CHARACTERISTICS OF MOUNTAIN WINDS AROUND A VALLEY MOUTH: A CASE STUDY IN THE UPPER COURSE OF THE TAMA RIVER, TOKYO

Masanori KANOU and Takehiko MIKAMI

Abstract To clarify the characteristics of mountain winds around a valley mouth, the local climate in Oume City, Tokyo, was observed. Mountain winds showed seasonal variation in velocity and duration; they developed more readily in cold season, when it is cold and the humidity is low, than in warm season. The diurnal variation of the wind circulation around the valley mouth showed seasonal variation. In the evening, the mountain wind near the valley mouth is replaced by a valley breeze in winter, and by a sea breeze in summer, respectively. As a result of the strong mountain winds in the valley, a neutral layer was formed in the vertical distribution of temperature.

Key words: mountain wind, valley mouth, seasonal variation, water vapor, vertical distribution

1. Introduction

Mountain/valley wind systems develop in valleys on clear days when there is a gentle pressure gradient. During the day, a valley wind blows from the plain toward the valley. Conversely, at night, a mountain wind blows from the valley toward the plain. Since the work of Defant (1951), many studies have examined the circulation systems formed in mountainous areas. In recent years, many have conducted numerical simulations to study the winds that blow inside valleys. For example, McNider and Pielke (1984) simulated the winds that blow down valley slopes, and those that blow in the direction of the valley. By comparing observed and simulated values, they determined that mountain winds develop in valleys. Whiteman *et al.* (1999) observed the local circulation in valleys and examined the relationship with topography, which was formed by thermal effects in the Colorado highlands, in the winter season, using a wind persistence and wind rose. Interestingly, this research found differences between the actual and the predicted locations of winds. The wind blows downstream along the valley in the day, and in the reverse direction at night. This indicates that in some places, the effect of the valley wall slope on the wind is stronger than those of the mountain or valley breezes.

Also, some studies investigated atmospheric phenomena, which occurred in valley in Japan. For example, Kuwagata and Kimura (1995) showed that a boundary layer developed in deep valleys during the day. However, most researches have examined the relationship between mountain winds and cold air drainage, and have reported a relationship between the formation of an inversion layer and mountain winds, at a relatively small scale (*e.g.*, Nakamura and Takayama 1995, 1996). When there is a large temperature inversion in the upstream of the valley, mountain winds blow in the valley. However, Nakamura and Takayama (1995, 1996) only observed wind at two sites, and the valley they studied was relatively shallow (relative elevation: 100 m).

Few studies have used simultaneous multi-point observations to examine how mountain winds blow around valley mouths. Moreover, although Aoyama (1984) described the diurnal variation in mountain winds, the seasonal variation is not clear. In order to consider the effects of mountain winds on the heat island in an urban area located at a valley mouth, it is necessary to clarify the behavior of the mountain winds around the valley mouth. Therefore, this study examined the behavior of mountain winds in a deep valley, including the seasonal variation, by conducting simultaneous multi-point observations around the valley mouth.

2. Meteorological Observations and Data

Study area

Local climatological observations were carried out in Oume City, Tokyo. The locations of the research area and observation sites are shown in Fig. 1. Oume City is located on the western edge of the Musashino Plateau, and is about 50 km west of the center of Tokyo. Here, alluvial fan is formed that slopes gently to the east. The population of Oume City is about 140,000 in 2000. The valley has a very deep V-shape around stations (Sta.) 1 and 2. Station. 1 is located in a deep (relative elevation: 350 m) valley on the western side of the study area. The urban area extends from Sta. 4, located near the valley mouth, towards the southeast. The southeastern part of Oume City is an industrial area. The rural area spreads to the north (near Sta. 12), northeast, and east (near Sta. 11), and there are many paddy fields and tea plantations. Station. 2 is located 300 m apart from the river. Station. 3 is located behind a hill, and Sta. 4 is located to the south of a hill.

Observational data

Field observations were carried out from October 1999 to November 2000. Observations were made for about one month in each season (Table 1). The parameters observed were air temperature, relative humidity, and wind speed and direction. Air temperature and relative humidity data were recorded every ten minutes, using data loggers (SATO Keiryoki Mfg. Co., Ltd. and TABAI ESPEC Co., Ltd.), in instrument shelters at a height of 1.5 m. Wind speed and direction were measured with a sensor (Makino Applied Instruments Inc.), at a height of 13 or 14 m, and recorded every ten minutes.

