

## Modeling Seasonal Changes in the Temperature Lapse Rate in a Northern Thailand Mountainous Area

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### ABSTRACT

Temperature data in the mountain forest regions are often extrapolated from temperature data recorded at base stations at lower elevation. Such extrapolation is often based on elevation differences between target regions and base stations at low elevation assuming a constant temperature lapse rate throughout the year. However, this assumption might be problematic where slope circulation is active and decoupled from the regional circulation. To model the seasonal change in the lapse rate, the authors compared daily maximum ( $T_{\max}$ ) and minimum temperatures ( $T_{\min}$ ) observed at a mountain forest site (Kog–Ma; 1300-m altitude) with those observed at the bottom of the basin (Chiang–Mai; 314-m altitude) in northern Thailand, where slope circulation is active and decoupled from the regional circulation. The difference in  $T_{\max}$  between Kog–Ma and Chiang–Mai ( $\Delta T_{\max}$ ; Kog–Ma minus Chiang–Mai) was relatively unchanged throughout the year. However, the difference in  $T_{\min}$  between Kog–Ma and Chiang–Mai ( $\Delta T_{\min}$ ) changed seasonally. Thus, assuming a constant lapse rate throughout the year could cause large errors in extrapolating  $T_{\min}$  data in mountainous areas in northern Thailand. The difference  $\Delta T_{\min}$  was related to nighttime net radiation (Rn), suggesting that nocturnal drainage flow affects the determination of  $\Delta T_{\min}$ . This relationship would be useful in formulating seasonal changes in the lapse rate for  $T_{\min}$ . As Rn data are generally unavailable for meteorological stations, an index that relates to the lapse rate for  $T_{\min}$  and is calculated from  $T_{\max}$  and  $T_{\min}$  data is proposed. This index might be useful for accurately estimating  $T_{\min}$  values in mountainous regions in northern Thailand.

### 1. Introduction

Photosynthesis and transpiration in forests is a critical topic in various research fields, such as meteorology, hydrology, ecology, and forestry (e.g., Vertessy et al. 2001; Komatsu 2003, 2004, 2005; Matsumoto et al. 2008). Temperature is a critical factor affecting photosynthesis and transpiration in forests (e.g., Cunningham and Read 2002; Kumagai et al. 2004, 2008; Komatsu et al. 2006a,b). Furthermore, temperature affects the leaf phenology, canopy structure, and species compositions of forests (e.g., Elliott et al. 2006; Wangda and Ohsawa 2006a,b).

As human beings have generally destroyed forests in lowlands and converted them to other land uses, forests tend to remain in mountainous regions (Kanae et al. 2001; Sawano et al. 2007). Therefore, examining the temperature regime in mountainous regions is important for clarifying forest photosynthesis and transpiration. However, few meteorological stations are located in such regions (e.g., Friedland et al. 2003; Richardson et al. 2004; Tang and Fang 2006). This is especially the case in developing countries.

When considering photosynthesis and transpiration in mountain forests on a regional scale, it is often necessary to extrapolate temperature data in the mountain forest regions from temperature data recorded at base stations at lower elevation. Such extrapolation is often based on elevation differences between target regions at high elevation and base stations at low elevation assuming a

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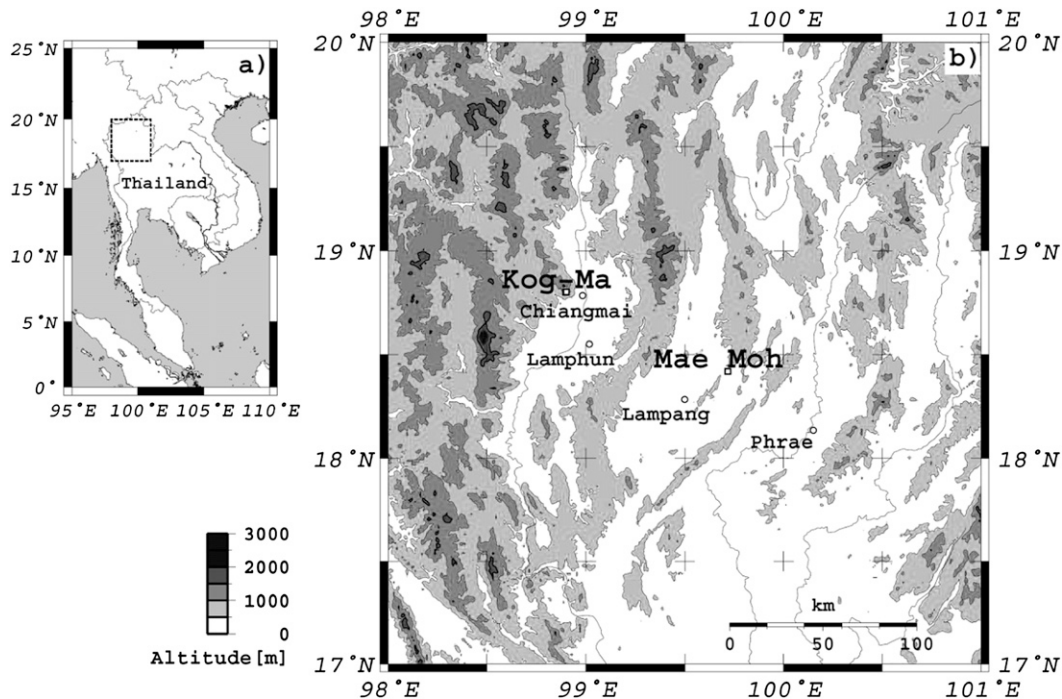


FIG. 1. (a) Map showing northern Thailand. (b) Locations of the Kog-Ma site, Chiang-Mai station, and Mae-Moh site.

temperature lapse rate (e.g., Running et al. 1987; Waring and Running 1998; Lundquist and Cayan 2007). It is preferable to use the rate empirically determined from data for the region (Running et al. 1987; Bolstad et al. 1997, 1998; Tang and Fang 2006). However, when the empirically determined lapse rate is unavailable, it is necessary to use a typical value ( $\sim 6^{\circ}\text{C km}^{-1}$ ) throughout the year.

A temperature lapse rate is affected by slope circulation such as nocturnal drainage flow (Kondo et al. 1989; Kondo 2000; Rolland 2003). This suggests that assuming a typical lapse rate throughout the year might be problematic where slope circulation is active and decoupled from the regional circulation. Thus, it is critical to examine temperature differences between a mountain forest site and a base station for such regions. We examined temperature differences using data for northern Thailand, where nocturnal drainage flow frequently occurs (Komatsu et al. 2003, 2005), and thus slope circulation is active and decoupled from the regional circulation.

In this study, we compare daily maximum and minimum temperature data at a forest site (1300-m altitude) located on the slopes of a basin with data recorded at a meteorological station located at the bottom of the basin (314-m altitude) and examine the seasonality of the temperature differences between the two sites. We then identify a factor corresponding to the seasonality of the temperature differences (and the temperature lapse rate).

We discuss background mechanisms of the temperature difference seasonality. In this discussion, we also consider temperature data recorded at a lowland plantation site (380-m altitude). Finally, we propose a method to determine the temperature lapse rate in the region.

This study is also important from the viewpoint of nature conservation in Thailand. Despite the drastic decrease in the forested area in Thailand in the last century (Kanae et al. 2001) evergreen forests still remain in the hills of northern Thailand (Fox and Vogler 2005; Tanaka et al. 2007). Thus, conservation of these forests is considered critical. Clarifying meteorological conditions (e.g., temperature and rainfall) for the forests is important for their conservation.

