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Vertical structure of the thermal belt in the western slope of Mt. Tsukuba: an observational study on 10−11 December, 2004

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Abstract

Thermal belt formation on the western slope of Mt. Tsukuba was observed during the nighttime of December 10−11, 2004. At four sites on the slope, vertical profile of air temperature was observed up to 100 m above the land surface by using captive balloon equipped with a temperature data logger. In addition, infrared thermography was used to take the thermal images of the slope. The result shows a temperature inversion of +3.6˚C between the mid-slope and the foot of Mt. Tsukuba. Over the thermal belt, a thin inversion layer up to 15 m above the surface was observed with an overlying isothermal layer. While over the plain, a same structure was observed with a much thicker inversion layer (up to 150 m above the surface). Rawinsonde observations revealed that the height of the isothermal layer in the slope corresponded to that over the plain. Thermography images revealed that the thermal belt is located at the elevation band of 150−350 m a.s.l. with variation in temperature dependant to topography. Abrupt decrease in temperature occurred around 0300 JST, which was centered at 50 m a.s.l. and is suggestive of a larger-scale cold-air advection. This study shows that the existence of a thermal belt is dependant on both (a) mechanisms maintaining the 1-dimensional temperature profile and (b) the influence of a larger scale advection of cold air into the mountain area.

Key words: thermal belt, surface inversion, cold air drainage, thermography

1. Introduction

Mt. Tsukuba is an isolated mountain located in the Ibaraki Prefecture, Japan. Its altitude is 877 m above sea level (a.s.l.), and the southern to western slope of the mountain faces the Kanto Plain. It is well known that a remarkable thermal belt appears at the mid-slope of Mt. Tsukuba (Yoshino, 1986). Mandarine oranges have been cultivated on the mid-slope (centered about 150 m a.s.l.) taking advantage of the mild climate due to the thermal belt since the 1950's.

Many observational studies have been conducted at Mt. Tsukuba in order to examine the distribution of thermal belt. Mito Local Meteorological Observatory examined daily value of maximum and minimum temperatures ranged from July 1953 to December 1956 (Ibaraki Prefecture, 1955; Ibaraki Prefecture and Mito Local Meteorological Observatory, 1957; Gunji, 1958) and revealed that the altitude of the thermal belt is centered about 200−300 m a.s.l. According to the observation by Yoshino (1982), the altitude of the thermal belt gradually rose during the nighttime and became the maximum at dawn on the southern slope of Mt. Tsukuba.

Recently, Ueda *et al.* (2003) observed a warm zone centered about 200−250 m a.s.l. and a vertical profile of air temperature which was indicative of an overlying isothermal layer. However, they did not observe the vertical profile higher than 40 m above the land surface, and no comparison has been made against the rawinsonde observations. In this study, vertical temperature profiles up to 100 m was clarified by using captive balloons and compared with thermography observations to distinguish the surface inversion layer and the overlying isothermal layer.

Infrared thermography is a useful tool to acquire the mountain-scale temperature distribution. For instance, the surface temperature of trees measured by the thermography is almost equal to the air temperature at night (Kurose and Hayashi, 1993). Kobayashi (1979) used a thermal image taken from an aircraft and revealed the distribution of the thermal belt, which was consistent with previous studies. In this study, multiple thermal images were acquired from a fixed location to reveal the temporal change in surface temperature.

In this study, a combination of vertical air temperature profile observations and thermography observation was made to give a total view of the thermal belt formation in Mt. Tsukuba.

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2. Observation and data

The western slope of Mt. Tsukuba is the target of observation in this study. The top of Mt. Tsukuba is 877 m a.s.l. and the western foot of the mountain is about 20 m a.s.l. and is adjacent to the Kanto plain. Figure 1 shows the map of the observational sites. The observation was carried out from 1700 JST December 10 through 0700 JST December 11. By use of captive balloons equipped with temperature data loggers, vertical profile of air temperature was observed at four sites: A (Sakura River; 24 m a.s.l.), B (Lake Tsukushi; 50 m), C (Hikari farm; 145 m) and D (sediment control dam; 410 m) in Fig. 1. Additionally, we also observed the wind by use of Byram air meter with wind vane, and the air temperature at 1.5 m above the surface by the Assmann aspiration psychrometer at these sites. In site C, land surface temperature was observed by spot radiation thermometer. Black body is assumed and the emissivity of the surface was set at 1.0 for the observation of the radiation thermometer. Observation period was from 1700 JST to 0700 JST on 10-11 December 2004. Time interval of the observation was 1 hour.

