Tsukuba Geoenvironmental Sciences, Vol. 13, pp. 1-12, Dec. 22, 2017

Diurnal and seasonal variation of air temperature profile in the mountain forest at Sugadaira, central Japan

Kenichi UENO[a], Seiya UEDA[b], Ryuji KANAI[c], Daisuke MASAKI[c], Miyuki SATO[c], Son RIN[d] and Mitsuru HIROTA[a]

Abstract

Air temperature profiles were observed for a year with micro-climate observation in and around the mixed mountain forest. The shading effects of tree crown, depending on the solar elevation angle and abscission of broad leaf species, controlled the diurnal and seasonal variation of radiation budget and temperature gradients in the forest. Vertical mixing of air in the forest was infrequent even the wind speed over the forest was high. *Sasa albo-marginata* served as another important daytime heat source at the forest floor in snow-free season. In the forest, weak but clear diurnal wind variation was observed on fair summer days indicating prevailing of daytime up-slope winds and nocturnal gravity currents. After leaf abscission, the nocturnal temperature inversion prevailed in and out of the forest. The importance of the local winds blowing through the forest and their effect on the data from the station in an open space are discussed with regard to the long-term assessment of mountain meteorological and forest phonological data.

Key words:air temperature, mountain forest, phenology, diurnal variation

1. Introduction

The impacts of global climate change to the ecosystem, water resources, and human society in mountainous areas are serious worldwide concerns (Price, 2015). In Japan, almost 70% of lands are mountainous areas covered by forests, and even the weather of urban cities in the coastal areas is indirectly affected by the thermodynamic functions of mountains (Sato and Kimura, 2005; Takane and Kusaka, 2011). For instance, Kimura and Kuwagata (1995) demonstrated that mountain valley circulation and amounts of sensible heat strongly depend on the horizontal scale of topographic undulation. Furthermore, the diurnal processes of the heat budget at mountain slopes are different from the general flat bare/grasslands or pastures due to the forests (Oak, 1987). In the case of dense forests with a crowded canopy, the crown surfaces absorb insolation (Araki, 1995), but the response is not the same as over the ground surface. Hattori (1984; 1986) reported that a crowded hinoki cypress forest reflects 10% of shortwave radiation, about 30% is transferred upward as long-wave radiation, and 50-60% is used for evapotranspiration as sensible heating. Accordingly, less insolation in the forest results in less sensible heating and causes daytime cooling of the air temperature. Additionally, radiative cooling at the surface in the forest is compensated for by downward long-wave radiation from the trees. Then, the surface air temperature in the forest is 2-3 K lower for the daytime maximum and 1-2 K higher for the nighttime minimum on calm fair days (Araki, 1995). Observation and numerical simulation in the overseas countries have demonstrated that forests in a large area reduce surface albedo, provide water vapor, increase surface roughness, and modulate in situ mesoscale atmospheric circulations (Dolman *et al*., 2004). However, in Japan, where mountain topography is complex, forests are not always composed of a single unique spices, and oceanic weather is dominant over the coastal mountain ranges, there is uncertainty about which areas of mountain forests affect the local circulations, under which weather conditions, and how.

In the one-dimensional heat budget, we need to consider the heat storage of trees and air in the forest with photosynthesis and respirations. Oliphant *et al*. (2004) pointed out that the heat storage term shows a large diurnal variation and affects the energy closure. McCaughey (1984) showed that the storage term is especially important in the nocturnal energy balance and varies depending on the soil moisture. In Japan, Kondo *et al*. (1991) proposed a simple method of heat-storage estimation by assuming a tree is a combination of columns with a thermal conduction process. Saito *et al*. (2010) and Saito (2014) quantitatively evaluated the amount of energy storage during snow-cover and snow-free periods via tower observation in Takayama evergreen conifer forests. Their results showed that a large day-to-day variability exists

[a] Faculty of Life and Environmental Sciences, University of Tsukuba, Japan
[b] Japan Weather Association, Japan
[c] Sugadaira Research Station, Mountain Science Center, University of Tsukuba, Japan
[d] Graduate School of Life and Environmental Sciences, University of Tsukuba, Japan

in the diurnal storage terms, and the magnitude of stored energy and heat release by photosynthesis and respiration dominated as the same amount of sensible heating. Forests with deciduous trees provide a more complicated environment because they change the forest structure, such as proportion of canopy, trunk, and forest floor. Winter snow cover in the forest also has complex and interesting effects on heat storages. In the case of a mixed forest with evergreen and deciduous trees, the important issue is to reveal which species strongly contribute to the storage term and control the micro-climate in the forest.

Recently, elevation-dependent warming has become a hot topic worldwide with regard to future climate prediction for high elevations (MRI-EDW, 2015). In Japan, many scientists are also interested in the trend of temperature changes depending on altitude, however, the existence of only a few stations at high elevations and the lack of long-term data records have prevented accurate evaluations of mountain climate variability (Suzuki, 2013). Ueno *et al*. (2013) archived meteorological data from multiple observatories above 1500 m maintained by national university research centers and found large variabilities in the diurnal variation of temperature among stations even over the 2000 m level above the atmospheric boundary layer. The results indicate that differences in the stations' surrounding environment, such as whether they are forested or above the tree lines, strongly affect the heat budget of the observation area. Thus, even though we have a long record of station data from an open (deforested) area on the mountain slope, we cannot accurately detect trends in the synoptic-scale climate without assessing local factors such as the advection effect from the forest. As most mountain slopes are covered by forests in central Japan, meteorological tower observation above the canopy is the most plausible method to monitor the atmospheric environment. The AsiaFlux network is one of the key nodes where a CO_2 flux in forest phenology is continuously monitored in Japan (http://www.japanflux.org/), such as at Takayama, Fujiyoshida, Karuizawa and Mt. Naeba, and the data has been used to validate satellite estimates and numerical simulation results. However, most of the tower station do not place automatic weather station (AWS) in adjacent deforested areas, and micro-climate differences between inside and outside forest are not evaluated.

In 2015, a canopy access tower was set in the red pine forest of Sugadaira Research Station, Mountain Science Center, University of Tsukuba for educational usage. Sugadaira is a highland at 1300 m a.s.l. in Nagano Prefecture. Inland sunny weather with convective clouds dominates in summer, and an almost 1 m deep snow cover exists in winter due to the winter monsoon. The research center has a long history of meteorological observation, since 1971, and Shimizu (2012) reported a significant increasing trend in precipitation amounts with a weakening of wind speed. Adjacent to the pine tree forest, a *Miscanthus* grass field provides a good opportunity to compare the micro-climate inside and outside the forest. Intensive micro-climate observation was conducted for almost a year in 2016, using the tower and the grass field. Diurnal and seasonal variabilities of temperature profile in the forest and temperature differences inside and outside the forest were analyzed. Characteristics of the temperature profile variability were identified, and the importance of the radiation budget and the seasonal change affected by forest structure and phenology were discussed.