## 2. Data

### a. Hill evergreen forest site, Kog-Ma

The hill evergreen forest site in the Kog-Ma Experimental Watershed ( $18^{\circ}48'N$ ,  $98^{\circ}54'E$ ; 1300-m altitude) was located on the slopes of the Chiang-Mai basin (Fig. 1). Figure 2a is a detailed topographical map of the site. The site was about 1 km east of a ridge that runs from north to south. The area above  $\sim 800$ -m altitude was covered with hill evergreen forest.

The top of the canopy at the site was approximately 30 m above the ground (Fig. 3a). The projected leaf-area

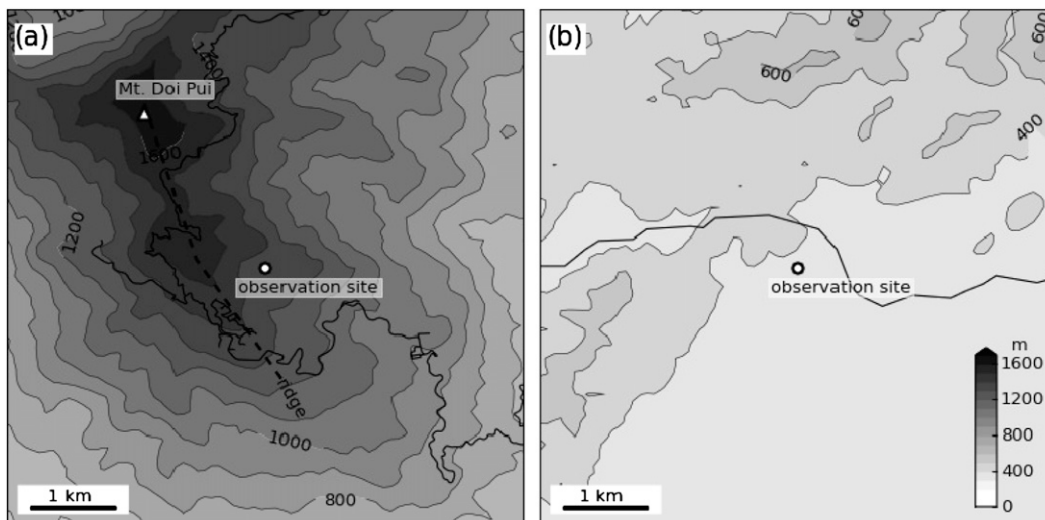


FIG. 2. Detailed topographical maps for (a) Kog-Ma and (b) Mae-Moh sites.

index ranged between 3.5 and 4.5, with a slight seasonal variation. Typical species of the forest were *Cinnamomum porrectum*, *Lithocarpus elegans*, *Castanopsis acuminatissima*, and *Schima wallichii* (Kume et al. 2007; Tanaka et al. 2008).

An observation tower 50 m in height was installed at the site to collect meteorological data. We used data on temperature, downward and upward solar radiation, net radiation, and downward and upward longwave radiation during 1998–2002, which were measured at 10-min intervals (Table 1). We also used rainfall data recorded in an open space near the observation tower.

#### b. Station at the bottom of the basin, Chiang-Mai

The Chiang-Mai meteorological station (18°47'N, 98°59'E; 314-m altitude) is located at the bottom of the Chiang-Mai basin (Fig. 1). In the basin, the central area of Chiang-Mai city (5 km × 5 km) is urban. The surrounding areas are generally paddy fields. The station is situated in the city center, near its western edge. An aerial photograph of the area is available at the Weather Quality Reporter Web site (<http://weather.gladstonefamily.net/site/VTCC>). The Chiang-Mai station is situated ~10 km east of the Kog-Ma site.

Daily rainfall and daily maximum and minimum temperature data have been collected by the Thai Meteorological Department (TMD). Temperature data were measured using a mercury-in-glass thermometer located 1.2 m above the ground. We used these data components for 1998–2002. Temperature data were obtained from the Japan Meteorological Business Support Center (<http://www.jmbc.or.jp/>) and rainfall data were obtained from the TMD.

#### c. Lowland plantation site, Mae-Moh

The Mae-Moh site (18°25'N, 99°43'E; 380-m altitude) was situated in a basin 80 km east of the Chiang-Mai basin (Fig. 1). Figure 2b shows a detailed topographical map of the site. The site was at the foot of the slopes of the basin. The area within ~1 km of the site is generally covered with plantation forest. Surrounding areas are mainly paddy fields and forests.

The mean annual precipitation and temperature during 2000–04 were 1284 mm and 25.8°C, respectively. The vegetation at the site was deciduous teak plantation (*Tectona grandis* Linn. f), planted in 1968 (Figs. 3b,c). The tree density was 380 stems ha<sup>-1</sup> and the top of the canopy was approximately 20 m above the ground. Leaf appearance and leaf fall typically occur in March–May and January–March, respectively. A more complete description of the site has been given by Yoshifuji et al. (2006).

An observation tower 41 m in height was installed at the site to collect meteorological data. We used data on temperature, downward and upward solar radiation, and downward and upward longwave radiation measured in 10-min intervals (Table 1). We also used rainfall data recorded in an open space near the observation tower.

### 3. Results and discussion

#### a. Temperature differences between Kog-Ma and Chiang-Mai

Table 2 summarizes annual rainfall; the annual maximum, mean, and minimum of daily maximum temperature ( $T_{\max}$ ); and the annual maximum, mean, and minimum of

(a)



(b)



(c)



FIG. 3. Photographs of (a) Kog-Ma and (b),(c) Mae-Moh sites; (a) and (b) were taken during the wet seasons and (c) was taken during a dry season.

daily minimum temperature ( $T_{\min}$ ). The annual maximum, mean, and minimum  $T_{\max}$  were lower for Kog-Ma than for Chiang-Mai. The annual maximum and mean  $T_{\min}$  were lower for Kog-Ma than for Chiang-Mai. However, the annual minimum  $T_{\min}$  was comparable between Kog-Ma and Chiang-Mai. The annual minimum  $T_{\min}$  was slightly higher for Kog-Ma than for Chiang-Mai for 3 yr (1998–2000) among the 5 yr despite the elevation difference between Kog-Ma and Chiang-Mai being  $\sim 1000$  m.

Figure 4 shows time series of rainfall,  $T_{\max}$ , and  $T_{\min}$  at Kog-Ma and Chiang-Mai for the 5 yr. Downward solar radiation ( $S$ ) and net longwave radiation ( $L$ ) measured at Kog-Ma are also shown in the figure. (Note that  $S$  and  $L$  data were unavailable for Chiang-Mai.) For both Kog-Ma and Chiang-Mai,  $T_{\max}$  was higher in late dry seasons (March–April) than in other seasons (Fig. 4d). For both Kog-Ma and Chiang-Mai,  $T_{\min}$  was lower in early dry seasons (December–February) than in other seasons (Fig. 4e). However, the amplitude of the seasonal change in  $T_{\min}$  was less significant in Kog-Ma than in Chiang-Mai. This agrees with the fact that though the annual maximum  $T_{\min}$  was lower for Kog-Ma than for Chiang-Mai by  $\sim 5^{\circ}\text{C}$ , the annual minimum  $T_{\min}$  was comparable between Kog-Ma and Chiang-Mai (Table 2).