Surface temperature at western slope of Mt. Tsukuba was observed by thermography, which located at site T (Fig. 1). Thermal images were taken every 10 minutes from 1700 JST to 0300 JST on 10-11 December 2004.

Hourly surface wind and air temperature observed by the AMeDAS (Automated Meteorological Data Acquisition System) were also analyzed around Mt. Tsukuba. Vertical profile data of air temperature by rawinsonde at the Tateno station (about 20 km south of Mt. Tsukuba) was utilized.

Synoptic weather chart and infrared image of the GOES-9 (Geostationary Operational Environmental Satellite) were used to assess the synoptic weather condition. Figure 2 shows (a) the surface weather chart and (b) the infrared image around Japan at 0300 JST on December 11, 2004. Two cyclones were located in the eastward of Japan and a cold front passed over northeast Japan. Siberian anticyclone gradually extended eastward in the back of these cyclones. Infrared image shows that it was fine around the Kanto area, while cloud was visible over north Japan. Weather condition in the observation site was fine until 0300 JST. After then, deep fogs were observed at site A and B.

3. Results

3.1. In situ observation

Figure 3 shows the time series of surface air temperature at four sites during the observation period. After sunset (about 16:24 JST), the temperature at plain (site A) fell more rapidly than at the slope, and reached 5.0˚C at 0200 JST on December 11. After midnight, temperature difference between site A and other sites became larger, which is indicative of a strong temperature inversion between the plain and the slope. The temperature difference between C and A was 3.6˚C at 0200 JST.

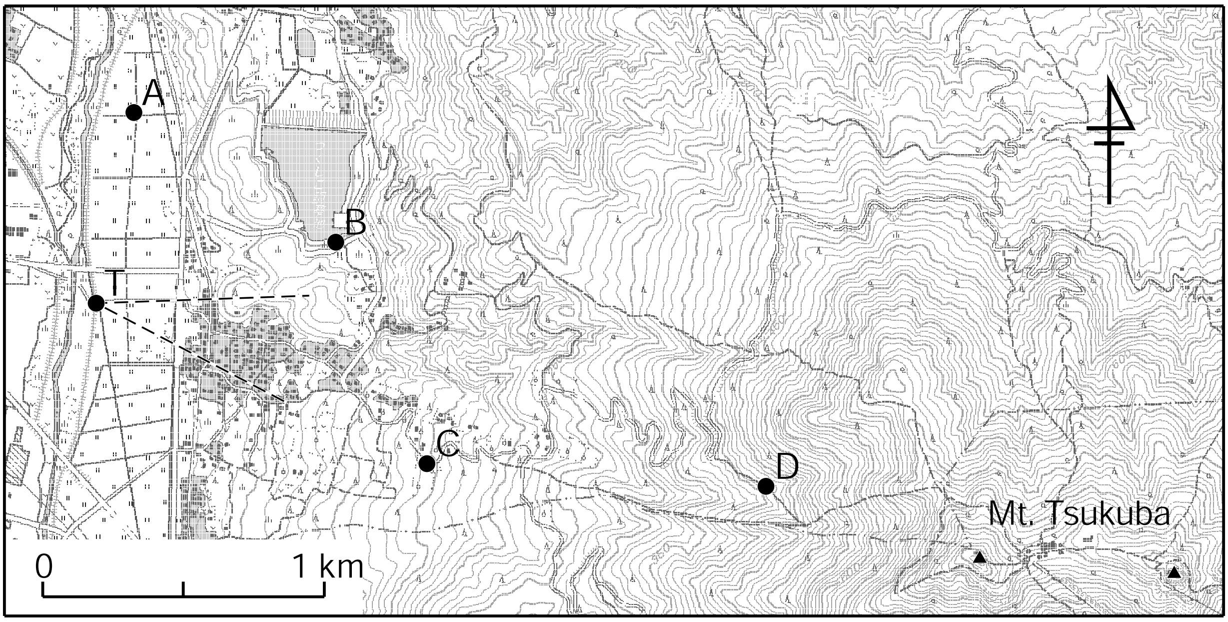

Fig. 1 Map of observational sites. Four points (A-D) denote the sites of in situ observations (A: Sakura river; B: Lake Tsukushi; C: Hikari farm; and D: sediment control dam). Thermography images are taken from site T. Broken lines indicate the line of sight.