2. Observation

Continuous meteorological observation was conducted from May 30, 2016, to May 16, 2017, at a tower 17.3 m high in an 8.5 ha red pine forest area of the Sugadaira Research Station (36°31'26"N, 138°20'51'E,1320 m a.s.l.). The area consists a mixed forest of not only pine trees (*Pinus and Larix*) but also broadleaf trees such as *Betula*, *Quercus* and others. The canopy is composed not of a single layer but of multiple layers (Fig.1a). The forest floor is covered by *Sasa albo-marginata* throughout a year (Fig. 1b), except that it is covered by almost 1 m of snow in winter. According to the Sugadaira AMeDAS meteorological data, snow-covered period was estimated to be from Dec. 10, 2016 to April 16, 2017, a normal length in climatology.

The top floor of the tower is almost level with the canopy height where an AWS (Onset Co.,U30-NRC) and a four component radiation sensor (Kipp&Zonen Co., CNR4) was set. The location name of tower top is T6, and the height of the sensors from the ground surface is 19 m. Along a tower post, an air temperature/humidity sensor with natural ventilation (Onset Co., U23) and a solar shade were set at five levels: T5, 14.35 m; T4, 8.55 m; T3, 5.4 m; T2, 1.9 m, and T1, 0.6 m. The sensor at T1 was removed after November to prevent a snow-cover effect. The sensor at T3 had battery trouble, and the data after March 15, 2017, is missing. Near the tower foot, a net radiation sensor (Prede Co., Q7) and micro-anemometer (Makino Co.) were set at a 2 m height (location name; TB2) from July 15 to August 10. A 6 ha *Miscanthus* grass field is located west of pine tree area. An AWS and four component radiation sensors were set (S1, 2 m) in the center of the field. The distance between the tower and S1 is almost 660 m. The temperature data used in this analysis is measured using the same type of sensor with a

Figure 1 a) observation tower in a mixed forest; b) net-radiation sensor over *Sasa albo-marginata* at the forest floor (May 28, 2016).

catalog sensitivity of 0.2°C, and the observation interval is 10 minutes.

The Sugadaira Research Station conducts meteorological observation at the southwestern corner of the *Miscanthus* grass field, where a force-ventilated temperature/humidity sensor and present weather detectors (Vaisala, PWD22) are located. According to a comparison of the natural ventilated air temperature sensor with the force-ventilated one for two days, the root-mean-square error of temperature was 0.6°C. Thus, we assume that resolution of temperature data is around 0.5°C. The data of PWD22 are used for day-to-day weather classification as explained in the next chapter.

Multiple heat sources, such as leaf, stem at multiple levels and ground surface, exists in the forest. General methods to evaluate the surface heat budget, such as the Bowen ratio method and the bulk method, cannot be applied because of multiple non-homogeneous sources, so direct turbulence measurement is the best method. However, in this study, direct evaluation of sensible heat and latent heat using turbulence measurements was not conducted. Instead, the tendencies of diurnal and seasonal change in the vertical air temperature gradient with temperature differences between the inside and outside of the forest area were qualitatively assessed to reveal the diurnal and seasonal tendency of heat storage in the forest.

3. Weather variability and leaf abscission

The surface heat budget is strongly affected by daytime radiation variability, surface wetness, and surface wind speed. Usually, the development of a boundary layer is evident when the synoptic-scale disturbances are not active. In mountains with a high elevation, the diurnal weather change is more abrupt than that in lower, flat areas. We excluded severe-weather days to identify the effects of the forest on the micro-climate. Next, daily weather patterns were classified according to the data from 6:00 to 14:00 throughout a year into the following three categories: (a) occurrence of precipitation, (b) radiation amount, and (c) wind speed over the forest. Evening data were not used because the morning insolation is more important for surface heating, and the afternoon weather is sometimes modified by local development of convective clouds. For (a), a precipitation day was defined as when the present weather detector indicated precipitation, drizzle, or rain for more than 1 hour; other days were classified as non-precipitation. For (b), a cloudy (fair) day was defined as when the averaged downward shortwave radiation was less (more) than 320 W/m². For (c), a windy (calm) day was defined as when the averaged wind speed exceeded (was below) 1.6 m/s at T6. The thresholds for (b) and (C) were set experimentally to separate the daily weather clearly from June to October, and accordingly, cloudy (windy) days accounted for 40% (20%) of the total days.

Figure 2 shows weather categories according to classification of (a) to (c). Precipitation days, cloudy days, and windy days occupied 46%, 50% and 29%, of the observed year, respectively. From December to February, cloudy and precipitation days prevailed due to the winter monsoon. Calm days tended to prevail throughout the year