Figure 5 shows time series of the differences in  $T_{\max}$  and  $T_{\min}$  between Kog-Ma and Chiang-Mai (Kog-Ma minus Chiang-Mai) for the 5 yr. The difference in  $T_{\max}$  ( $\Delta T_{\max}$ ) was typically about  $-10^{\circ}\text{C}$ ;  $T_{\max}$  in Kog-Ma was almost always lower than that in Chiang-Mai by  $\sim 10^{\circ}\text{C}$ . This indicates that the lapse rate for  $T_{\max}$  was relatively conservative throughout the year. However, there was a slight seasonal change in  $\Delta T_{\max}$ ;  $\Delta T_{\max}$  was lowest in April (i.e., late dry season) and highest in September (i.e., wet season). This seasonality in  $\Delta T_{\max}$  might be partly explained by the difference between the dry and saturated adiabatic lapse rates (Kondo 2000; Arya 2001).

The difference in  $T_{\min}$  between Kog-Ma and Chiang-Mai ( $\Delta T_{\min}$ ) was approximately  $-5^{\circ}\text{C}$  during wet seasons (Fig. 5). However,  $\Delta T_{\min}$  during dry seasons was greater than that during wet seasons and often positive (i.e., higher  $T_{\min}$  at Kog-Ma than at Chiang-Mai) despite Kog-Ma being at higher elevation than Chiang-Mai. Further,  $\Delta T_{\min}$  during dry seasons differed between years. This indicates that the lapse rate for  $T_{\min}$  changed seasonally and annually. Thus, the assumption of a constant lapse rate throughout the year and between years could cause large errors in extrapolating  $T_{\min}$  data in the mountain region.

#### *b. Factor corresponding to seasonal changes in $\Delta T_{\min}$*

Figure 6 shows the relationship between nighttime net radiation ( $R_n$ ) at Kog-Ma and  $\Delta T_{\min}$ . Here, nighttime

TABLE 1. Instrumentation at Kog–Ma and Mae–Moh.

| Component                   | Equipment                        | Height above the ground (m) |
|-----------------------------|----------------------------------|-----------------------------|
| Kog–Ma                      |                                  |                             |
| Temperature and humidity    | Vaisala, HMP35A                  | 43                          |
| Downward solar radiation    | Eko, MS-601                      | 50                          |
| Upward solar radiation      | Eko, MS-42                       | 43                          |
| Net radiation               | Eko, CN-11                       | 43                          |
| Downward longwave radiation | Eko, MS-201F                     | 50                          |
| Upward longwave radiation   | Eko, MS-201F                     | 43                          |
| Mae–Moh                     |                                  |                             |
| Temperature and humidity    | Eko, MH020S                      | 39                          |
| Downward solar radiation    | Kipp and Zonen, CM21             | 41                          |
| Upward solar radiation      | Kipp and Zonen, CM21             | 37                          |
| Downward longwave radiation | The Eppley Laboratory, Inc., PIR | 41                          |
| Upward longwave radiation   | The Eppley Laboratory, Inc., PIR | 37                          |

Rn is defined as the average for the period 9 p.m.–3 a.m. local standard time. This definition of nighttime is somewhat arbitrary. However, changes in Rn from sunset to sunrise were relatively small (described later in Fig. 8b). Thus, our conclusions are not affected when using other definitions of nighttime (e.g., the period of 7 p.m.–5 a.m. local standard time).

We observed a systematic relationship between Rn and  $\Delta T_{\min}$ . Thus, the seasonality of  $\Delta T_{\min}$  corresponded to that of Rn. When  $\Delta T_{\min}$  was positive, Rn was very negative. This suggests that the positive  $\Delta T_{\min}$  was caused by nocturnal drainage flow. Nocturnal drainage flow is a phenomenon where air cooled on slopes of a basin due to negative Rn flows to the bottom of the basin (Kondo 2000; Whiteman 2000). Consequently, the nighttime temperature decline on slopes is relaxed when negatively large Rn is recorded. This suggestion is supported by the following:

First, Komatsu et al. (2003) reported the frequent occurrence of nocturnal drainage flow when Rn was very

negative. They measured wind speeds at 34, 43, and 50 m above the ground at Kog–Ma (i.e., 4, 13, and 20 m above the canopy) and reported that the wind speed at 50 m tended to be low when Rn was very negative, indicating that the region including Kog–Ma was governed by a high pressure system. They reported that the wind speed at 34 m was often higher than wind speeds at 43 m and 50 m when Rn was very negative, suggesting the vertical wind speed maximum was at 34 m rather than at 50 m. Such a profile is representative of nocturnal drainage flow (e.g., Manins and Sawford 1979; Kondo and Sato 1988; Amanatidis et al. 1992).

Second, the temperature decline at night  $\delta T$  was much smaller than the potential temperature decline at night ( $\delta T_{\text{pot}}$ ). Here,  $\delta T$  is defined as the difference between temperature just after sunset ( $T_0$ ) and  $T_{\min}$  recorded the next morning, and  $\delta T_{\text{pot}}$  is the temperature decline required for balancing upward and downward longwave radiation (Kondo 2000; Iijima and Shinoda 2002). Here  $\delta T_{\text{pot}}$  satisfies the equation

TABLE 2. Annual rainfall ( $P$ ) and  $T_{\max}$  and  $T_{\min}$  at Kog–Ma and Chiang–Mai.

|                 | 1998        | 1999   | 2000   | 2001   | 2002   | Mean   | Std dev |     |
|-----------------|-------------|--------|--------|--------|--------|--------|---------|-----|
| Kog–Ma          |             |        |        |        |        |        |         |     |
| $P$ (mm)        | 1262.3      | 1883.0 | 1643.0 | 1789.6 | 2458.7 | 1807.3 | 434.3   |     |
| $T_{\max}$ (°C) | Annual max  | 29.3   | 28.3   | 27.7   | 29.0   | 29.0   | 28.7    | 0.7 |
|                 | Annual mean | 23.9   | 21.9   | 22.1   | 22.4   | 22.4   | 22.5    | 0.8 |
|                 | Annual min  | 14.6   | 9.6    | 16.3   | 15.3   | 15.9   | 14.3    | 2.7 |
| $T_{\min}$ (°C) | Annual max  | 23.8   | 22.8   | 23.1   | 24.0   | 24.1   | 23.6    | 0.6 |
|                 | Annual mean | 18.6   | 17.7   | 17.7   | 17.8   | 18.0   | 18.0    | 0.4 |
|                 | Annual min  | 11.5   | 4.0    | 11.6   | 10.0   | 11.4   | 9.7     | 3.3 |
| Chiang–Mai      |             |        |        |        |        |        |         |     |
| $P$ (mm)        | 755.9       | 1141.5 | 1133.1 | 1210.4 | 1592.5 | 1166.7 | 297.4   |     |
| $T_{\max}$ (°C) | Annual max  | 40.1   | 38.2   | 37.8   | 39.4   | 39.8   | 39.1    | 1.0 |
|                 | Annual mean | 33.5   | 31.4   | 31.4   | 31.7   | 31.7   | 31.9    | 0.9 |
|                 | Annual min  | 20.5   | 13.7   | 23.2   | 21.5   | 16.3   | 19.0    | 3.9 |
| $T_{\min}$ (°C) | Annual max  | 27.0   | 32.2   | 29.5   | 27.1   | 27.5   | 28.7    | 2.2 |
|                 | Annual mean | 21.0   | 21.4   | 20.9   | 21.2   | 21.2   | 21.1    | 0.2 |
|                 | Annual min  | 8.7    | 3.8    | 10.3   | 10.0   | 12.5   | 9.1     | 3.2 |