To determine the vertical air distribution in the valley and near the valley mouth, towersonde observations were conducted at Stas. 1 and 4 on November 5 and 6, 1999. Towersonde is a kite-balloon system, developed by Atmospheric Instrumentation Research, Inc., U.S.A., that observes five meteorological variables (air temperature, relative humidity, wind speed and direction, and air pressure), at different heights, simultaneously. Observations throughout the night were not possible at Sta. 1 because the wind was too

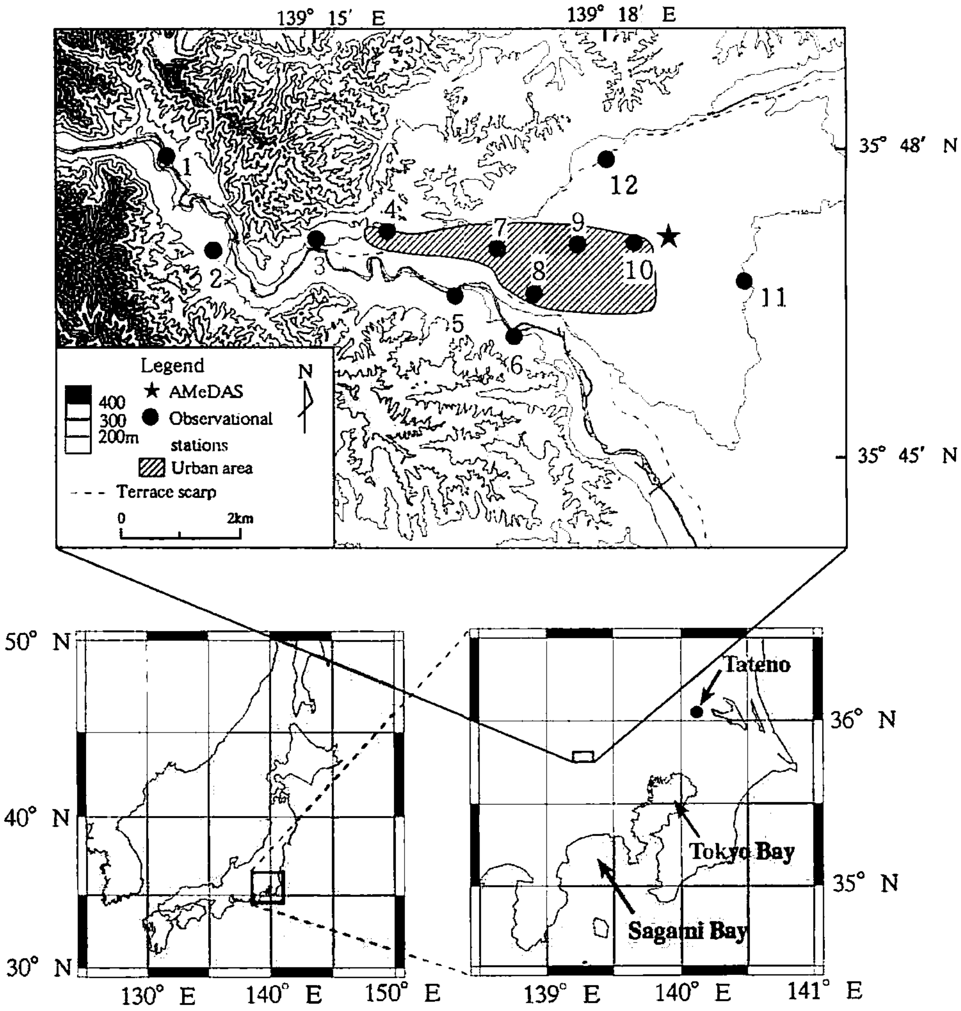

Fig.1 Study area.

strong at night.

3. Characteristics of the Mountain Winds

Seasonal variation

In this study, winds inside the valley that blew from the valley toward the plain were defined as mountain winds. To examine seasonal variation of the mountain winds, we analyzed data for days when 1) the pressure gradient was weak on a synoptic scale, and 2) the wind velocity at 850 hPa was 10 m/s, or less, at Tateno (36°03' N, 140°07' E), which is the closest meteorological observatory to the study area (Fig. 1). In these days, the weather was clear that a valley breeze blew during the day at Sta. 1, and that this changed into a mountain

Table 1 Observational periods and sites

	periods	sites
Spring	2000. 4.19 - 5.31	1 - 11
Summer	2000. 8. 9 - 9. 6	1 - 11
Autumn	1999.10.27 - 11.12	1 - 11
	2000.10.23 - 11.22	1 - 12
Winter	2000. 2. 2 - 3. 7	1 - 11

wind around sunset. Therefore, we calculated the average wind velocity on days that met these criteria at Sta. 1, in each season. Here, the warm season means spring and summer, while the cold season corresponds to autumn and winter.