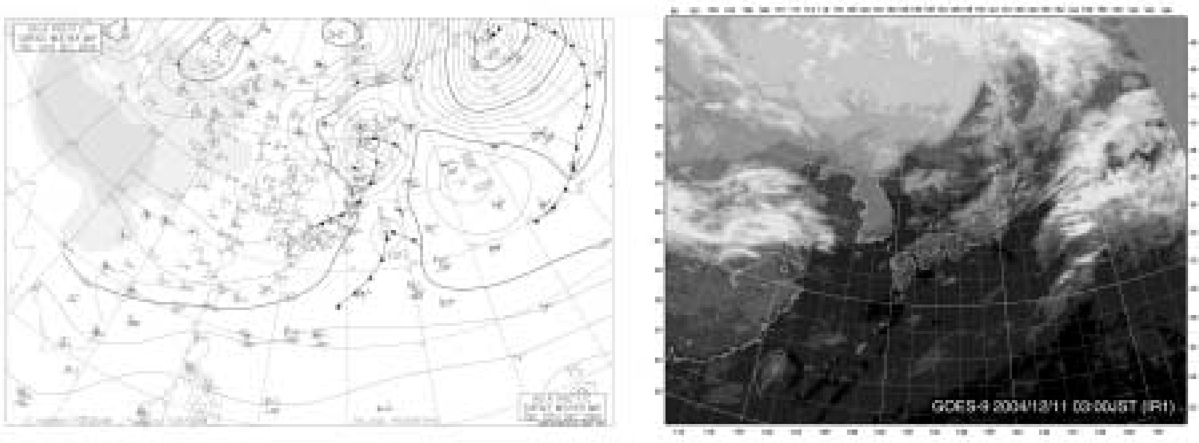

Fig. 2 (a) Synoptic weather chart and (b) GOES-9 infrared image around Japan at 0300 JST on December 11, 2004.

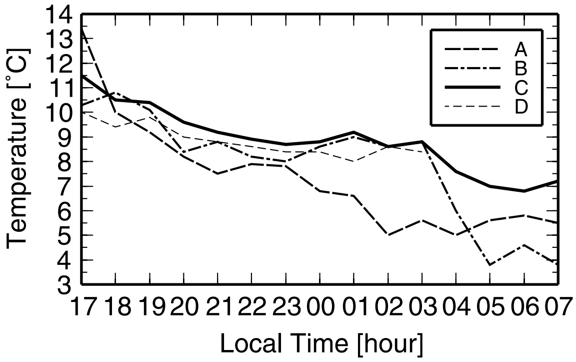

Fig. 3 Time series of air temperature at 1.5 m above the surface. Data from four sites are shown (A: broken line; B: chain line; C: solid line; and D: dotted line).

These results are consistent with previous studies (Ueda *et al.*, 2003). After 0300 JST, more rapid decrease in temperature occurred at sites on the slope. At site B, surface air temperature was 8.8˚C at 0300 JST, and it became 3.8˚C at 0500 JST, which was lower than site A.

Evolution of the vertical temperature profiles at different altitude was compared at Fig. 4. At the observation site of Sakura River (site A), the minimum value was recorded near surface, and the temperature increased with height. At 2100 JST (Fig. 4b), the temperature was about 8˚C near the surface, while it was about 12˚C at 60 m over site A. After that, the temperature decreased until about 6˚C near the surface, while the maximum value was about 10.5˚C at 50 m height at 0100 JST (Fig. 4c). These results indicate that the temperature inversion intensified with time. The temperature over site B presents a profile similar to that over site A at 1700 and 2100 JST. The inversion of temperature at 0100 JST, however, tends to decline with a range of about 9˚C near the surface to about 11˚C at 40 m height. Site C was covered with a much thinner layer of inversion (less than 20 m thick) than sites A and B. Over the inversion layer, the profile was almost constant or slightly reduced, at least up to 100 m above the surface of site C. The vertical profile observed at site D shows the weakest inversion and the coldest at the top of inversion.

