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Observation of thermal belt on an open slope by use of infrared thermography

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Abstract

An observation utilizing an infrared thermography was conducted on January 9, 2005, in the southern slope Mt. Houkyou and its accompanying slope holding a quarry where vegetation is scarce. The objective was to compare the diference over two mountain slopes with contrasting land surface condition in maintaining the nocturnal drainage flow and the surface inversion layer in the surrounding plain. It was found that the cooling rate over the open slope is –2.0˚C / hr and is larger than the slope covered with vegetation where the rate was –1.6˚C/hr. The vertical profile of both slopes revealed a temperature peak near 100-300 m, which was consistent with the data provided by aerosonde observations and the temperature logger observations in the nearby Mt. Tsukuba. Furthermore, the strength of temperature inversion along the slope revealed a linear increase against the elevation of +0.68˚C/100 m. The result is suggestive of the effect of nocturnal drainage flow being stronger at the foot of the slope.

Key words: thermal belt, thermography, land surface condition, nocturnal drainage flow, Mt. Tsukuba

1. Introduction

Thermal belt is known as an elevated band along mountain slopes where nighttime surface temperatures remain relatively high compared with the temperatures above and below. Its existence was long known among farmers who cultivated the mountain slope for growing crops and vineyards. Geiger (1965) reported that in Germany, such locations were favored for earliest villages, monasteries, and country houses. In Japan, thermal belt was used since the Edo period as a location of growing native species of mandarin oranges in spite of the relatively cold climate of the Kanto plain (Murakami, 1967). During 1953-1956, the Mito meteorological observatory conducted an observation of nighttime minimum temperature with other meteorological variables over the western slope of Mt. Tsukuba (877 m asl, Ibaraki prefecture, Japan) to investigate the adaptability of fruit trees in the thermal belt (Gunji, 1958). In the late 1950’s, mandarin orange farms were established by the local population as a tourist attraction (Kobayashi and Koshizuka, 1983).

Many studies have been carried out in Mt. Tsukuba to reveal the temporal and spatial structure of the thermal belt as well as its intensities and geographical conditions in which they appear. One of the unique features of Mt. Tsukuba is that it is an isolated mountain with its western slope descending gradually towards the Kanto plain. This distinct topographical feature is favorable for the existence of nocturnal drainage flow and the resultant thermal belt. Many observations were conducted in Mt. Tsukuba by means of direct temperature measurement by thermometers (Yoshino, 1968; Sato, 1978; Yoshino, 1982) or by use of aerological or satellite driven thermal images (Kobayashi, 1979; Kondoh *et al.*, 1992; Kurose and Hayashi, 1993; Inanaga *et al.*, 1997).

Recently, observations with enhanced accuracy and detailed time-resolution were made possible through deployment of automated temperature loggers (Ueda *et al.*, 2003; Hori *et al.*, 2005; Watarai *et al.*, 2005). These studies have confirmed previous results that the thermal belt exists primarily at the elevation of 200-300 m asl. It was also shown that the thermal belt appears in 42-53% of the observation days, mostly under a calm cloudless night. While the temperature of the thermal belt became colder in January, the height at the center of the thermal belt and the strength of temperature inversion remained the same magnitude.

One topic that has been raised from these more accurate observations is that a bias towards high temperatures was apparent in areas covered by dense population of chinquapin trees located in the northwestern slope of Mt. Tsukuba. It is suggested that the such warm bias is a result of both (a) intensified thermal belt in the region due to local topography and (b) vegetation effects creating an favorable environment for warmer temperature conditions by weakening the wind speed among in the canopy and by altering the radiation balance.

To address such issues, it is expected to make an observation comparing densely covered vegetation and scarce or no vegetation under a same weather condition.

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In theory, a regional atmospheric model can be utilized to calculate the effect of land surface difference under the same topography. However, simulation of thermal belt requires calculation with high resolution in the near-surface boundary layer where the nocturnal drainage flow is strong, and an accurate estimation of the radiative transfer between the land surface and the overlying vegetation, which makes the use of numerical models impractical, if not impossible.

Fortunately, Mt. Houkyou (461 m asl) is located 8 km southeast of Mt. Tsukuba and its accompanying slope holds a large quarry (property of the Tsukada Ceramics Co.) where vegetation is scarce. Comparing the thermal characteristics of the quarry to the slope of Mt. Houkyou, where vegetation is abundant, makes it an exceptional site for observing the impact of vegetation in the thermal belt.