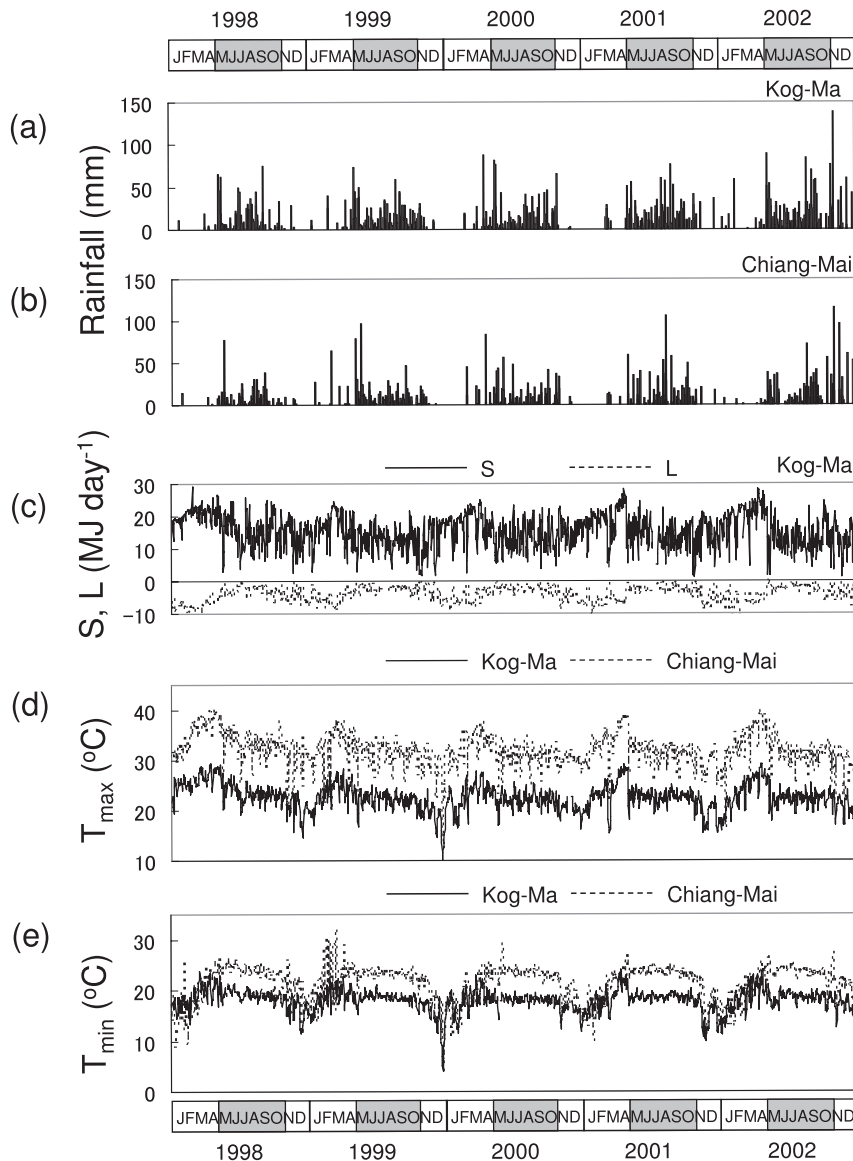


FIG. 4. Time series of meteorological factors: (a) rainfall at Kog-Ma, (b) rainfall at Chiang-Mai, (c)  $S$  and  $L$  at Kog-Ma, (d)  $T_{\max}$  at Kog-Ma and Chiang-Mai, and (e)  $T_{\min}$  at Kog-Ma and Chiang-Mai. Blank and shaded bars indicate dry (November–April) and wet (May–October) seasons, respectively.

$$Rn_0 = \sigma(T_0 - \delta T_{\text{pot}})^4 - \sigma T_0^4, \quad (1)$$

where  $Rn_0$  is  $Rn$  just after sunset and  $\sigma$  is the Stefan-Boltzmann constant. The right-hand side of this equation is approximated as  $-4\sigma T_0^3 \delta T_{\text{pot}}$  (Kondo 2000; Iijima and Shinoda 2002) and therefore  $\delta T_{\text{pot}}$  is calculated as

$$\delta T_{\text{pot}} = -Rn_0 / (4\sigma T_0^3). \quad (2)$$

Figure 7a shows the relationship between  $Rn_0$  and  $\delta T$  during dry seasons in Kog-Ma. The solid line indicates

conditions for  $\delta T = \delta T_{\text{pot}}$ . In Kog-Ma, observed  $\delta T$  values were much smaller than  $\delta T_{\text{pot}}$  values expected from  $Rn_0$  values. This contrasts with the case of Mae-Moh, located at the foot of slopes of a basin. Figure 7b shows the relationship between  $Rn_0$  and  $\delta T$  during dry seasons in Mae-Moh. Observed  $\delta T$  values in Mae-Moh were comparable to  $\delta T_{\text{pot}}$  values expected from  $Rn_0$  values. These results suggest that cold air due to negative  $Rn$  at Kog-Ma was effectively drained from the site by nocturnal drainage flow. Note that Kog-Ma is located near a ridge and therefore cold air that passes into the site from higher elevation is less significant than that

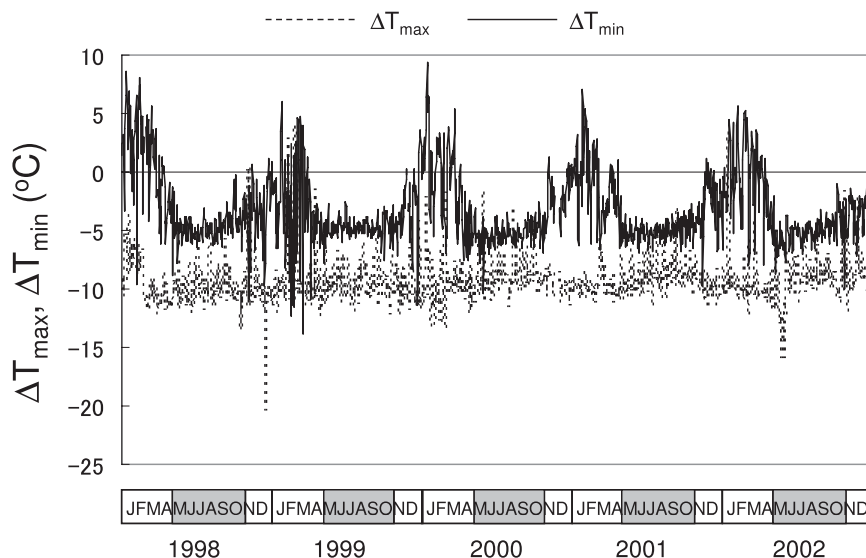


FIG. 5. Time series of  $\Delta T_{\max}$  between Kog–Ma and Chiang–Mai (Kog–Ma minus Chiang–Mai) and those of  $\Delta T_{\min}$  between Kog–Ma and Chiang–Mai (Kog–Ma minus Chiang–Mai). Blank and shaded bars indicate dry (November–April) and wet seasons (May–October), respectively.

draining away from the site. In Mae–Moh,  $\delta T$  was still less than  $\delta T_{\text{pot}}$ . This might be explained by several factors. For example, sensible heat fluxes from the soil to the air were relatively large owing to the absence of leaf canopy during the dry season in Mae–Moh, resulting in relaxation of the temperature decline at night. Mae–Moh is located at the foot of slopes, not at the bottom of the basin, implying that limited cold air drainage occurs at this site.