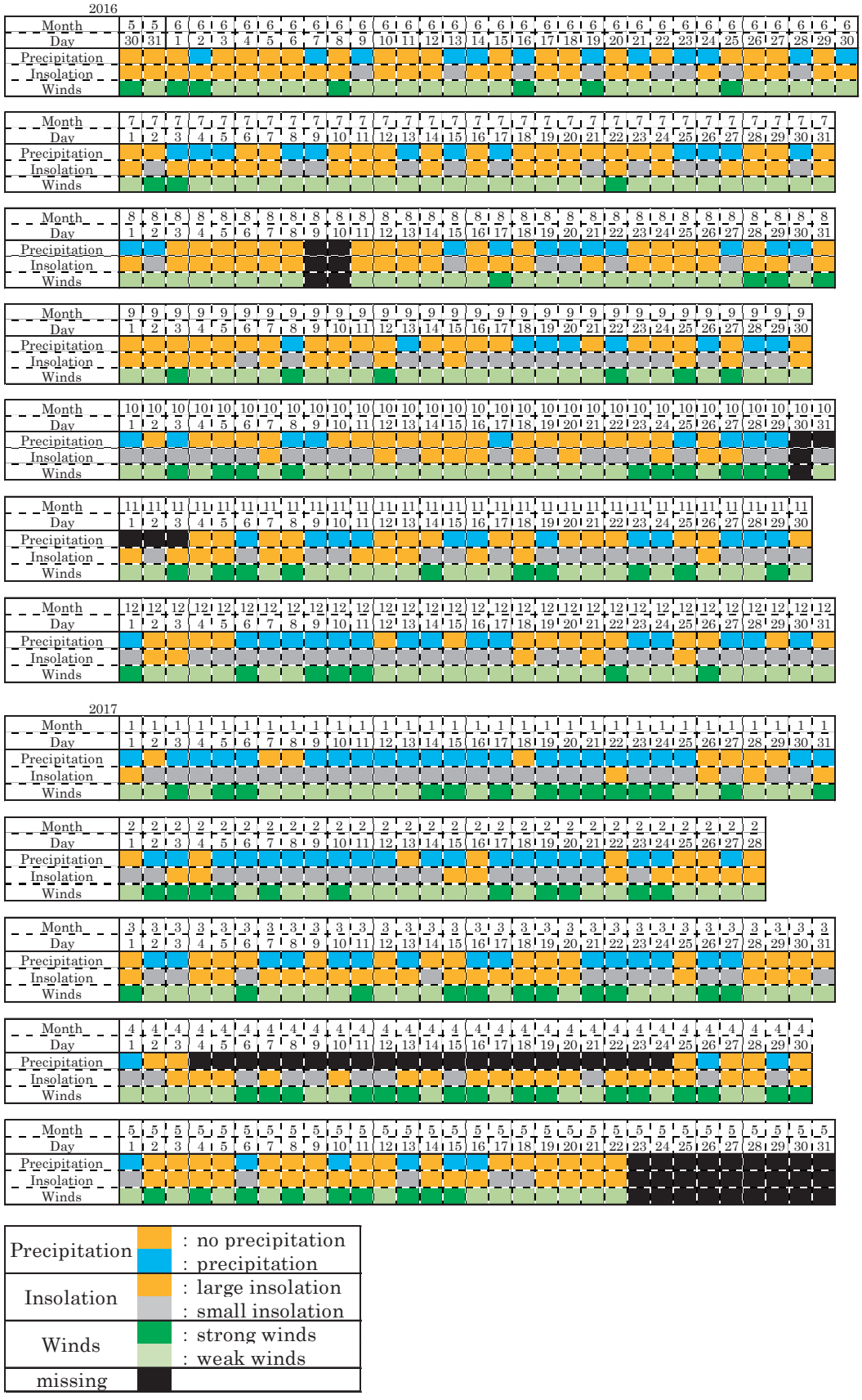

Figure 2 Weather classification calendar from May 30, 2016 to May 22, 2017.

except in winter. As the anemometer at T6 was not high enough to monitor winds in the atmospheric boundary layer above the forest, canopy roughness around the tower top affected the wind speed data. Windy days in April and May might be due to passing extra-tropical cyclones. Fair and non-precipitation days prevailed in summer and they were used to assess the diurnal variation of air temperature gradients in Chapter 5.

Forest phenology, especially with regard to the timing of autumn leaf abscission, indicates significantly changes of the forest structure and micro-climate. According to phenology-monitoring data by the Center for Global Environmental Research (http://db.cger.nies.go.jp/gem/ja/flux/fujiphenologyf.html), a Japanese larch tree forest at the foot of Mt. Fuji (1100 m) began leaf fall around Oct. 18, completed the falling around Nov. 19, and had the first snow cover on Nov. 24, 2016. In spring, snow cover ceased on April 6, and trees started to sprout after April 25. Sugadaira is located almost 150 km north of the above mentioned site with higher elevation, and the dominant red pine tree is an evergreen. There is no monitoring system by a fisheye lens in the forest; however, monthly base multiple leaf-trap observations have been conducted at the forest floor. In the forest, six plots were located, and five traps were set in each plot; dry weight of litter was measured depending on the spices and parts of tree, such as the *Pinus* leaf and *Betula* bark etc. This study compared the month-to-month variability of the averaged litter weight of five traps at plot 4, observed seven times from June 10 to Nov. 27, to identify which kind and parts trees contributed for leaf abscission in the autumn 2016 (Fig. 3). Plot 4 was chosen because the tree species around are most similar to those around the tower. The laves, fruit, sub-branch of *Pinus* and other broad leaf made up most of the total weight; heavier weight of *Pinus* leaves was recorded especially in early June, at the end of October, and at the end of November (Fig. 3a). *Pinus* does not fall the leaves grown in the same year but fall previous years' leaves, and their amount depends on the climate condition of this year (Han *et al*., 2003). Among the broadleaf trees, *Betula leaves* increased in the middle of September, and the amount of "other broadleaf" increased in the middle of October (Fig. 3b). Here, "other broadleaf" includes materials of uncertain classification. The contribution of *Quercus* was not obvious. Those tendencies are almost the same as in other plots. Therefore, we concluded that broadleaf trees started to drop materials in September and October, prior to the red pine trees, which drop materials after the end of October. These timings are very important to assess which tree spices cause air temperature profile changes in autumn.

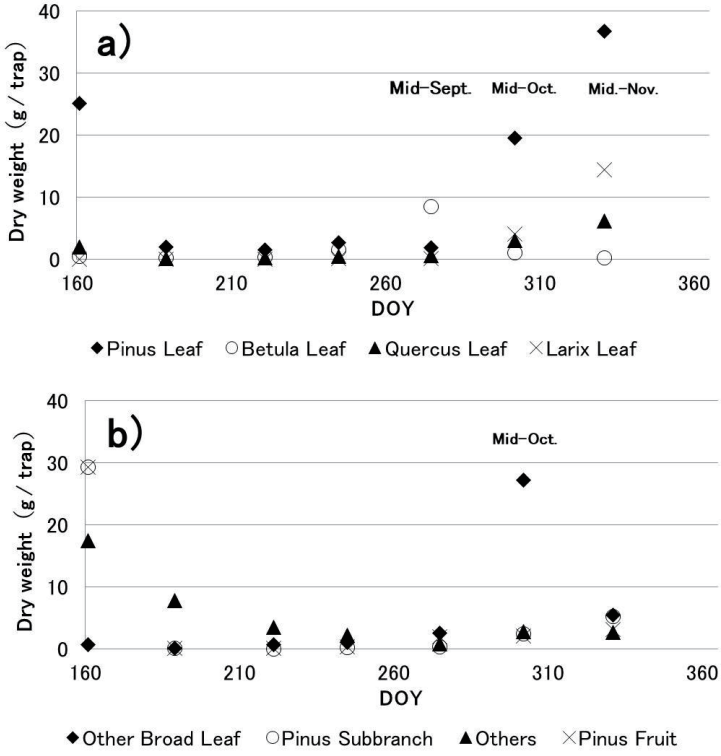

Figure 3 Monthly scale dry weight changes observed at plot 4. The data are simply averaged value observed by five traps depending on different parts with spices of trees.