In this study, an observation utilizing an infrared thermography is carried out under a calm cloudless night where thermal belt exists typically. The purpose of this study is (a) to deduce the effect of vegetation on the thermal belt by comparing the cooling rate under differing land surface conditions and (b) to measure the strength of the inversion layer created along the slope of Mt. Houkyou in order to quantify the role of the nocturnal drainage flow in maintaining the thermal belt.

2. Observation and data sources

2.1. Observation

Figure 1 shows the map of the observation field. The infrared thermography is targeted northwards to Mt. Houkyou and its accompanying slope that holds the quarry, from a distance of 2000-3000 m. In the figure, the mountain ridges are presented by dotted lines, and it can be seen that a shallow ridge separates the slope of Mt. Houkyou and the quarry. This topographical

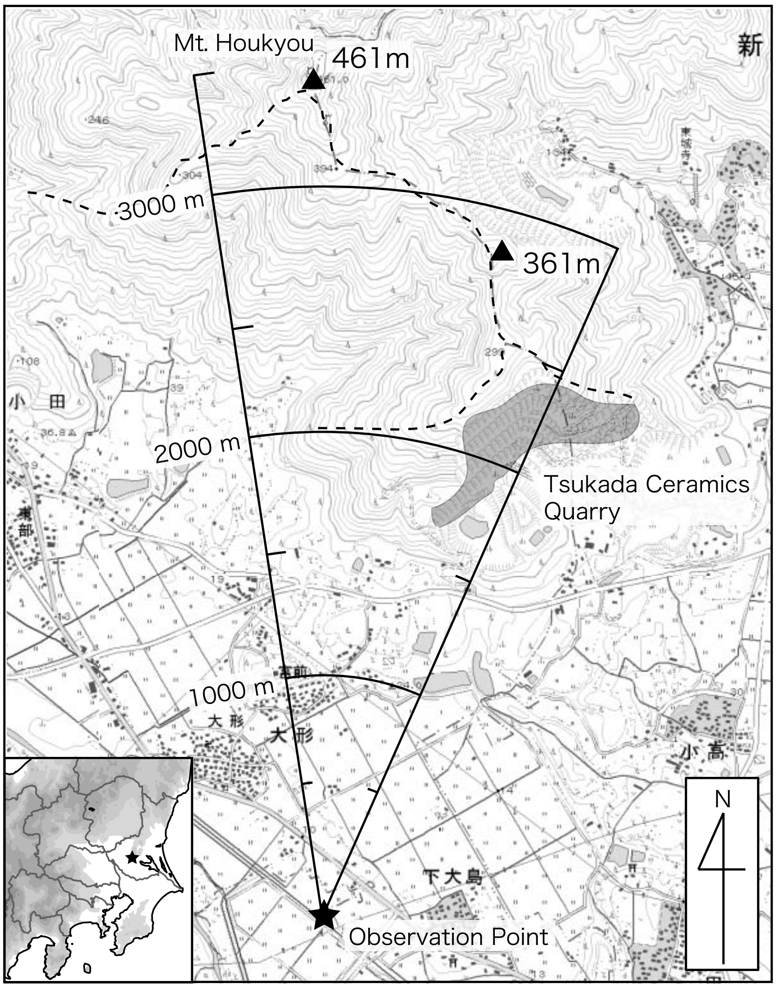

Fig. 1 Field of observation. The observation point is shown by a star. View area from the observation point and mountain ridges are shown in a dotted and broken lines respectively.

separation of the two slopes assures that the nocturnal drainage flow in one slope does not influence the other, and is favorable for our observation.

The image of both slopes from the point of observation is shown in Fig. 2. The elevation scale for Mt. Houkyou is given in the left, while that of the quarry is given in the right. It should be noted that the peak of Mt. Houkyou is located 1000-1500 m behind the quarry, and the scale is calculated to show the apparent reduction in size. Since the observation was conducted during winter when the effect of absorption of radiation due to water vapor is minimal, we applied no adjustment to the observed radiance temperature to accommodate this difference in observational distances. Each mountain slope rises in a nearly equal elevation angle from a plain having an elevation of 20-30 m asl and covered mostly by rice fields.

The instrument used in the observation is an infrared thermography (TH3102MR by NEC San-Ei Instruments) equipped with a mercury cadmium telluride (HgCdTe) detector cooled by a Helium Stirling cooler. Detection range of the instrument is –50˚C -200˚C with a minimum temperature interval of 0.08˚C at 30˚C. Each thermal image is raster scanned into a grid of 239×207 lines with a frame time of 0.8 seconds.