Next, temperature lapse rate observed at the mountain slope was compared with aerological data. Figure 5 illustrates the vertical profiles of (a) air temperature and (b) potential temperature at 2100 JST on December 10 (solid line) and 0900 JST on December 11 (chain line), observed by rawinsonde at Tateno station, which has the same altitude but is located about 20 km south of site A. The profile at 2100 JST clearly shows a surface inversion and accompanying strong stable condition. The top of the inversion was about 160 m a.s.l. and 12˚C, while the temperature near the surface was 7.5˚C. At 0900 JST, the top of the inversion became higher (about 350 m a.s.l.) and the temperature near the surface became colder (about 6.5˚C). This indicates the development of the surface inversion in the nighttime.

Vertical profiles observed by captive balloon at four sites are superposed in Fig. 5, as a function of altitude a.s.l. The profile at site A was similar to that at Tateno, which suggests that the profile at Tateno represents the atmospheric condition of a larger scale which includes the area of Mt. Tsukuba. At the observation sites on the slope (*i.e.*, sites B, C and D), the surface air temperature was 2 to 2.5˚C colder than the rawinsonde temperature at the same altitude. However, the temperature at the top of the surface inversion over their sites was almost the same as the rawinsonde temperature. It is found that the isothermal layer over site C corresponds to the maximum temperature at the top of the inversion layer.

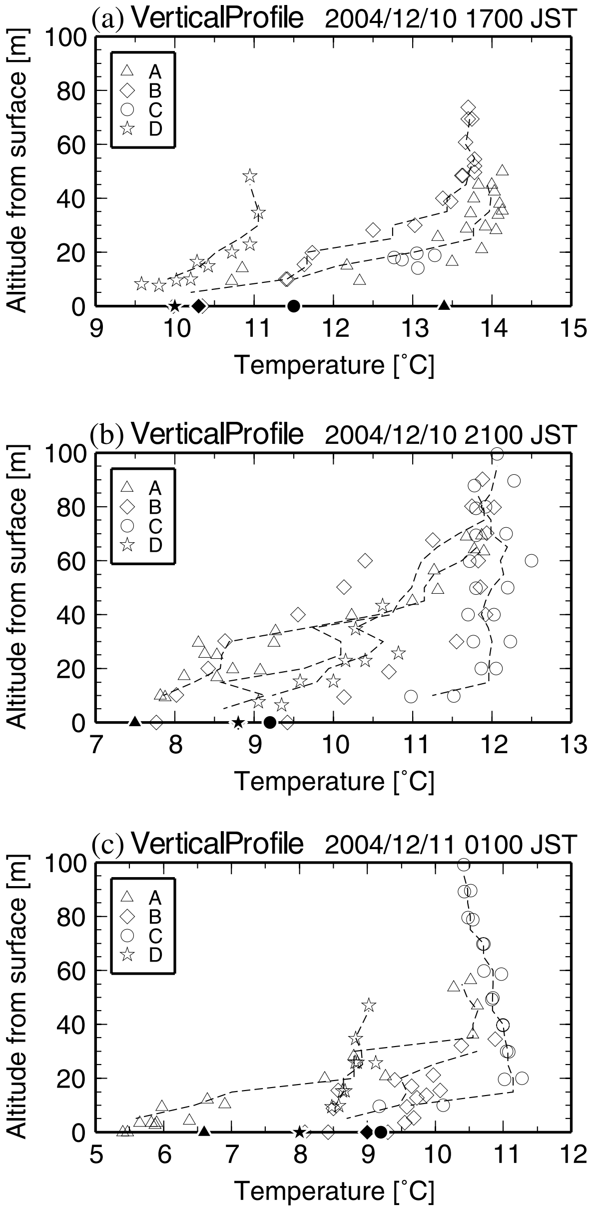

Fig. 4 Vertical profile of air temperature at four sites (A: triangles; B: diamonds; C: circles; and D: stars) observed by captive balloon. Filled symbols denote air temperature at 1.5 m above the surface observed by Assmann aspiration psychrometer. Ordinate is set in altitude above the surface. Shown are the profiles at (a) 1700 JST on December 10, 2005, (b) 2100 JST on December 10, 2005 and (c) 0100 JST on December 11, 2005.

3.2. Thermography

Results of thermal images taken by the infrared thermography are summarized in Fig. 6. Figure 6a shows the surface temperature averaged from 1800 JST on December 10 to 0300 JST on December 11. Warm area of nearly 10˚C spreads zonally over the side of Mt. Tsukuba ranging from 150 to 350 m a.s.l. In contrast, the surface temperature of plain was colder (less than 5˚C). In detail, the surface temperature in the valley is slightly colder than that in the range, which implies dependence towards the topography.