4. Seasonal change of air temperature profile in the forest

The vertical air temperature profile was calculated at each level from T6 to T1, and diagrams showing diurnal seasonal changes were plotted as six columns in Fig. 4. The data starts in May 30, 2016 (150 DOY), and continues for almost a year, and a temperature difference of less than ±0.1 K/m was not shaded. Red (blue) coloring indicates temperature warming (cooling) as elevation going up (down) where energy flux is downward (upward). The profiles at T4-T3 and T3-T2 were blank after March 15, 2017, due to the missing data from T3. To compensate for the missing periods, a temperature gradient between T4 and T2 was calculated and shown on the right end. The pattern of T4-T2 is quite similar to that of T4-T3 and T3-T2 during a cold season, indicating that T4-T2 also represents a seasonal change in the temperature gradient after March in the mid-lower layer of the forest.

The temperature gradient near the tower top (canopy top) (T6-T5) indicated a positive tendency in the daytime. Usually, the temperature decreases when elevation going up above the canopy in the daytime due to forest surface heating as observed in the ground surface. A reversed signal observed in T6-T5 indicated that the location of T6 is not high enough to be above the surface boundary layer, and it is still measuring the heating of the crown in the canopy. In the detail of diurnal variation, the gradient was weakening at noon when the next layer (T5-T4) showed positive gradients. This is due to more insolation at the lower level as the solar elevation angle increased at noon. In October, the daytime positive gradient was weakening, and it turned negative after around 300DOY (Oct. 26) indicating temperature cooling as going up the elevation around the tower top. The evident change in the temperature gradient was due to defoliation. According to the trap observation at the forest floor (Chapter 3), the broadleaf trees were major contributors in October. We need to be careful for this evidence, because, even the mixed forest is categorized as a red pine tree area on the map, micro-meteorology in the forest might be controlled by broadleaf trees. Further assessment is expected to evaluate whether *Betula* and *Quercus* trees contribute to the category of "Other broad leaf tree".

At noon, the temperature gradient at T5-T4 showed a positive signal in summer as direct insolation reached this level. It became stronger in the core winter season

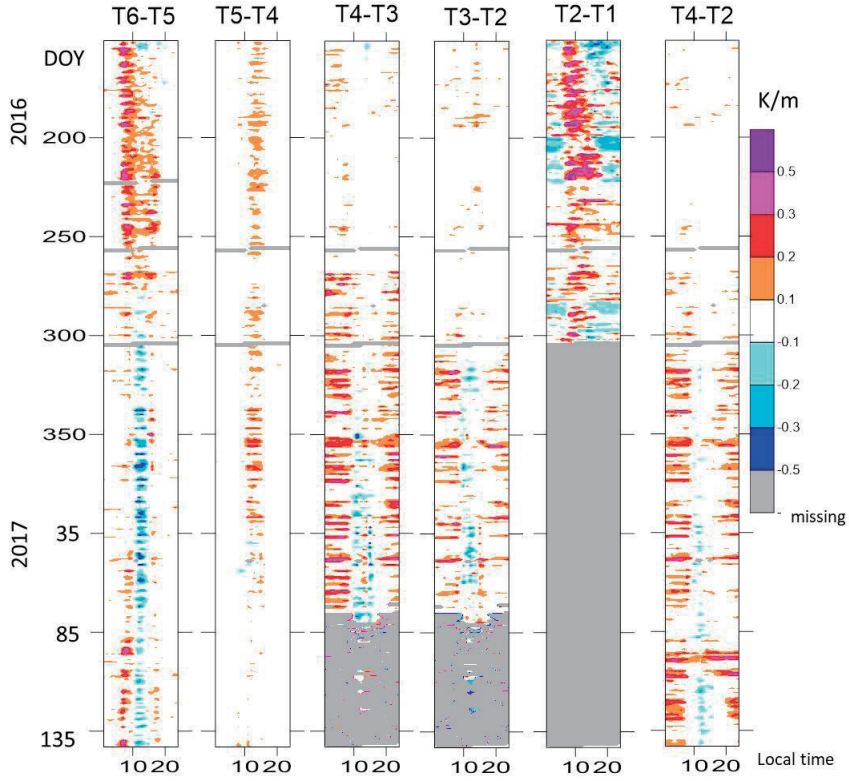

Figure 4 Air temperature gradient distribution as a function of local time (horizontal) and day of year (vertical) at five levels, such as T6-T7 from the top to T2-T1 at the ground surface. Positive value with warm color indicates the temperature increase as elevation going up. Due to missing data from T3, a temperature gradient between T4 and T2 was calculated and shown on the right side to compensate for the information from spring.

(December to January) and diminished after the end of February. At T4-T3 and T3-T2, the temperature gradient became negative in winter. Snow cover captured on neighbor Pinus sub-arches and the observation tower itself would be one factor causing heat sink around the T4 level and strengthening the upper positive and lower negative temperature gradient. At night, days with a large positive gradient at T4-T3 and T3-T4 appeared frequently after October indicating strong nocturnal cooling in the bottom layers. However, nighttime air temperature differences between the inside and outside of forest were not obvious on those days, as will be explained in Chapter 6. We speculated that radiative cooling dominated the entire mountain area after defoliation and cold gravity currents prevailed on the mountain slopes. For further investigation, nocturnal weather classification is needed to confirm the day-by-day variability of radiative cooling.

The lower-most gradient at T2-T1 showed another evident signal in the warm season. A positive gradient was especially evident from the morning until noon. This signal confirmed that *Sasa albo-marginata* is another important heat source that absorbs direct and scattering shortwave radiation at the forest floor. A night, strong cooling occurred on several days under the *Sasa albo-marginata*, but not every day. The lower-most observation was stopped after the leaves had fallen, and we could not confirm whether the nocturnal temperature gradient in the T4-T2 layer continued to the surface.

5. Diurnal variation of air temperature during warm season

One of unique characteristics in Fig. 4 is a bimodal variation of the daytime temperature gradient in the canopy (T6-T5) during the warm season. Such a characteristic was also found in the temperature difference between S1 and T2 after February as will be introduced in Chapter 6. Those features revealed that the radiation budget in the forest primarily controls the diurnal temperature variability. In this chapter, fair weather days without precipitation from July to September were extracted, and the diurnal variation of micro-meteorology in the forest was examined.