It should be noted that the radiance temperature observed by the thermography is not air temperature, but a composite temperature of various surfaces, such as the bare ground, tree barks, and remaining leaves. Kurose and Maki (1988) reported that night time surface temperature on the mountain slope is in good correlation with directly measured air temperature at 4 m above the surface (r = 0.9), which suggests that radiance temperature observed by the thermography can be used as a proxy of air temperature.

The observation was conducted in a 7 hour period of 15-22LT on January 9, 2005 which includes the local sunset time for this date which was 16:40 LT. The weather condition was fair with a prevailing northeasterly wind, less than 2 m/s according to the local AMeDAS observation. The synoptic weather was under the influence of a large high-pressure system over the Japan Sea, which has contributed to the fair condition, and no significant cloud cover was visible throughout the observation period.

During the earlier part of the observation, thermography images were taken at 5-minute intervals. During 19-22LT, images were taken in a 10-minute interval. Removing erroneous images, a total of 67 successful thermography images were obtained.

2.2. Additional data sources

In addition to the thermography image, rawinsonde observation at 21LT by courtesy of the Aerological Observatory of the Japan Meteorological Agency located 9 km south of the observation field is used as a reference of surface temperature inversion.

Also, air temperature logger data from the western slope of Mt. Tsukuba located 8 km to the northwest were

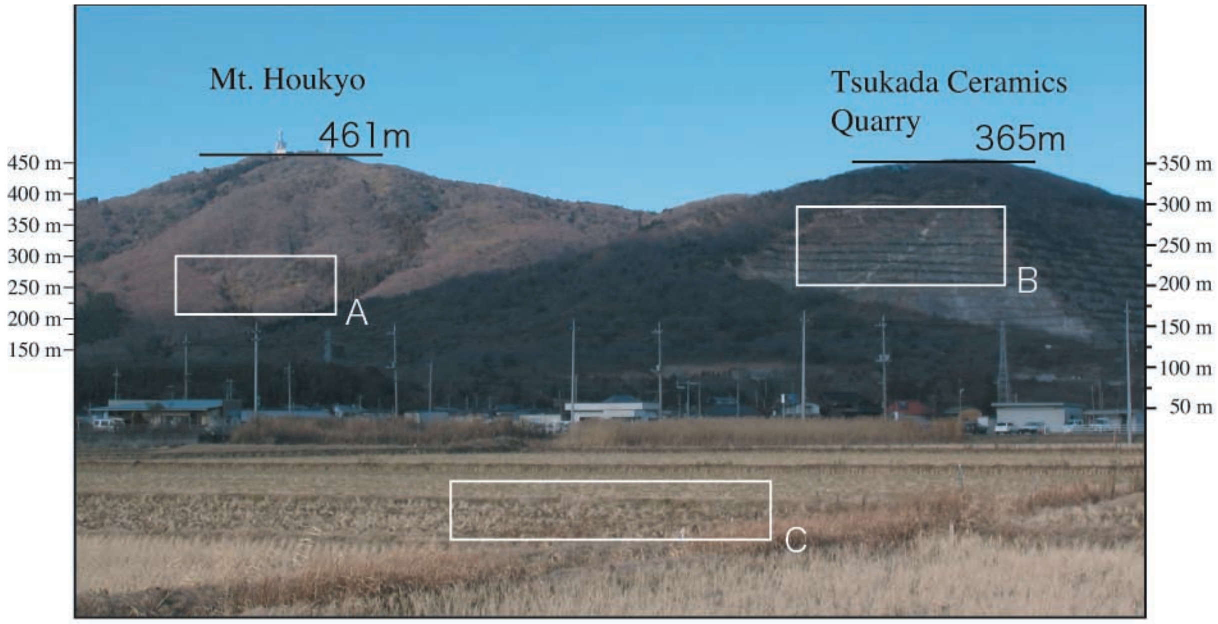

Fig. 2 Photograph from the observation point. The approximate elevation scale for Mt. Houkyou is shown on the left, and that of the Tsukada Ceramics quarry on the right.

provided by Yuuichi Ikeda of the University of Tsukuba and were used for comparison with the rawinsonde observation.