In each season, the velocity of the mountain wind gradually increased with time, and peaked in the morning (Fig. 2). This characteristic is in agreement with Aoyama (1984). Therefore, the maximum mountain wind occurs in the morning. The frequency of mountain winds throughout the observation period was 41.9% in spring, 44.8% in summer, 34.0% in autumn, and 48.6% in winter. Mountain winds are most frequent in winter and least frequent in autumn. The maximum velocity of mountain winds was about 3.2 m/s in autumn and winter, but only 2.2 m/s in summer and 2.7 m/s in spring.

Temporal variation

Next, we examined the relationship between air temperature and mountain winds in the study area by using the isopleths. The isopleths were drawn using data for days that satisfied the criteria of the previous section.

Figure 3 is a typical example, showing the mountain winds on February 3 and 4, 2000.

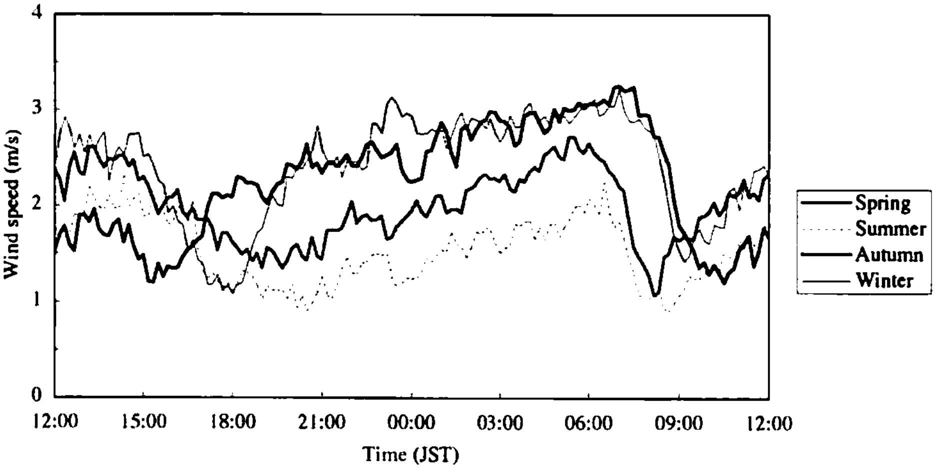

Fig.2 Seasonal variation of mountain wind at Station 1.