Firstly, the wind condition was examined because sensible heat may be primarily diffused and transferred by turbulence and local currents. From July 15 to Aug. 10, a micro-anemometer with a resolution of 0.1 m/s was set at the foot of the tower, then 19 days without precipitation with high insolation were extracted. The averaged diurnal variation of wind speed was compared between the tower top (T6) and tower foot (TB2) in Fig. 5a. An increase in daytime wind speed was clearly observed at T6; however, the wind was very weak in the forest.

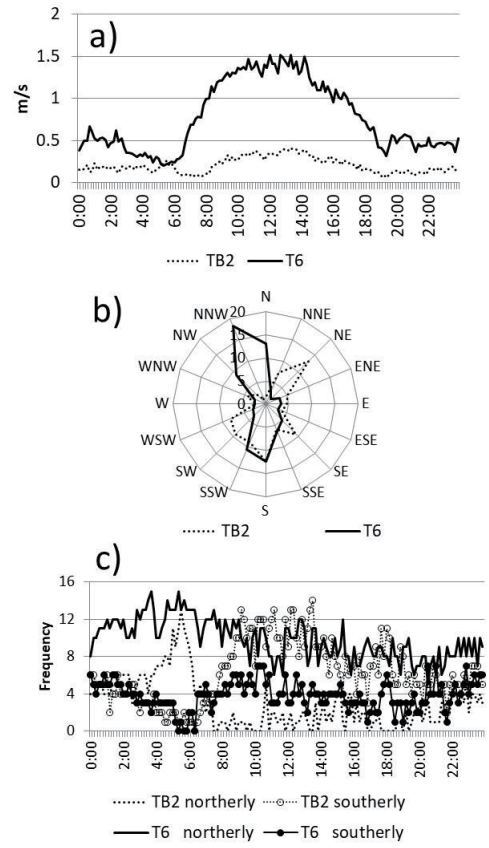

Figure 5 a) Diurnal variation of wind speed, b) frequency distribution of wind direction, and c) diurnal changes of wind direction frequencies for northerly and southerly component at the tower foot (TB2) and tower top (T6). The data was resampled for 19 non-precipitation days with high radiation in the warm season.

Wind roses, showing frequency of wind direction more than 0.1 m/s of wind speed, are shown in Fig. 5b. East-west component winds were infrequent, southerly winds prevailed at both sites, and winds from the NNW (NE) prevailed at the tower top (foot). Northerly and southerly components of the wind were calculated, and the diurnal variations of their frequency are shown in Fig. 5c. At the tower top, both northerly and southerly winds prevailed through the day, but the frequency of the northerly component increased during the night, when the southerly component was reduced. The S-NNW direction shown as the wind rose in Fig. 5b corresponds to valley-shaped topography composing the Sugadaira area running from Sugadaira-guchi in the south to Susaka in north, not the slope direction toward the Neko-Azumaya mountain ridges. Therefore, we suspect that the wind system over the forest is primarily controlled by the large-scale flows crossing over the Sugadaira area between the Ueda and Nagano areas along the eastern mountain ranges compos-

ing Mt. Neko, not a mountain-valley circulation along the local mountain slopes. Additionally, the micro-scale forest canopy around the tower may affect wind observation. On the other side, the increase of southerly (northerly) winds clearly prevailed in the daytime (after midnight) at the tower foot even when the wind speed was weak. Specifically, nighttime northerly winds are mostly from the NE, corresponding to the mountain-slop direction toward Mt. Neko. This feature indicates daytime valley winds coming from the Sugadaira-guchi valley, and a nocturnal gravity current coming from the Neko and Azumaya mountain ranges intrudes into the forest horizontally, affecting the low-level temperature profiles.

Next, the radiation budget around the forest was examined. Twenty-nine days of fair days without precipitation were extracted from May 30 to July 31, and the diurnal variation of the averaged net radiation (Rn) at the tower top (T6), the tower foot (TB2), and outside the forest (S1) was compared, as shown in Fig. 6a. The Rn at S6 was about 150 W/m² higher than that at T1, indicating that the forest absorbs more radiation than do the grasslands. The upward long-wave radiation is several 10 W/m² higher at S1 than at T6 (Fig. 6b); however, the daytime albedo was reduced more than 10% at T6 as compared to the S1 contributing to the large increase of Rn at the top of forest. At the forest floor (TB2), the Rn almost dropped below 50 W/m² in the morning, but it increased to 200 W/m² at noon due to direct insolation with a large solar elevation angle. Rn in the afternoon is low, but higher than in the morning, and may be due to the increase in downward long-wave radiation associated with heat stored by trees. At night, the Rn at TB2 is almost 0 W/m². The Rn is negative at T6 and S1 due to radiative cooling; however, the amount is around 25 W/m² and is considered low.

From May 31 to Oct. 29, except for Aug. 8-9, the diurnal variation of heat storage of the air in the forest was estimated by the temporal difference of temperature as follows;

$$\mathrm{Qn} = \rho c_p \frac{\Delta \mathrm{Tn}}{\Delta \mathrm{t}} \qquad \ldots(1)$$

where Qn [W/m³] is the quantity of heat at six levels (n=1-6), ρ [kg/m³] equals air density, c_p [J/kg/K] equals the specific heat at a constant pressure, and Δt [s] is set as an hourly interval. ρ is set to 1.045 kg/m³ as a constant value at 870 hPa and 15°C, and c_p equals 1005 J/kg/k. The missing air temperature at T2 (1.9 m) for July 15 to Aug. 10 and at T3 (5.4 m) for Sept. 17 to Oct. 11 were interpolated from the neighbor level data by linear regressions.

The averaged Qn during the period is shown in Fig. 7a. The average net radiations at the top and foot of the tower are also shown in the figure as references of radiation condition. Qn was positive for 5:00 to13:00, with a