3. Results

Based on the images taken, an hourly average has been made of the radiance temperature. A particular 1-hour average uses data taken during the past hour; therefore, 1 hour average for 16LT (as in Fig. 3a) is an average of observations after but not including 15LT up until 16LT (inclusive). Figure 3 shows such 1 hour averaged radiance temperatures throughout the observation period. Darker shading indicates a lower radiance temperature and lighter shading a higher temperature with the exception of the sky region where shading is removed. The color scale for each passing hour is decreased in a range of 2˚C.

One of the consistent features during the whole observation is that the radiance temperature over the quarry is always higher than the rest of the slope, with values exceeding 12˚C at 16LT. This is due to the emmisive energy stored by solar insolation before sunset. The surface temperature is always lower on the plain in stark contrast with the mountain slopes, where the surface temperature is always 4-5˚C higher than the plain especially after 19LT. At 22LT, the difference in radiance temperature between the quarry and the slope of Mt. Houkyou becomes more obscure, indicating a stronger cooling over the quarry than the slope covered with vegetation.

To reveal the change of radiance temperature under different surface conditions, the time series of area averaged radiance temperature is presented in Fig. 4. Each time series is taken from the boxed area shown in Fig. 2, where area A is located in the slope of Mt. Houkyou covered by dense vegetation, area B is located in the slope of the quarry where vegetation is scarce, and area C located in the lower plains covered with resting rice fields. Proportions of the slopes are taken into account by changing the size of the boxed area. Area C covers only a portion of the surrounding plains, however, as seen in Fig. 3, the surface temperature in the plain is mostly uniform, and it can be considered to represent a larger area of the plain. All time series is presented in difference from the value at 15LT to hightlight the cooling effect after sunset. A slight increase observed in area C after 21LT is considered to be a result of temporary intrusion of southerly wind that caused meso-scale air masses, shifting from urban area to the observation field.

Overall, the cooling rate in the plains reaches a maximum with –2.7˚C/hr for 17-21LT. This is due to

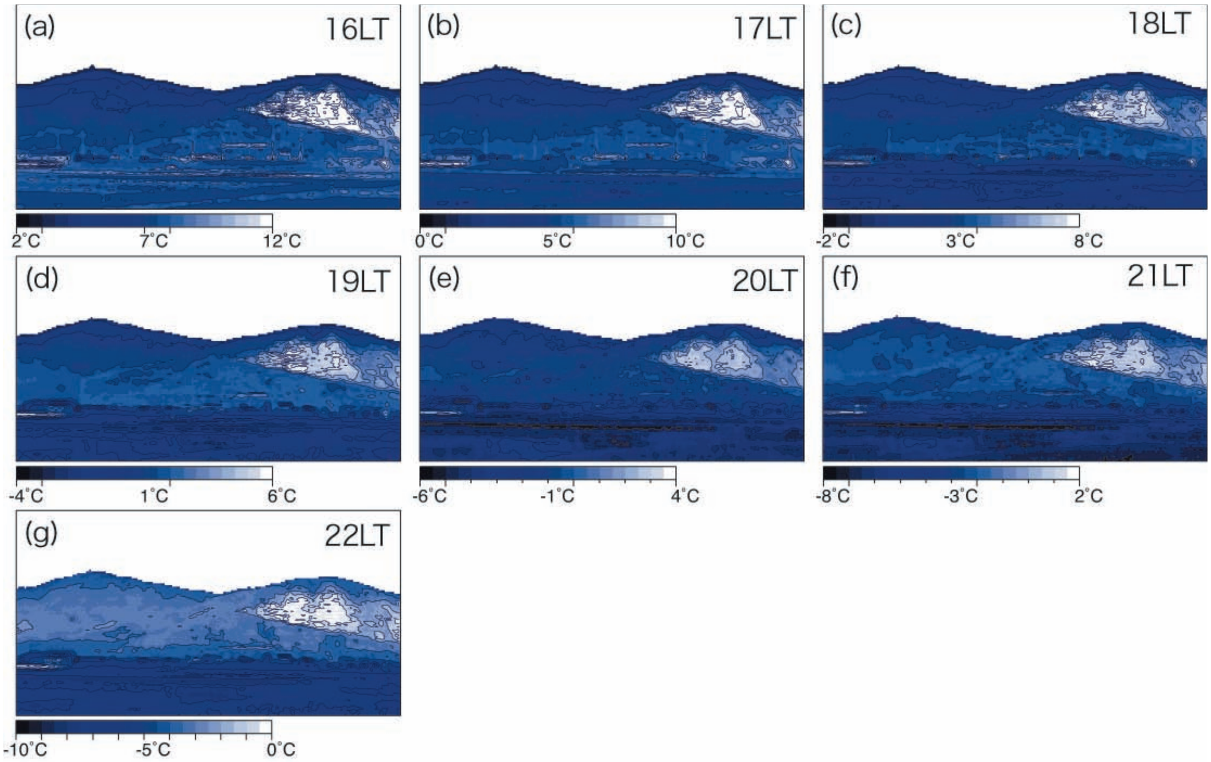

Fig. 3 Hourly change of the thermography image during the observational period of 16-22LT. The temperature scale decreases 2˚C with advance of observation time.