Third,  $R_n$  observed in Kog–Ma during clear nights in dry seasons was relatively unchanged throughout the night. Figure 8 shows temporal changes in temperature and  $R_n$  at Kog–Ma averaged for 10 days during a dry season. For comparison, this figure also shows temporal changes in temperature and  $R_n$  at Mae–Moh averaged for 10 days during a dry season. The temperature decline at night was less significant in Kog–Ma than in Mae–Moh (Figs. 8a,c); that is, the amplitude was less significant for Kog–Ma. This agrees with the results shown in Fig. 7.  $R_n$  increased (i.e., approached zero) at night for both Kog–Ma and Mae–Moh (Figs. 8b,d), indicating that the land surface was more effectively cooled than the overlying air was at both sites. However, the change in  $R_n$  for Kog–Ma was less drastic than that for Mae–Moh, indicating that the land surface at Kog–Ma was less effectively cooled by negative  $R_n$  than that at Mae–Moh. This supports the suggestion proposed above that cold air due to negative  $R_n$  was effectively drained at Kog–Ma via nocturnal drainage flow.

Positive  $\Delta T_{\min}$  values (i.e., higher  $T_{\min}$  values at higher elevation) have been reported in many earlier studies (e.g.,

Horst and Doran 1986; Barr and Orgill 1989; Kobayashi et al. 1994; Mori et al. 1995; Kondo 2000). Background mechanisms of this phenomenon are understood fairly well (e.g., Kondo et al. 1989; Kondo 2000; Whiteman 2000). However, most of the studies were based on short-term observations (e.g., for several days), and therefore, seasonal and interannual variations in  $\Delta T_{\min}$  have not

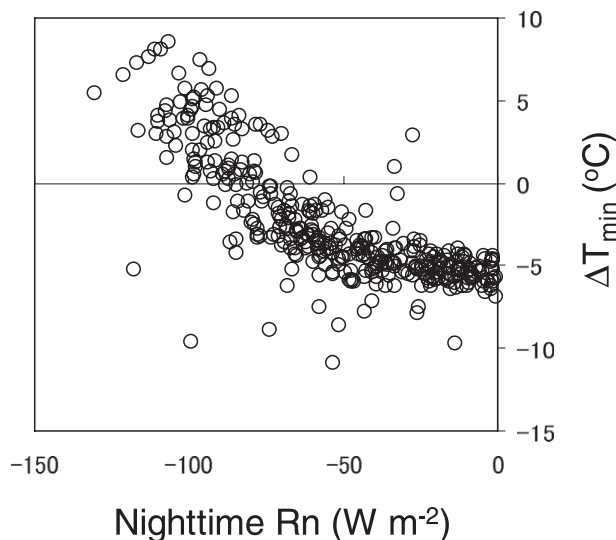


FIG. 6. Relationship between nighttime  $R_n$  (average for 2100–0300 local standard time) and  $\Delta T_{\min}$  between Kog–Ma and Chiang–Mai. (Drawn on the basis of 1-yr data for 1998 because the ratio of missing  $R_n$  data was the lowest for this year among the years 1998–2002.)

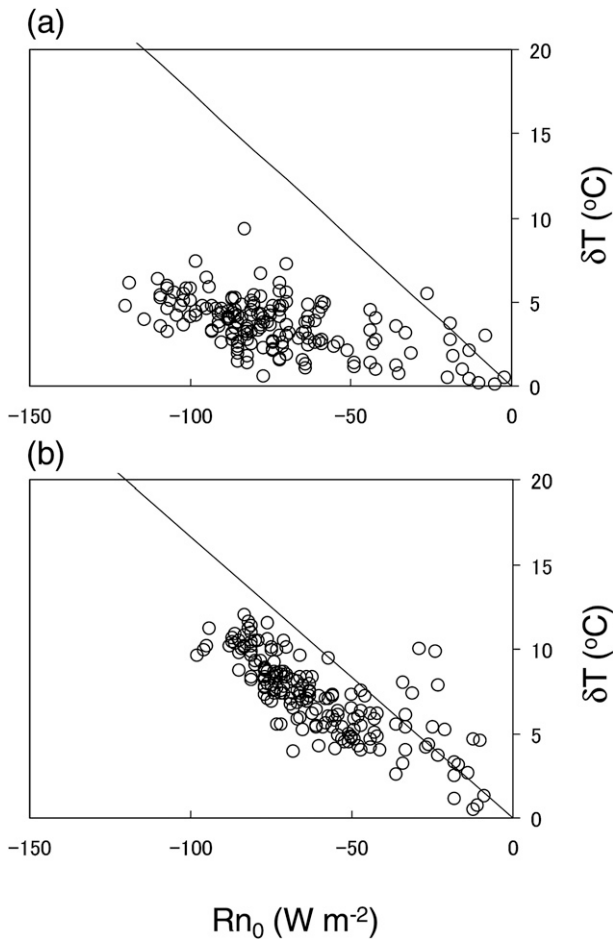


FIG. 7. Relationships between  $Rn_0$  and  $\delta T$  at (a) Kog-Ma and (b) Mae-Moh. Here,  $Rn_0$  is net radiation just after sunset (i.e.,  $Rn$  when solar radiation first drops to zero in the evening) and  $\delta T$  is the temperature decline at night. Solid lines indicate conditions with  $\delta T = \delta T_{\text{pot}}$ , where  $\delta T_{\text{pot}}$  is the potential temperature decline at night. In calculating  $\delta T_{\text{pot}}$ , typical  $T_0$  values for each site were assumed: 20°C and 25°C for Kog-Ma and Mae-Moh, respectively. Figures 5a,b are based on data recorded during dry seasons (January–April and November–December) in 1998 and 2006, respectively.

been examined sufficiently well. There are several exceptional studies that examined spatial variability in temperature in mountainous regions on the basis of long-term data (Iijima and Shinoda 2000, 2002; Pepin and Kidd 2006; Lundquist et al. 2008). These studies were performed in temperate regions and only a few studies (e.g., Du et al. 1990; Nomoto et al. 1990) were performed in tropical monsoon regions.

### c. Relationship between $\Delta T_{\text{min}}$ and synoptic conditions

As shown above, the seasonality of  $\Delta T_{\text{min}}$  corresponded to that of  $Rn$ . The seasonality of  $Rn$  is related to

changes in synoptic conditions. This suggests that there is a systematic relationship between  $\Delta T_{\text{min}}$  and synoptic conditions.

The greatest change in synoptic conditions in Thailand is the onset–offset of the Asian monsoon (Matsumoto 1997; Kiguchi and Matsumoto 2005; Yokoi et al. 2007). The onset of the Asian monsoon is often determined by a rainfall index, that is, the 5-day running mean of rainfall (Lau and Yang 1997; Zhang et al. 2002). The threshold of the index is often set at the annual mean daily rainfall (Matsumoto 1997). We used this method to determine the onset date of the Asian monsoon.