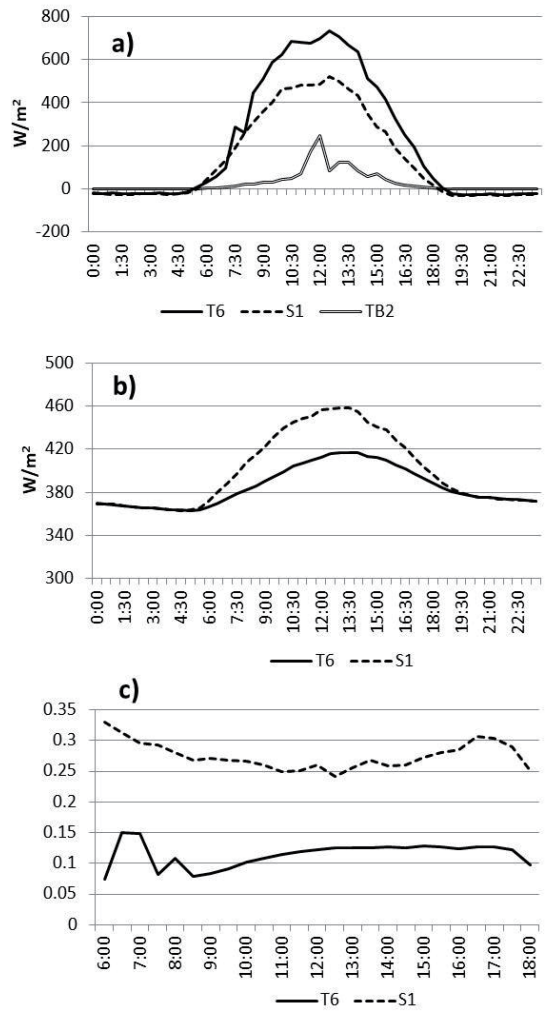

Figure 6 Diurnal variation of a) net radiation at the tower top (T6), grass field (S1) and tower foot (TB2), b) upward long-wave radiation at S1 and T6, and c) daytime albedo changes at T6 and S1. The data was resampled for 29 non-precipitation days with and high radiation in the warm season.

maximum at around 7:00. Almost all of the levels showed similar tendencies, except the topmost level (T6) showed a rapid increase to 0.33 W/m³ just after sunrise. This may be due to the warming of only the canopy top due to a small solar elevation angle. Qn decreased linearly and became negative after 14:00. The minimum Qn appeared at 17:00 when the higher level released more energy. After the midnight, Qn stayed around -0.05 W/m².

Next, the tendency was compared between two samples, one is a group with precipitation (53 days) and the other is a group with non-precipitation (98 days), as shown in Fig. 7b. Amplitudes were significantly reduced at all levels for precipitation days. Two causes were attributed, such that increase of cloud amount reduced available radiation energy at the forest top, and the net-radiation was used to

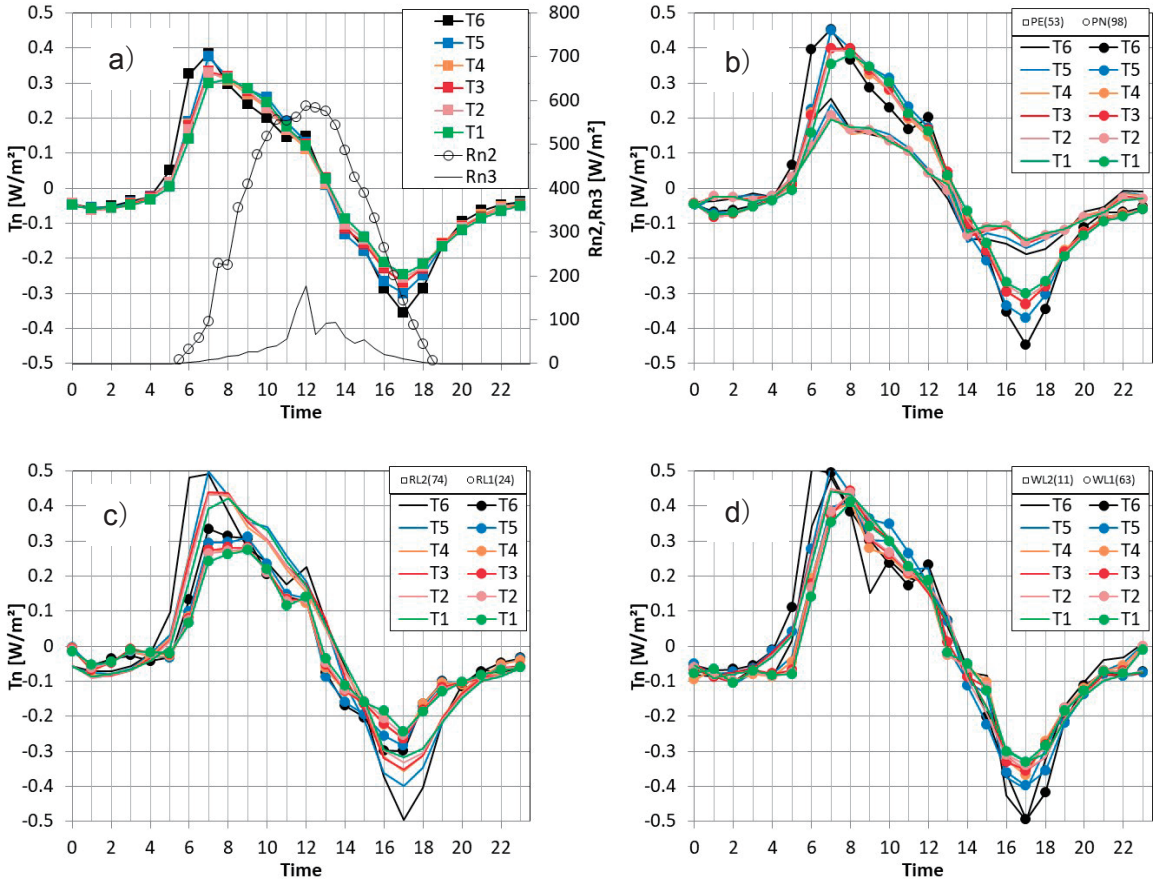

Figure 7 Diurnal variation of air heat storage in the forest at six levels, T6-T1, in the warm season.
(a) Average for all days with net radiation at T6 (Rn2) and S1 (Rn3), (b) days with precipitation (PE, line only) and without precipitation (PN, line with marker), (c) the same for large (RL2) and small (RL1) insolation, and (d) the same for high (WL2) and low (WL1) wind speed at T6. The sample number for the average is shown in parentheses.

latent heat by interceptions of trees. A second comparison was done between two groups with high and low radiation amounts. Member of the group is 24 and 74 days, respectively. A group with high radiation caused a larger Qn throughout a day. A group with low radiation resulted in a negative Qn earlier, and the minimum value in the evening was smaller than that on precipitation days. These characteristics may be due to the concentration of low-radiation days in the later season with a shorter day length. A third comparison was done between the strong and weak wind days (63 and 11 days, respectively) using wind speed data from the tower top (T6). It was obvious that two samples did not show clear difference in the Qn profile (Fig. 7d). The results indicated that air temperature profile in the forest was not affected by the vertical mixing of momentum with wind speed variability above the canopy. Furthermore, even on the precipitation day, a diurnal temperature change exists in the forest because of daytime surface heating and horizontal advections on a large scale.