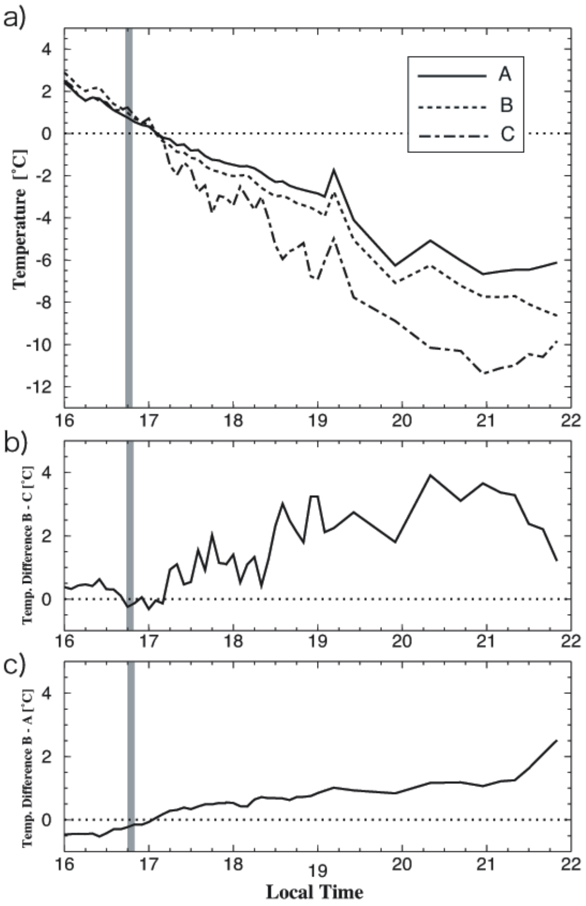

Fig. 4 Time series of (a) area averaged surface temperature for each region shown in Fig. 2, (b) area averaged surface temperature for area B minus area C, and (c) same as (b) but for area B minus area A. All time series is given as a difference from 15LT. The thin colored line indicates the approximate sunset time in the area.

both a strong radiative cooling, and an intrusion of cold drainage flow from the mountain slopes. On the other hand, the cooling rate of area B (–2.0˚C/hr) is larger than that of area A (–1.6˚C/hr). This is owed to the fact that a) nocturnal drainage flow becoming weaker in a land surface covered by vegetation and b) radiative cooling being weaker inside of the canopy due to absorption and re-emission of long-wave radiation by the surrounding vegetation.

Ignoring the elevation angle and assuming the emissivity of black body for both land surface conditions, the magnitude of nocturnal drainage flow can be estimated by taking the difference of radiance temperatures in areas B and C, which is shown in Figure 4b. Seeing that area B is comprised by a land surface where vegetation is scarce, the difference in surface temperature is mostly due to decresing temperature by nocturnal drainage flow over the plain, which corresponds to around +3-3.5˚C at 21LT. Line fitting shows that such an effect amounts to 1.1˚C/hr difference in terms of cooling rate. Similarly, the difference in radiance temperatures between areas A and B shown in Figure 4c yields the influence of differing surface conditions in these two areas. Line fitting reveals that the contribution of vegetation towards sustaining a higher temperature in the slope is 0.5˚C/hr difference in terms of cooling rate.