Figure 9 shows time series of the rainfall index and 5-day running mean of  $\Delta T_{\text{min}}$  based on data for 1998–2002 at Kog-Ma. The threshold value was set at 5.0 mm day<sup>-1</sup>. This value was nearly identical to thresholds used by Lau and Yang (1997) and Zhang et al. (2002) to determine the onset date across Southeast Asia. The index tended to be lower than the threshold value during November–April. The index tended to be higher than the threshold value during May–October, which is approximately the period when westerly winds strengthen over the Indochina Peninsula (Lau and Yang 1997; Kanae et al. 2001; Zhang et al. 2004). During November–April  $\Delta T_{\text{min}}$  changed greatly, and it was relatively conservative during May–October. Thus, assuming a constant lapse rate is valid only after the onset of the Asian monsoon. The lapse rate changed greatly before the onset when a high pressure system was dominant, and thus nighttime  $Rn$  was very negative. The synchronicity between the index and the lapse rate suggests that the lapse rate might also be an indicator for determining the onset–offset of the Asian monsoon. However, note that the synchronicity was observed only on a seasonal basis. We calculated and compared anomalies for both indices after removing the seasonality. We found no systematic relationship between the anomalies (data not shown), suggesting that the synchronicity between the indices does not hold at a shorter time scale.

### d. Vertical temperature gradient at Kog-Ma

The temperature data at Kog-Ma used in this study were not recorded at the canopy top but 13 m above the canopy top. This contrasts with the case for Chiang-Mai, where temperature data were recorded 1.2 m above the ground. If there was a strong temperature gradient above the canopy at Kog-Ma, our results presented above would be affected. This would be the case for a calm clear night when  $Rn$  is very negative and the background wind speed is low (i.e., very stable conditions).

Komatsu et al. (2008) measured temperatures 14 m above the canopy top (44 m above the ground) and at the canopy top (30 m above the ground) using thermometers (Onset, Stow-Away-IS Temp) during October–November



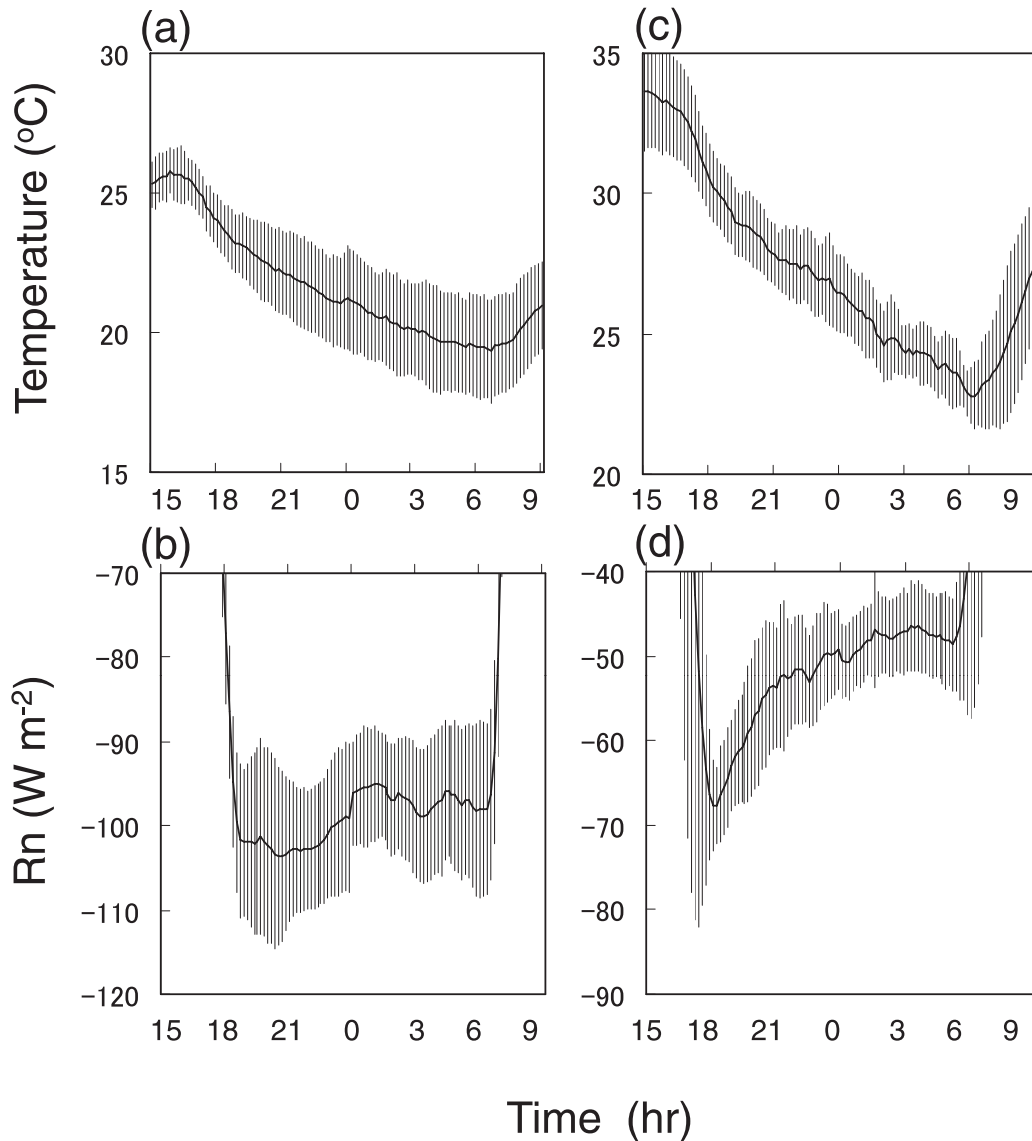


FIG. 8. Temporal changes in (a) temperature and (b) net radiation at Kog-Ma averaged for 10 days during a dry season (1–10 Mar 1998). Temporal changes in (c) temperature and (d) net radiation at Mae-Moh averaged for 10 days during a dry season (1–10 Mar 2006). Vertical bars indicate standard deviations. Times are local standard times.

2000 when the nighttime temperature gradient above the canopy would have been the greatest during the year, owing to the low wind speeds in these months (Komatsu et al. 2003). According to their data, the difference between daily minimum temperatures at 44 and 30 m (temperature at 44 m minus that at 30 m) is negatively correlated ( $R^2 = 0.50, p < 0.001$ ) with nighttime Rn;  $y = -0.0152x + 0.0297$  (data not shown).

Thus, the lapse rate for  $T_{\min}$  calculated directly from  $\Delta T_{\min}$  (Fig. 6) is affected by the vertical temperature gradient at Kog-Ma. Figure 10a shows the relationship

between nighttime Rn and the lapse rate calculated based on the temperature 43 m above the ground. When we adjusted the temperature data recorded at 43 m by the regression equation mentioned above to consider the vertical temperature gradient above the canopy, the relationship became that shown in Fig. 10b. Though the lapse rate after the adjustment was nearly the same as that before the adjustment for larger Rn (Rn nearer to zero), it was somewhat different for smaller Rn (more negative Rn). We use the lapse rate after the adjustment in the following discussion.

