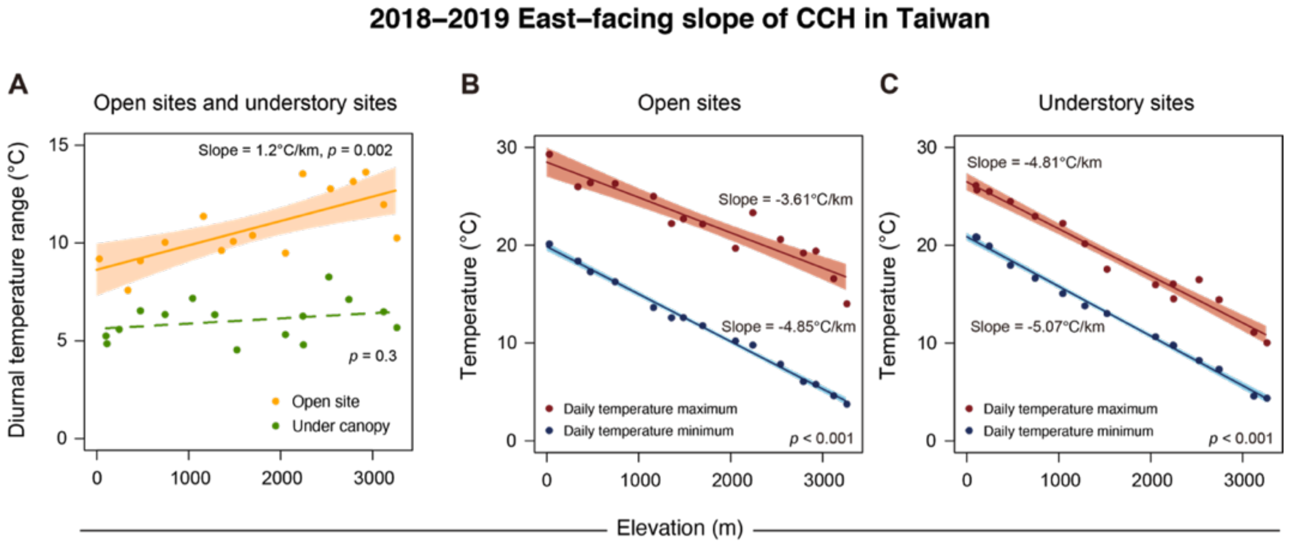

Figure 3. (A) Elevational pattern of DTR from 2018 to 2019. Solid circles are the averaged DTR of every observational site in the understory and open field. The elevational pattern of Tmax and Tmin from 2018 to 2019 in the (B) open field and (C) understory. Solid circles are the averaged Tmin and Tmax of every observational site in the understory and open fields. Lines represent the least-squared means, and shaded areas represent 95% confidence intervals. The dashed line indicates no significance.

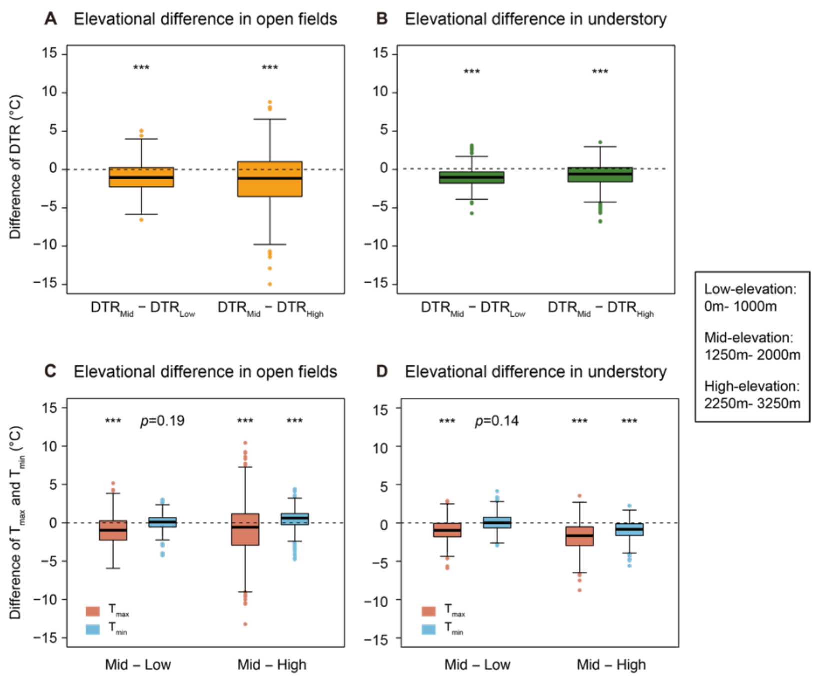

Figure 4. Elevational difference of detrended DTR, Tmax, and Tmin between mid-elevation and low-elevation (left) and between mid-elevation and high-elevation (right) in (A,C) open fields and (B,D) understory. The box represents the 25th and 75th percentile along with the median of 2018–2019 daily data. The upper and lower fences represent 1.5 times the interquartile range. Solid dots represent potential outliers. The p values were obtained from one-tailed tests, and *** represents a 0.1% significant difference.