6. Differences of air temperature inside and outside the forest

Figure 8 shows diagrams of diurnal seasonal changes similar to those in Fig. 4: (a) temperature differences between inside and outside the forest, (b) grassland and above the forest (middle), and (c) the top and bottom of the tower. It is obvious that the daytime surface air temperature outside the forest is warmer, by more than 1.5°C, especially in the warm season (Fig. 8a). The difference exists even in the winter season with snow cover, suggesting that the snow surface temperature may differ inside and outside the forest. After February, a bimodal temperature difference appeared by reducing the differences around noon indicating that direct radiation at the forest floor with a large solar elevation angle may provide uniform snow or ground surface temperature. The nocturnal temperature was sometimes warmer in the forest, but the difference amount was small. The temperature at the grassland is warmer than that above the forest in the daytime (Fig. 8b), and this tendency was strengthened by

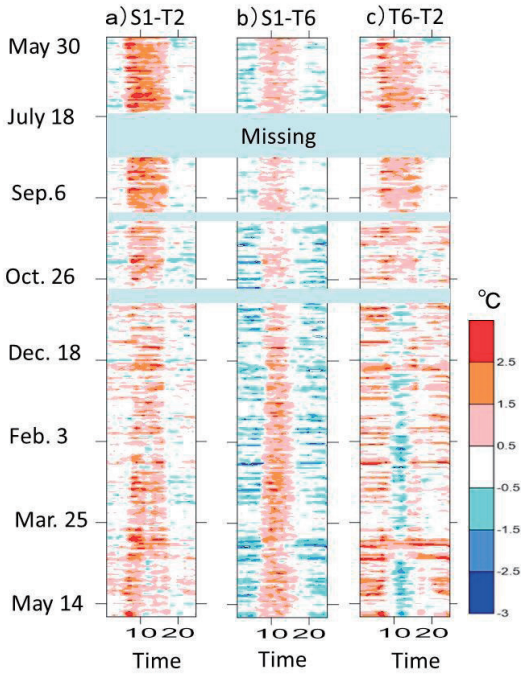

Figure 8 Same as Fig. 4, but for temperature differences for a) S1 (grassland) to T2 (tower bottom in the forest), b) S1 (grass land) to T6(tower top), and c) T6 (tower top) to T2 (tower bottom).

more than 1°C after leaf fall. We suspect that a cold air intrusion from the forest may have reduced the air temperature differences between S1 and T6 during summer, when broadleaves provide shade from the radiation at the upper forest. In Fig. 8c, the upper temperature was warmer than the lower one in the summer daytime, however, the gradient reversed after leaf fall in the end of October. This would be due to warming of the lower air temperature by tree stems. During the nighttime, days of large air temperature differences between S1 and T6 coincided with those between T6 and T2, indicating that cooling at the tower bottom induced both temperature differences. A cold gravity current may prevail into the forest and cause the temperature differences. An ultra-sonic anemometer needs to be employed to detect the gravity current.

7. Summary

Air temperature variabilities inside and outside the forest were analyzed via one year of continuous observation using a canopy access tower in a red pine forest and an AWS in an adjacent grassland. A large daytime temperature gradient in the upper layer of the forest and a reversed gradient after October indicated warming of tree crowns due to insolation and the effects of leaf abscission. According to the monthly base leaf-trap observation, broadleaf trees in a mixed-tree forest shed leaves and change the radiation budget in the upper forest. In the middle to lower levels, a nocturnal temperature inversion sometimes developed after October without temperature differences inside and outside the forest. Nocturnal gravity currents due to mountain-slope radiative cooling may prevail not only in the deforested area but also in the forest after the falling of leaves in the whole neighborhood. At the forest floor, *Sasa albo-marginata* was another important daytime heat source in warm season.

On fair-weather days without precipitation in the warm season, a wind system dominating south-northwest component was observed at tower top that corresponding to the running direction of large-scale concave topography between the Ueda and Nagano basin, and the component of local mountain-valley circulations along the slope of Mt. Neko was not dominant. On the other hand, the wind system in the forest was weak but showed evident diurnal changes over the *Sasa albo-marginata*, such as daytime southerly winds from the direction of Sugadaira-guchi, a gateway to the Ueda basin, and nighttime northeasterly winds from the direction of Mt. Neko. The net radiation at the tower top was almost 150 W/m² greater than that at the grassland outside the forest due to a decrease of more than 10% in the daytime albedo. As the solar elevation angle increased at noon, insolation reached to the lower level of the forest, and then the temperature gradient at the top was diminished, and the gradient at the second level increased. This tendency was more evident after the falling of the leaves. In winter, the temperature gradient at the middle level of the forest showed a rather complicated signal, and the effects of snow cover captured by tree branches or leaves were expected. Air temperature data definitely indicated the effects of intra-seasonal forest phonological changes. Further automatic observation of the leaf area index (LAI) at different elevations is needed to capture and explore weekly forest phonological changes. The diurnal variation of heat storage of air in the forest was primarily reduced by the occurrence of precipitation and a shortage of downward shortwave radiation due to cloud amount increases. Vertical mixing of air in the forest was infrequent even the wind speed over the forest was high. This study demonstrated that even the forest was categorized as pine tree area; broadleaf trees determine the radiation budget in the forest and change temperature profiles. Especially, year-to-year variability of LAI changes in the autumn and spring seasons should be identified with nation-wide scale climate variability.

At the forest floor, a weak but evident diurnal variation of winds was observed over the *Sasa albo-marginata*, such as southerly daytime flow and northeasterly nocturnal flow from the mountain side. Daytime tempera-

ture differences between the grass field and tower top increased after leaf abscission. We speculated that the grassland summer temperature was suppressed by the advection of cool air due to valley winds blowing through the forest. Many mountain site observatories are set in an open space surrounded by forests. Therefore, the data may be strongly affected by the advection from the forest where the signals of climate variability are modulated. Pair observation of the microclimate above and outside the forest is needed to evaluate both the local and synoptic factors at once. After autumn, the surface inversion layer frequently prevailed both inside and outside the forest at night. Ueno *et al*. (2015) observed frequent development of needle ice after the clear-cutting of a mountain forest in winter due to the enhancements of nocturnal radiative cooling and the daytime direct solar radiation at the surface. The leaf abscission in autumn may also enhance the diurnal heat budget at in the entire mountain slope and modulate basin scale local atmospheric circulations.