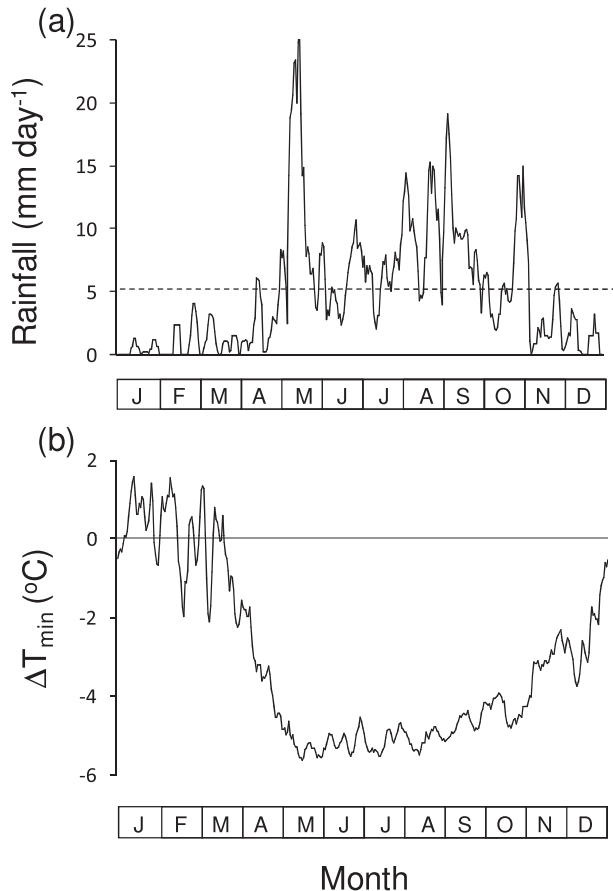


FIG. 9. Time series of (a) the rainfall index and (b) 5-day running mean of  $\Delta T_{\min}$  based on data for 1998–2002 at Kog–Ma. The dotted line in (a) indicates the threshold value used for determining the onset of the Asian monsoon (i.e., 5.0 mm day<sup>-1</sup>).

#### e. Implications for extrapolating temperature in hill evergreen forest regions

The close relationship between nighttime Rn and the lapse rate for  $T_{\min}$  (Fig. 10) indicates that using Rn data would be useful in improving the accuracy of  $T_{\min}$  estimates in hill evergreen forest regions based on station data. However, Rn data are not commonly available from meteorological stations in Thailand. We thus propose an index that is calculated based on  $T_{\max}$  and  $T_{\min}$  data obtained from stations at low elevation and could substitute Rn data.

The index is defined as the difference between  $T_{\max}$  of the previous day (usually recorded at around 2 p.m.) and  $T_{\min}$  of the present day (usually recorded early in the morning) at Chiang–Mai. The index would relate to the nighttime temperature decline ( $\delta T$ ) at Chiang–Mai;  $\delta T$  would further relate to nighttime Rn at Chiang–Mai and therefore Rn at Kog–Ma. Thus, the index and Rn at Kog–Ma are closely related ( $R^2 = 0.51$ ,  $p < 0.001$ ) (Fig. 11a),

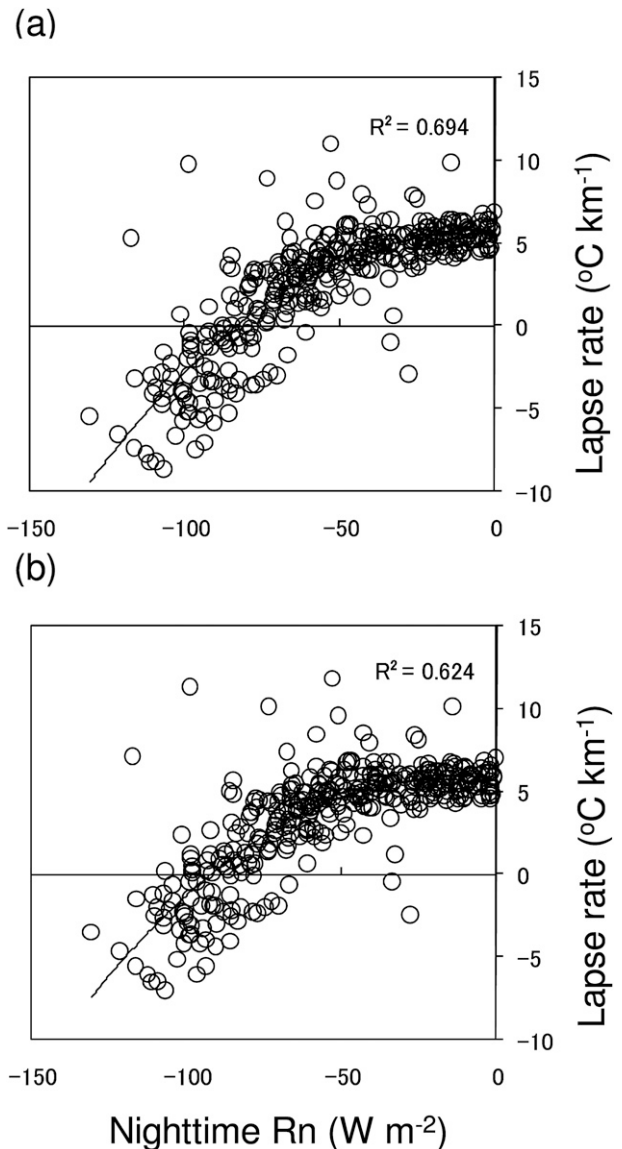
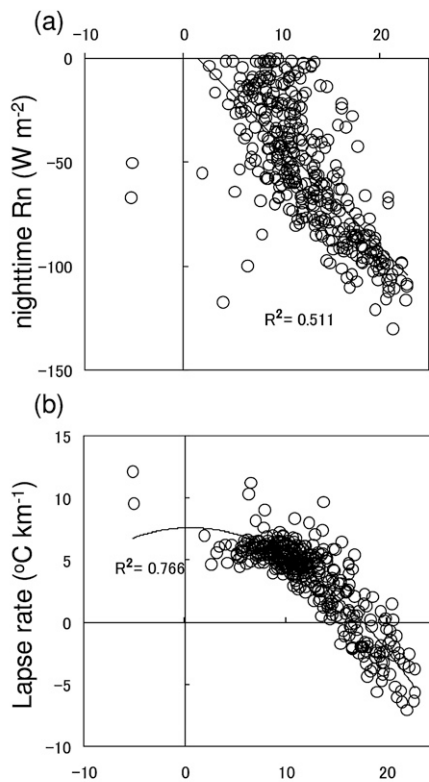


FIG. 10. (a) Relationship between nighttime Rn and the lapse rate for  $T_{\min}$  based on  $T_{\min}$  data at Kog–Ma recorded 43 m above the ground and data recorded at Chiang–Mai. (b) As in (a), but with the  $T_{\min}$  data at Kog–Ma adjusted to consider the vertical temperature gradient above the canopy at Kog–Ma. These figures are based on 1-yr data for 1998. The solid lines in (a) and (b), determined by the least squares method, are written as  $y = -0.00102x^2 - 0.0197x + 5.43$  and  $y = -0.00102x^2 - 0.0349x + 5.46$ , respectively.

resulting in a clear relationship between the index and lapse rate (Fig. 11b). (Note that it is still unclear whether the lapse rate is nearly constant when the index is very low, owing to a lack of data.) Thus, using the index may improve the accuracy of  $T_{\min}$  estimates in hill evergreen forest regions when using data obtained from stations at low elevation.



$T_{\max}$  of the previous day -  $T_{\min}$  of the present day ( $^{\circ}\text{C}$ )

FIG. 11. Relationships of  $T_{\max}$  of the previous day minus  $T_{\min}$  of the present day at Chiang-Mai with (a) nighttime Rn at Kog-Ma and (b) the lapse rate for  $T_{\min}$ . These figures are based on 1-yr data for 1998. The solid lines in (a) and (b), determined by the least squares method, are written as  $y = -4.92x + 7.61$  and  $y = -0.0259x^2 - 0.0272x + 7.59$ , respectively. The lapse rate data in (b) are adjusted to consider the vertical temperature gradient above the canopy.