To address such difference in cooling rate, the difference in radiance temperature for 22LT and 15LT is shown in Fig. 5. Strong cooling exceeding –12˚C (–2˚C/hr) can be seen in the lower plains. A comparable cooling of about –10˚C (–1.7˚C/hr) is evident over the quarry where the apparent surface temperature is large, but the cooling

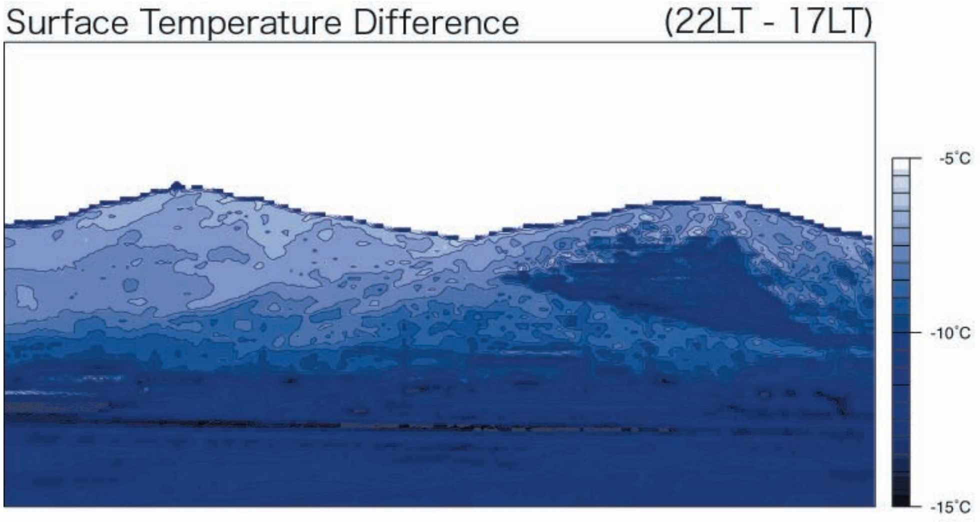

Fig. 5 Difference in surface temperature for 22LT minus 17LT.

rate is similar to that in the plain. Most of the mountain slopes covered in vegetation marks a temperature difference of –5˚C (–0.8˚C/hr) or less which contrasts with the quarry where vegetation is scarce. In detail, the difference in radiance temperature between the plain and the quarry of about +2-3˚C (0.3-0.5˚C/hr) is considered the effect of thermal belt without the influence of vegetation.

Comparison of Mt. Houkyou and the accompanying slope holding the quarry in terms of vertical profile of radiance temperature at 21LT is given in Fig. 6a. Surface temperature over the quarry around 150-300 m asl shows a strong residual warming by the solar insolation before sunset. However, profiles above 300 m and below 150 m where vegetation can be seen are comparable to the profile at Mt. Houkyou showing a value near –4˚C. Figure 6b compares this profile with the air temperature profile taken from a rawinsonde observation and temperature logger observation. The profile given in Fig. 6a is replicated as a grey line to facilitate the comparison. The observed value of air temperature exceeds the result of radiance temperature estimation by about 5-6˚C. This is partly due to the fact that radiance temperature represents the surface temperature or near-surface temperature of the object in observation and is nevertheless under the influence of strong radiative cooling in the region. However, the overall feature of the profile where a peak occurs around 100-300 m asl is consistent among all profiles, indicating the existence of a strong inversion layer.

The changes in inversion strength of the two slopes between 21LT and 17LT is given in Fig. 7 where the value is calibrated against the surface temperature of area C, namely:

$$[\,\mathrm{T}(21LT) - \mathrm{C}(21LT)] - [\mathrm{T}(17LT) - \mathrm{C}(17LT)] \qquad (1)$$

where T(t) stands for the vertical temperature profile, and C(t) stands for the spacial averaged surface temperature at area C at a particular time t. The value being negative or small signifies that the temperature inversion against the lower plain is diminishing or remaining the same after 17LT. A larger value signifies the existence of a strong temperature inversion after sunset.

In the figure, a region with small difference in inversion strength is observed over the quarry at the elevation of 150-280 m asl, which is indicative that the thermal belt is weaker in the quarry. Below or above the quarry, the inversion strength follows an unique linear profile as Mt. Houkyou with the rate of inversion strength increasing with elevation at +0.68˚C per 100 m. The