From an ecosystem point of view, intermittent forest succession is triggered by disturbances (Oliver and Larson, 1990). Disturbances by means of weather variability correspond with extreme events, such as a heat wave, storm, heavy snow, rain, or associated flooding. Some dominant species in the open area by disturbances, such as *Alnus hirsute* or *Betula*, show a faster elongation rate than do species in a the closed forest, such as *Aesculus turbinata* or *Fagus* (Ishida, 1992). On the other hand, experimental relations between the opening ratio and growth ratio in the open area change depending on the species (Gutiérrez *et al*., 2004; Takahashi *et al*., 2013), and a preferable environment for the species (a "niche") may vary depending on the species that promote forest diversity (Grubb, 1977). According to this study, temperature distribution in the forest is primarily controlled by the radiation profiles that change diurnally and seasonally depending on the structure of the forest. In other words, it might be said that forests determine their own environment of micro-climate during their life cycle. Further investigations are expected to reveal which species are more affected by which scale/timing of disturbances by means of extreme weather events in the mountain areas.

Acknowledgments

This study was mainly conducted as a graduation research of the second author. The authors are deeply grateful to Dr. Saitoh (Gifu University), who offered advised on meteorological techniques and scientific suggestions to improve the research.

References

Araki, M. (1995): *Forest Meteorology*. Kawashima Syoten, 76-82. (in Japanese)

Dolman, A.J., Molen, M.K., Maat, H.W. and Hutjes, R.W.A. (2004): The effects of forests on mesoscale atmospheric processes. In Mencuccini, M., Grace, J., Moncrieff, J., and McNaughton, K.G., eds., *Forests at the Land-Atmosphere Interface*, CABI Publishing, 51–72.

Grubb, P.J. (1977): The maintenance of species-richness in plant communities: the importance of regeneration niche. *Biological Review*, **52**:107–145

Gutiérrez, A.G., Armesto, J.J. and Aravena, J.C. (2004): Disturbance and regeneration dynamics of an old-growth north Patagonian rain forest in Chiloé Island, Chile. *J. Ecology*, **92**, 598–608.

Hattori, S. (1984): Radiation balance of a hinoki stand (I); Seasonal variation of the albedo. *J. Jap. For. Soc*., **66**(4), 149–156. (in Japanese with English abstract)

Hattori, S. (1986): Radiation balance of a hinoki stand (II); Seasonal variation of the radiation components and characteristics of radiation balance. *J. Jap. For. Soc*., **68**(2), 51–60. (in Japanese with English abstract)

Han, G., Kawasaki, T., Katahata, S., Mukai, Y. and Chiba, Y. (2003): Horizontal and vertical variations in photosynthetic capacity in a Pinus densiflora crown in relation to leaf nitrogen allocation and acclimation to irradiance. *Three Physiology*, **23**, 851–857.

Ishida, M. (1992): Distribution and height growth of young trees regenerated on a spoil bank in a beech forest. *J. Jap. For. Soc*., **74**, 337–341. (in Japanese)

Kimura, F. and Kuwagata, T. (1995): Horizontal heat fluxes over a complex terrain computed using a simple mixed-layer model and a numerical model. *J. Appl. Meteor*., **34**, 549–558.

Kondo, J., Nakazono, M., Yamazaki, T. and Kuwagata, T. (1991): Heat storage in forest trees. *Tenki*, **38**, 49–53. (in Japanese)

McCaughey, J.H. (1984): Energy balance storage terms in a mature mixed forest at Petawana, Ontario - A case study. *Boundary-Layer Meteorology*, **31**, 89–101.

Mountain Research Initiative EDW Working Group (2015): Elevation-dependent warming in mountain regions of the world. *Nature Climate Change*, **5**, 424–429.

Oliphant, A.J., Grimmond, C.S.B., Zutter, H.N., Schmid, H.P., Su, H.-B., Scott, S.L., Offerle, B., Randolph, J.C. and Ehman, J. (2004): Heat storage and energy balance fluxes for a temperate deciduous forest. *Agricultural and Forest Meteorology*, **126**, 185–201.

Oliver, C.D. and Larson, B.C. (1990): *Forest Stand Dy-*

namics. 467pp, McGraw-Hill, New York.

Price, M. (2015): *Mountains*. Oxford, p134.

Saitoh, T.M. (2014): Ecosystem respiration at canopy scale – Insights from carbon and heat cycles -. *News Letter of the Japanese Society of Photosynthesis Research*, **24**(1), 34–38. (in Japanese)

Saitoh, T.M., Tamagawa, I., Muraoka H. and Koizumi, H. (2010): Heat storage due to photosynthesis and respiration activities in forests. *J. Agric. Meteorol*., **66**(4), 289–298. (in Japanese with English abstract)

Saitoh, T.M., Tamagawa, I., Muraoka, H. and Koizumi, H. (2011): Energy balance closure over a cool temperate forest in steeply sloping topography during snowfall and snow-free periods. *J. Agric. Meteorol*., **67**, 107–116.

Sato, T. and Kimura, F. (2005): Diurnal cycle of convective instability around the central mountains in Japan during the warm season. *Journal of the Atmospheric Sciences*, **62**, 1626–1636.

Shimizu, S. (2012): Climatological trends for past 40 years in Sugadaira Mountainous Research Center. *Technical Reports of Tsukuba University* (*Tsukuba Daigaku Gijyutu Houkoku*), **32**, 42-49. (in Japanese)

Suzuki, K. (2013): Importance of meteorological observation in the Japanese Alps Region. *J. Geography* (*Chigaku Zasshi*), **122**, 553–570. (in Japanese with English abstract)

Takahashi, S., Matsushita, M. and Hoshino, K. (2013): Characteristics of growing trees and their competition in young riparian tree community. ESJ annual meeting 60th, Shizuoka, Abstract.

Takane, Y. and Kusaka, H. (2011): Formation mechanisms of the extreme high surface air temperature of 40.9°C observed in the Tokyo metropolitan area: Considerations of dynamic foehn and foehnlike wind. *Journal of Applied Meteorology and Climatology*, **50**, 1827–1841.

Ueno, K., Isono, J., Imaizumi, F., Inami, A., Kanai, R., Suzuki, K., Kobayashi, G., Tamagawa, I., Saito, T. and Kondo, A. (2013): Data archive of meteorological data created through the Japanese Alps Inter-University Cooperation Project. *J. Geography* (*Chigaku Zasshi*), **122**, 638–650. (in Japanese with English abstract)

Ueno, K., Kurobe, K., Imaizumi, F. and Nishii, R. (2015): Effects of deforestation and weather on diurnal frost heave processes on the steep mountain slopes in south central Japan. *Earth Surface Processes and Landforms*, **40**, 2013–2025.

Received 7 September, 2017
Accepted 16 October, 2017