Figure 6b illustrates surface temperature trend estimated linearly for 1800−0300 JST data. Although the entire land surface taken by the thermometer had the negative trend, a clear contrast between the plain and the mountain can be seen. The plain, which has the coldest surface temperature averaged over the nighttime, had a strong negative trend (less than -0.5˚C /hour). In the undermost slope of Mt. Tsukuba (less than about 100 m a.s.l.), the cooling rate was as strong as that in the plain (-0.4 to -0.6˚C /hour). On the other hand, the surface temperature on the slope of Mt. Tsukuba (more than 100 m height) shows a more moderate decrease (-0.1 to -0.3˚C /hour).

4. Discussion and conclusions

The thermal belt in the western slope of Mt. Tsukuba has been investigated during the nighttime of December 10−11, 2004. Vertical profiles of air temperature were observed at four sites ranging from the foot (24 m) to the mid-slope (410 m) of the mountain by captive balloons equipped with a temperature data logger. Thermal images of the western slope were taken by the infrared thermography.

Hori *et al.* (2005) examined multiple cases of thermal belt using an objective index and showed that the average surface air temperature inversion between the foot and the slope of Mt. Tsukuba was +5.2˚C for the composite of all cases during December 2002. In our study, the maximum difference of temperature between site C and A is +3.6˚C, which is a comparably weaker case of thermal belt. Nevertheless, we can see some general characteristics of a thermal belt in our observation.

The vertical profiles of air temperature observed by captive balloons indicated strong surface inversions over four observation sites. At 2100 JST on December 10, the air temperature measured by rawinsonde over Tateno station is consistent with the temperature over site A. Therefore, the rawinsonde profile is representative of an atmospheric condition in a larger scale including the foot of Mt. Tsukuba. The top of surface inversion over the plain corresponds with the altitude of site C, where the surface air temperature is the warmest in the slope. The surface inversion of site C is the thinnest of four sites (about 15 m) and an overlying thick isothermal layer is observed. A similar profile at site C was observed by Ueda *et al.* (2003). Including sites B and D, it is a common characteristic that the profile over the inversion