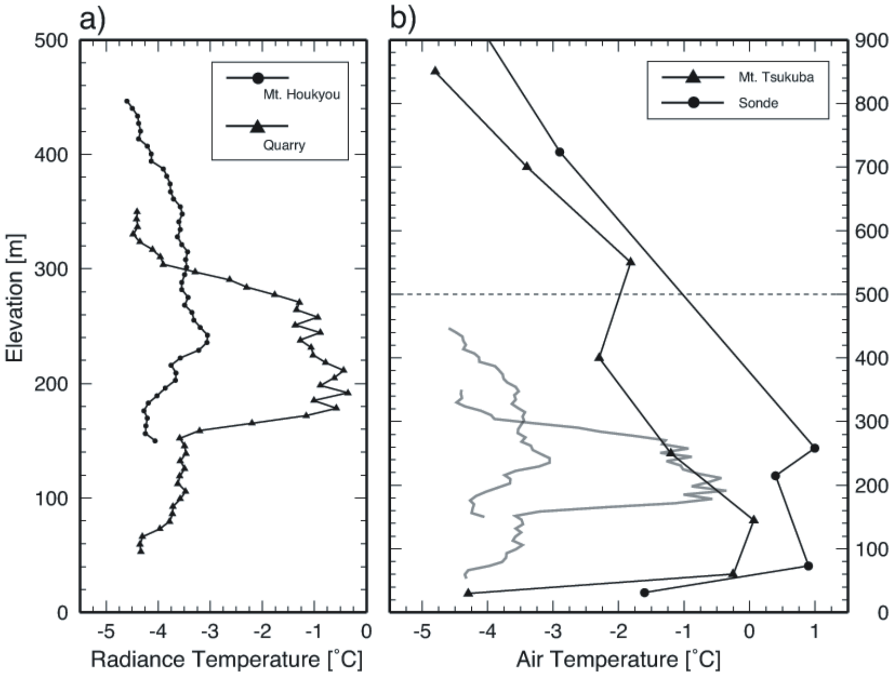

Fig. 6 Vertical profile of (a) surface temperature at Mt. Houkyou (●) and the accompanying slope holding the quarry (▲) and (b) air temperature obtained by aerosonde observation (●) and temperature logger observation at Mt. Tsukuba (▲). Dotted line indicates the vertical limit of (a) and thin colored line replicates the results of (a).

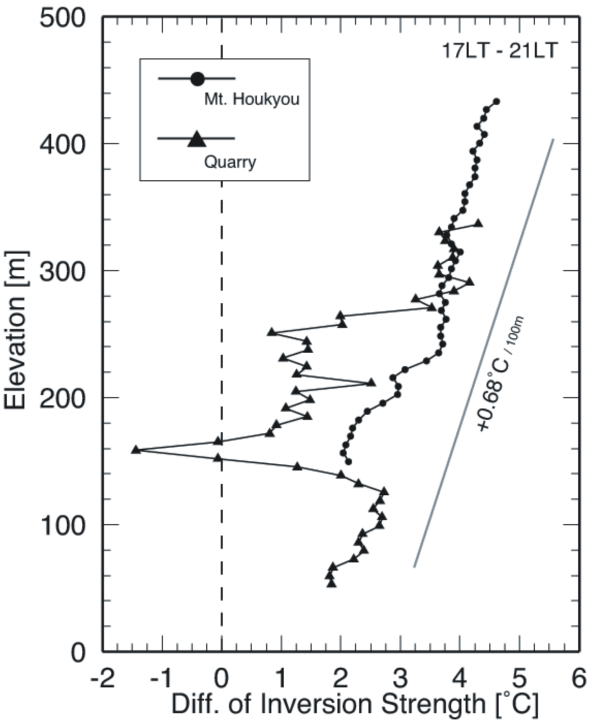

Fig. 7 Vertical profiles of the strength of surface inversion for Mt. Houkyou (●) and the quarry area (▲) between 21LT and 17LT.

rate at which the inversion layer is strengthened is smaller at the foot of the slope than the top, which indicates that the effect of nocturnal drainage flow is larger at the foot of the mountain.

4. Conclusion

In this study, an infrared thermography was utilized to observe the mountain slope of Mt. Houkyou and the accompanying slope that contains a quarry with scarce vegetation. The objective of the study was to reveal the influence of vegetation on the maintenance of the thermal belt and the role of land surface difference in creating the thermal belt.

The mountain slope over the quarry revealed a strong surface temperature throughout the observation period, which is the effect of strong daytime heating by solar insolation survives into the night. However, when converted into a cooling rate, the quarry showed a value of –2.0˚C/hr whereas the slope of Mt. Houkyou covered with vegetation showed a more moderate cooling of –1.6˚C/hr. It is suggested that a difference of these two cooling rates, +0.4˚C/hr, is due to effects of both radiative balance being altered in the canopy and the nocturnal drainage flow being decreased in the slope covered with vegetation.