Here, we assumed correlations between the index and nighttime Rn at the base station and between nighttime Rn at the base station and that in the target area. We could not test these assumptions for Chiang-Mai and Kog-Ma data because Rn data for Chiang-Mai were unavailable. Instead, we tested the assumptions using data for Mae-Moh and Kog-Ma. Figures 12a and 12b show the relationship between nighttime Rn and the index at Mae-Moh and that between nighttime Rn at Kog-Ma and nighttime Rn at Mae-Moh, respectively. We observed significant ( $p < 0.001$ ) correlations for the relationships. These results imply the validity of the assumptions for the northern Thailand regions.

On the other hand, the regression coefficients for the relationship between the index and the lapse rate for  $T_{\min}$  (Fig. 11b) would vary owing to various factors such as land cover, topography, and atmospheric pollutants. Land cover affects the surface energy balance (e.g., Chen et al. 1993; Jackson et al. 2008) and thus influences the

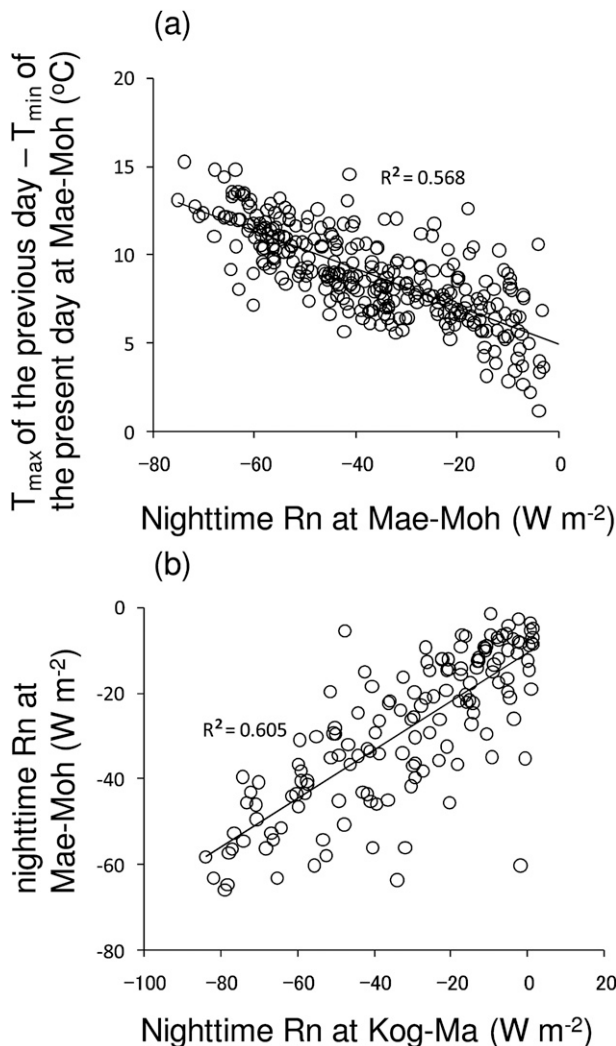


FIG. 12. Relationships between (a)  $T_{\max}$  of the previous day minus  $T_{\min}$  of the present day at Mae-Moh and nighttime Rn at Mae-Moh and (b) nighttime Rn at Mae-Moh and that at Kog-Ma. The solid lines in (a) and (b), determined by the least squares method, are written as  $y = -0.106x + 4.97$  and  $y = 0.563x - 10.6$ , respectively. These figures are based on 1-yr data for September 2005–July 2006, when Rn and temperature data for both Kog-Ma and Mae-Moh were available.

relationship between the index and nighttime Rn. Topography affects the significance of slope circulations (e.g., Kondo et al. 1989; Kimura and Kuwagata 1995) and thus influences the relationship between the index and nighttime Rn. Atmospheric pollutants affect the vertical decline in radiation (e.g., Jacobson 1998; Gomes et al. 2008) and thus influence the relationship between nighttime Rn at the base station and that in the target area. Thus, it is necessary to apply the index under various conditions to develop a general form of the relationship between the index and the lapse rate for  $T_{\min}$ .

#### 4. Conclusions

This study compared daily maximum ( $T_{\max}$ ) and minimum temperatures ( $T_{\min}$ ) at a mountainous forest site (Kog–Ma; 1300-m altitude) with those at the bottom of the basin (Chiang–Mai; 314-m altitude) based on a 5-yr period. The annual maximum, mean, and minimum  $T_{\max}$  were lower for Kog–Ma than for Chiang–Mai. The annual maximum and mean  $T_{\min}$  were lower for Kog–Ma than for Chiang–Mai. However, the annual minimum  $T_{\min}$  was comparable between Kog–Ma and Chiang–Mai despite the elevation difference between Kog–Ma and Chiang–Mai.

The difference in  $T_{\max}$  between Kog–Ma and Chiang–Mai ( $\Delta T_{\max}$ ; Kog–Ma minus Chiang–Mai) was approximately  $-10^{\circ}\text{C}$  throughout the year. The difference in  $T_{\min}$  between Kog–Ma and Chiang–Mai ( $\Delta T_{\min}$ ) was approximately  $-5^{\circ}\text{C}$  during wet seasons. However,  $\Delta T_{\min}$  during dry seasons was greater than that during wet seasons. Furthermore,  $\Delta T_{\min}$  was often positive during dry seasons (i.e., higher  $T_{\min}$  at Kog–Ma than at Chiang–Mai) despite the elevation difference. This suggests that assuming a constant lapse rate throughout the year could cause large errors in extrapolating  $T_{\min}$  data in mountainous areas in northern Thailand.

Values of  $\Delta T_{\min}$  were related to nighttime net radiation; i.e.,  $\Delta T_{\min}$  was greater when Rn was more negative. This relationship was due to nocturnal drainage flow when net radiation was very negative. The relationship would be useful in formulating seasonal changes in the lapse rate for  $T_{\min}$ . As Rn data are generally unavailable for meteorological stations in Thailand, we propose an index that relates to the lapse rate for  $T_{\min}$  and is calculated from  $T_{\max}$  and  $T_{\min}$  data. This index would be useful for accurately estimating the lapse rate for  $T_{\min}$ . However, this study is the first to examine temperature differences between mountainous regions and lowlands in northern Thailand. Thus, it is necessary to apply the index under various conditions to develop a general form of the relationship between the index and the lapse rate for  $T_{\min}$ .

This study is also important from the viewpoint of nature conservation in Thailand. Our results show that seasonal changes in temperature are moderate in Kog–Ma compared with those in Chiang–Mai (Table 2). Photosynthetic rates of tropical mountain trees are often very low when the temperature is less than  $5^{\circ}\text{C}$  or more than  $35^{\circ}\text{C}$  (Garcia-Nuñez et al. 1995; Rada et al. 1996; Cavieres et al. 2000). Thus, the hill evergreen forest in Kog–Ma would not suffer from serious decline in photosynthetic rates because of the moderate temperature. The effect of moderate temperature at Kog–Ma on photosynthesis and transpiration of the forest would be quantitatively evaluated when comparing forest carbon and water cycles

simulated by ecosystem models (e.g., Hingston et al. 1998; Wang et al. 2003; Chiesi et al. 2005) with the input of meteorological data recorded at Kog–Ma and Chiang–Mai, respectively. Such an attempt would be useful for clarifying how hill evergreen forests are maintained under a tropical monsoon climate despite the length of the dry season.

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