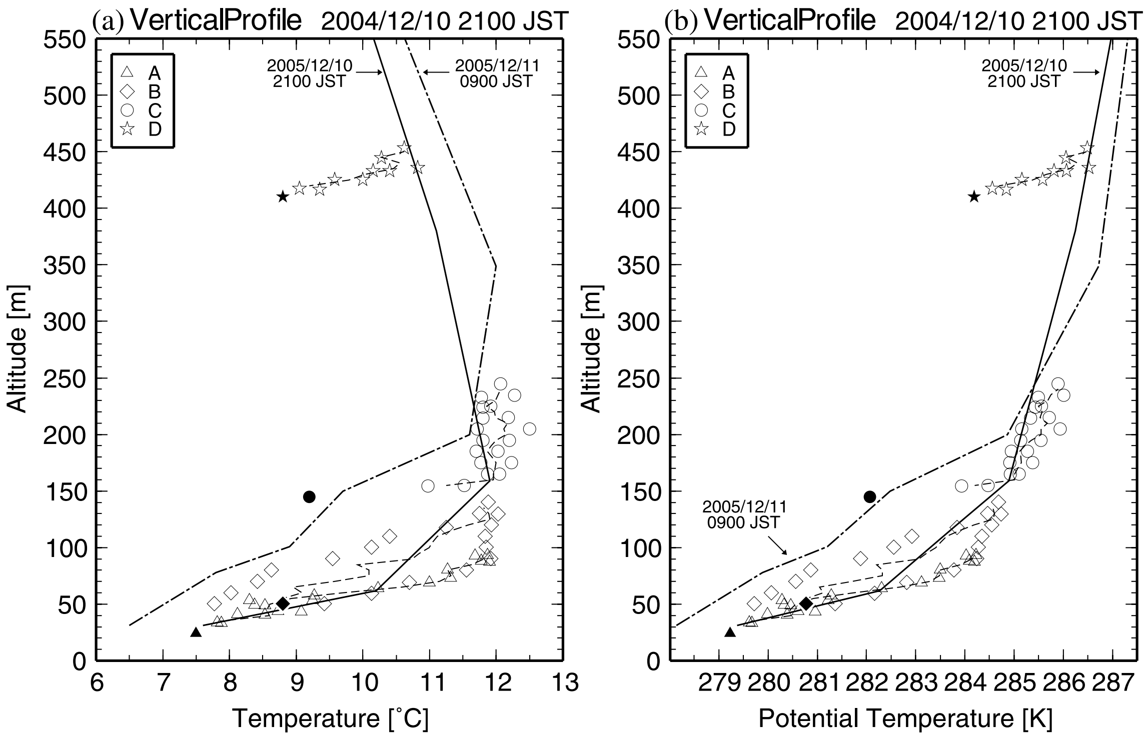

Fig. 5 Vertical profiles of (a) air temperature (˚C) and (b) potential temperature at 2100 JST on December 10, 2005 (solid line) and 0900 JST on December 11, 2005 (chain line), observed by rawinsonde at Tateno (36˚03.4’N, 140˚07.5’E). Profiles at 2100 JST on December 10 observed at four sites (Fig. 4b) are superposed, using the same representation as Fig. 4. Ordinate is set in altitude a.s.l.

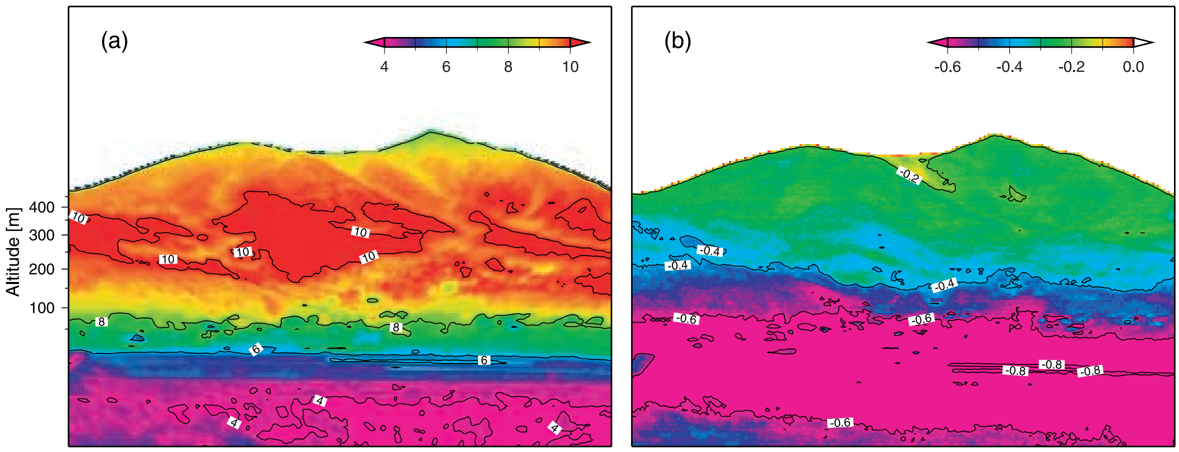

Fig. 6 Thermal image of the western slope of Mt. Tsukuba, taken from site T. These show (a) the averaged surface temperature (unit: ˚C) and (b) the linear temperature trend (unit: ˚C/hour), estimated for 1800 JST - 0300 JST data.

has the almost same value as the sonde data. This result suggests that the upper layer is free from the influence of the slope surface.

The behavior of the cold air drainage can be understood further by the distribution of potential temperature (Fig. 5b). For example, air parcel near the surface at site C (about 282 K) is heavier than the surroundings (about 285 K) and therefore should fall down along the slope up to about 50 m a.s.l., if it moves adiabatically. We found that most of the cold air drainage flow penetrating the surface inversion over the plain comes from the altitude below the thermal belt.

Figure 3 displays an abrupt decrease in surface air temperature observed around 0400 JST at site B. This cooling cannot be explained within the framework of radiative cooling or cold air drainage. Figure 7 shows the fields of surface air temperature and surface wind derived from AMeDAS, 50 km around the Mt. Tsukuba. At 0000 JST (Fig. 7a), the surface wind is calm on the western side of Mt. Tsukuba, which indicates a favorable condition for the intensification of surface inversion. Such a condition began about 1900 JST and continued into about 0100 JST. At 0200 JST (Fig. 7b), weak northwesterly wind (about 1 m/s) emerged and a cold air tongue spread southeastwards. The cold air below 6˚C covered the observation area at 0400 JST (Fig. 7c). Two possible explanation for this rapid temperature decrease is (a) the cold air drainage flow in a much larger Kanto-plain scale, or (b) the large-scale advection induced by synoptic disturbances.