In terms of absolute temperature, the vertical profile of surface temperature reveals a region suggestive of a thermal belt around the elevation of 100-300 m, which is mostly consistent with rawinsonde observations and temperature logger observations in the nearby Mt. Tsukuba. However, difference in the strength of the temperature inversion reveals a relation of +0.68˚C for every 100 m increase in elevation. This suggests that the effect of nocturnal drainage flow is stronger at the foot of the mountain than on the top. It is possible that the apparent height of the thermal belt is determined by the magnitude of the nocturnal drainage flow imposed on the vertical profile of the surface inversion layer of the Kanto plain. Where vegetation is scarce, this difference in magnitude was smaller which signifies that the effect of nocturnal drainage flow was stronger. Nonetheless, further studies including the drainage area and wind speed of the nocturnal drainage flow required to understand the role of vegatation in mediating the effect of nocturnal drainage flow.

Issues for further investigation includes the effect of mountain scale in determining the strength of the nocturnal drainage flow. The elevation of Mt. Houkyou used in this study is about half the elevation of Mt. Tsukuba. Despite the difference in scale, the temperature inversion had a peak of 100-300 m, which is consistent with the findings in Mt. Tsukuba. The question remains as to whether the location of the thermal belt is determined by the scale of the mountain and the drainage area of the nocturnal drainage flow, or by external effect of the surface inversion layer of the Kanto plain.

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References

Geiger, R. (1965): *The Climate near the Ground*. Harvard University Press, 437 p.

Gunji, T. (1958): On the surface inversion around Mt. Tsukuba. *Report of Industrial Meteorology,* **21**, 89-91. (*in Japanese*)

Hori, M., Ueda, H. and Nohara, D. (2005): Frequency and temporal characteristics of the thermal belt over the western slope of Mt. Tsukuba. *Geogr. Rev. Japan,* *in press*. (*in Japanese with English abstract*)

Inanaga, A., Watanabe, M., Mikami, T. and Nakayama Y. (1997): Relationship between the thermal belt of land surface temperature and land use on the southern slope of Mt. Akagi using LANDSAT/TM thermal data. *Geogr. Rev. Japan*, **70A**, 333-351. (*in Japanese with English abstract*)

Kobayashi, M. (1979): Thermal scanner measurement of thermal belt in Mt. Tsukuba. *Tenki*, **26**, 161-166. (*in Japanese*)

Kobayashi, M. and Koshizuka, A. (1983): On the distribution of orange garden and its association with microclimatology in Mt. Tsukuba. *Envir. Study in Tsukuba*, **7**, 195-202. (*in Japanese*)

Kondoh, A., Kanno, H. and Mikami, T. (1992): Analysis on the thermal belt on the mountain slope using LANDSAT images and a digital terrain model. *J. Remote Sensing Japan*, **12**, 33-42. (*in Japanese with English abstract*)

Kurose, Y. and Hayashi, Y. (1993): Evaluation of air temperature distribution using thermal image under conditions of nocturnal radiative cooling in winter season over Shikoku area. *J. Agr. Met.*, **49**, 11-17. (*in Japanese with English abstract*)

Kurose, Y. and Maki, T. (1988): Measurement of thermal belt on the slope of Mt. Osa by using infrared thermometer. *J. Agr. Met.*, **43**, 275-283. (*in Japanese with English abstract*)

Murakami, S. (1967): *A Study of Regionality in Citrus Fruit Farming*. Ehime publishing association, 1089 p. (*in Japanese*)

Sato, M. (1978): Diurnal and seasonal variability of air temperature along the southern slope of Mt. Tsukuba. *In* Ichikawa, M. and Yoshino M.M. *eds., Changes in Thermodynamical and Hydrological Budget under the Influence of Urban Development in Tsukuba City*. University of Tsukuba, pp. 67-76.

Ueda, H., Hori, M.E. and Nohara, D. (2003): Observational study of the thermal belt on the slope of Mt. Tsukuba. *J. Meteor. Soc. Japan*, **81**, 1283-1288.

Watarai, Y., Hori, M.E. and Hayashi, Y. (2005): Vertical Structure of the Thermal Belt in the Western Slope of Mt. Tsukuba: An Observational Study on 10-11 December, 2004. *Tsukuba Geoenvironm. Sci.*, **1**, 11-17.

Yoshino, M.M. (1968): Problems in local and micrometeorology in relation to agriculture in Japan. In Natural Resources Research VII. *ed., Agroclimatological methods: Proceedings of the Reading Symposium*. UNESCO, Reading, UK, pp. 269-280.

Yoshino, M.M. (1982): Extremely low air temperature and development of inversion layer in the Tsukuba region. *Environm. Res. Center Pap.*, **6**, 35-44.

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