The thermal image taken by the thermography (Fig. 6) displayed the thermal belt ranged from 150 to 350 m in height, which is consistent with the past observations (Ibaraki Prefecture, 1955; Gunji, 1958; Yoshino, 1982; Ueda *et al.*, 2003). However, we can see slight difference of surface temperature, which is partly due to the topography. For example, the small valley tends to have colder surface temperature and smaller cooling rate, which suggests small insolation in the daytime and large sensible heat transport to the land surface in the nighttime. Since the cold airflow along the slope can be considered to be a gravity current, the cold air drainage over the valley should become faster and thicker than the surroundings. It is therefore considered that the decrease of land surface temperature is suppressed, because the wind over the surface brings the sensible heat transport from the warm air to the cold surface. On the other hand, the influence of land coverage of vegetation should be considered. Inanaga *et al.* (1997; 1999) analyzed the thermal infrared images of LANDSAT/TM data in the Mt. Akagi area, and revealed that the warm zone at the mid-slope was partly due to the influence of the forest area, which has a warmer surface temperature than other land use. Hori and Watarai (2005) investigated the effect of vegetation on the thermal belt by observing the surface temperature of two nearby slopes; one covered by vegetation and another an open quarry. It was found that the existence of vegetation contributed to a warmer environment of about +0.4˚C per hour in terms of cooling rate. In further studies, such vegetation effects and its influence to the vertical profile should be investigated.

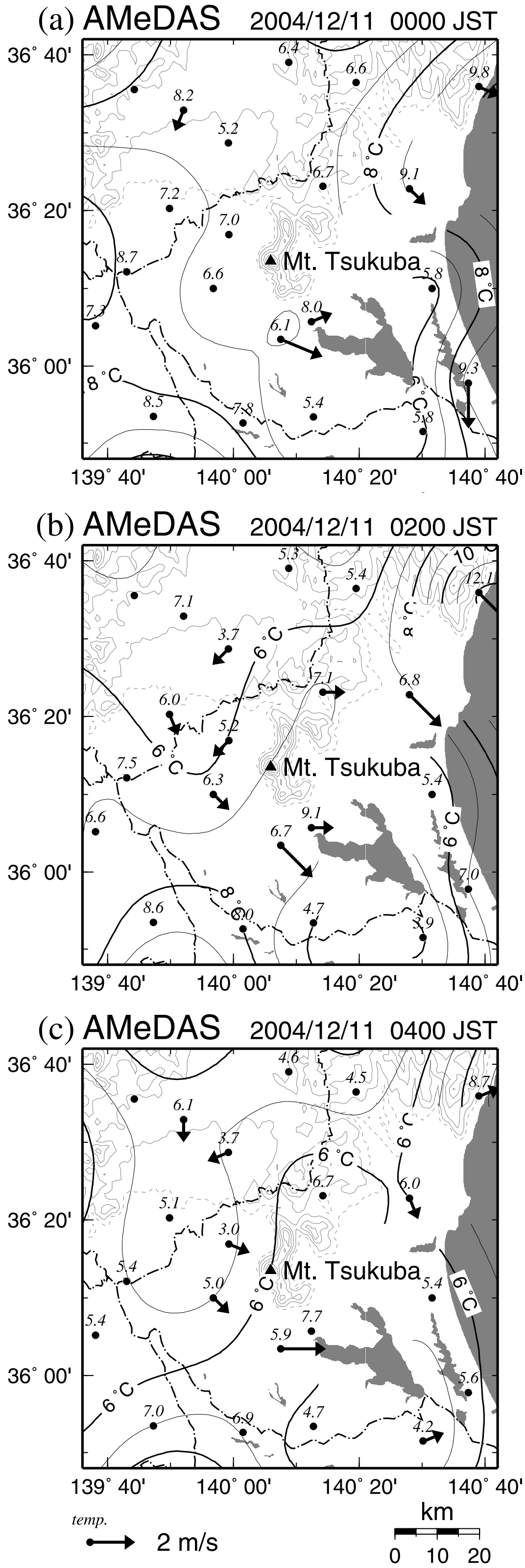

Fig. 7 Spatial distributions of temperature (contour or italic numbers) and wind (vector) at (a) 0000 JST, (b) 0200 JST and (c) 0400 JST on December 11, 2005 around Mt. Tsukuba, illustrated with AMeDAS data.

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