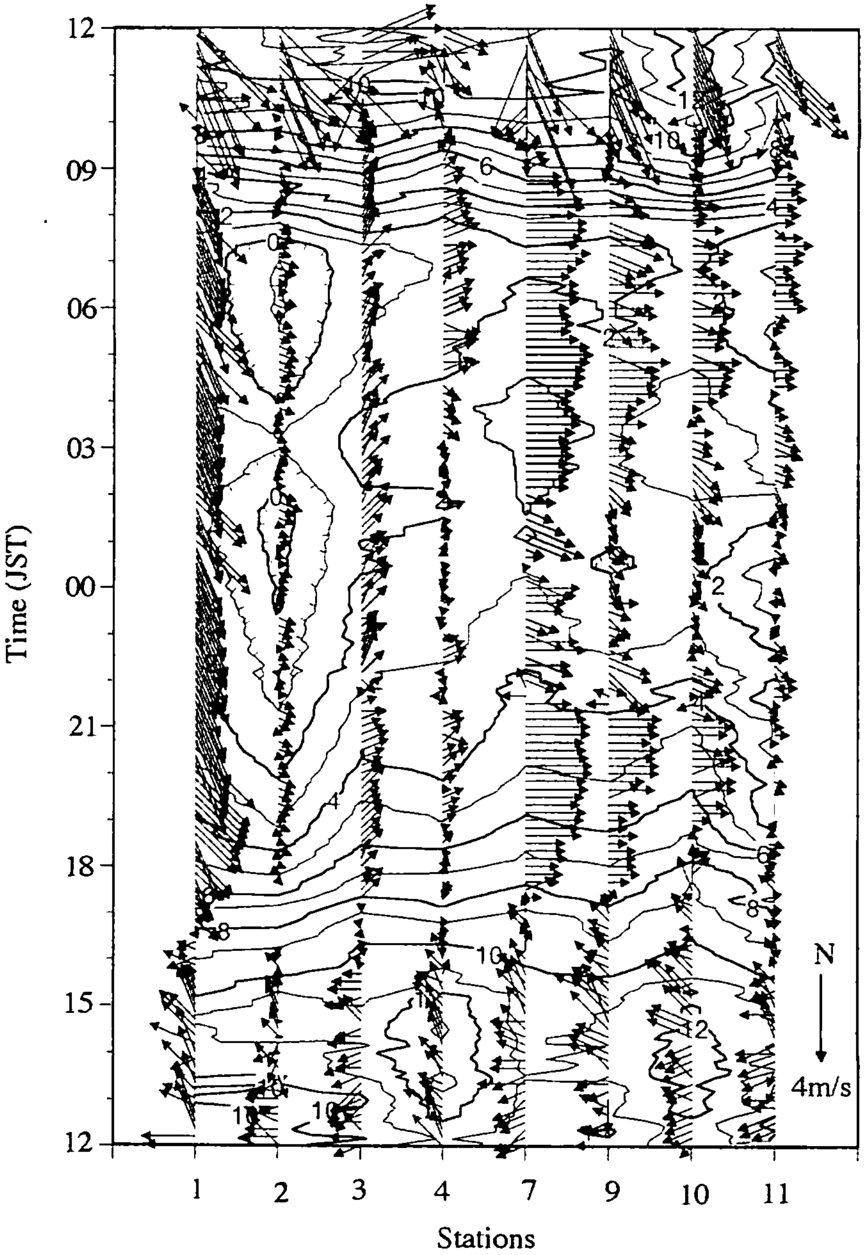

Fig.3 The temporal variation of air temperature and wind in February 3-4, 2000.
The downward arrow indicates the northerly wind. Solid line indicates iso-thermal line, drawn every 1 degree.

During the day, there was a transient southerly wind. For a while, the valley wind blew both in the valley (Stas. 1-4) and on the plain (Stas. 7, 9, 10, and 11). At night, a mountain wind appeared both in the valley and on the plain, although the wind was weak or non-existent throughout the night at Sta. 11, situated in the east of the study area. This pattern of change from a valley wind to a mountain wind on the plain was observed 15 times, which made up approximately half of the cases (33 cases) of mountain winds during the cold season.

Next, we considered the times at which mountain winds blew. At Sta. 1, located in the valley, mountain winds continued from around 18:00 to around 10:00 of the following day. The mountain winds began earlier in the upper valley, and later on the plain. By contrast, there was a little difference in the time when the mountain winds ended. The difference between Stas. 1 and 7 was only 30 minutes. At Sta. 2, which is located far from the river, a southwesterly wind preceded the mountain wind, and a northeasterly wind followed it. This wind system indicates a local circulation on the valley slope southwest of Sta. 2. Namely, a strong wind blew on the valley slopes before the mountain wind began. These winds on the slopes continued after the mountain wind stopped. This concurs with the results of Whiteman *et al.* (1999). However, the circulation system, which was formed on the slope, was collapsed when the mountain wind was blowing inside the valley.

During the day, the isothermal line has a horizontal distribution, indicating that changes of temperature generally occurred almost simultaneously. When a mountain wind began, however, the temperature fall was retarded east of Sta. 7 which tilted the isothermal lines. This tendency was common on nights when mountain winds developed. After sunrise, the temperature rose rapidly. Moreover, the urban area became relatively warm, and a cold area was formed near Sta. 2.

Figure 4 shows a typical example for the warm season, on August 28 and 29, 2000. In summer, the mountain winds were weaker than in winter. The diurnal variation of the wind also differed greatly from that in winter. A strong daytime south wind persisted for three hours after sunset in the plain. According to Kikuchi (1990), the sea breeze recognized from Tokyo and Sagami Bays on the southern Kanto plain in daytime (Fig. 1). The southerly wind observed in the study area appears to be a sea breeze blowing from Sagami Bay. As compared with the cold season, the transition of winds around the valley mouth occurred later in the evening, and earlier in the morning. This difference appeared due to seasonal differences in the duration of sunshine.

In 16 cases of the warm season, the wind in the plain changed from a sea breeze to a mountain wind. This made up approximately half of all (31 cases) when mountain winds blew in the warm season. The changes in air temperature were similar to those in winter. The temperature generally changed simultaneously during the daytime, and the temperature fall was retarded east of Sta. 7 when the mountain wind began. However, the decrease of air temperature was smaller in warm season than in cold season. Relatively warm air was located around Sta. 10 in the plain. The warm area was situated around the valley mouth (around Sta. 4) in winter, and moved east to around Sta. 3 in summer. Simultaneously, relatively cold air was observed in winter at Sta. 2. A regional difference was found with respect to the time when the mountain wind began in the upper reaches. This was observed both in warm season and in cold season.

The mountain wind appeared to induce fluctuations of air temperature. In addition, the

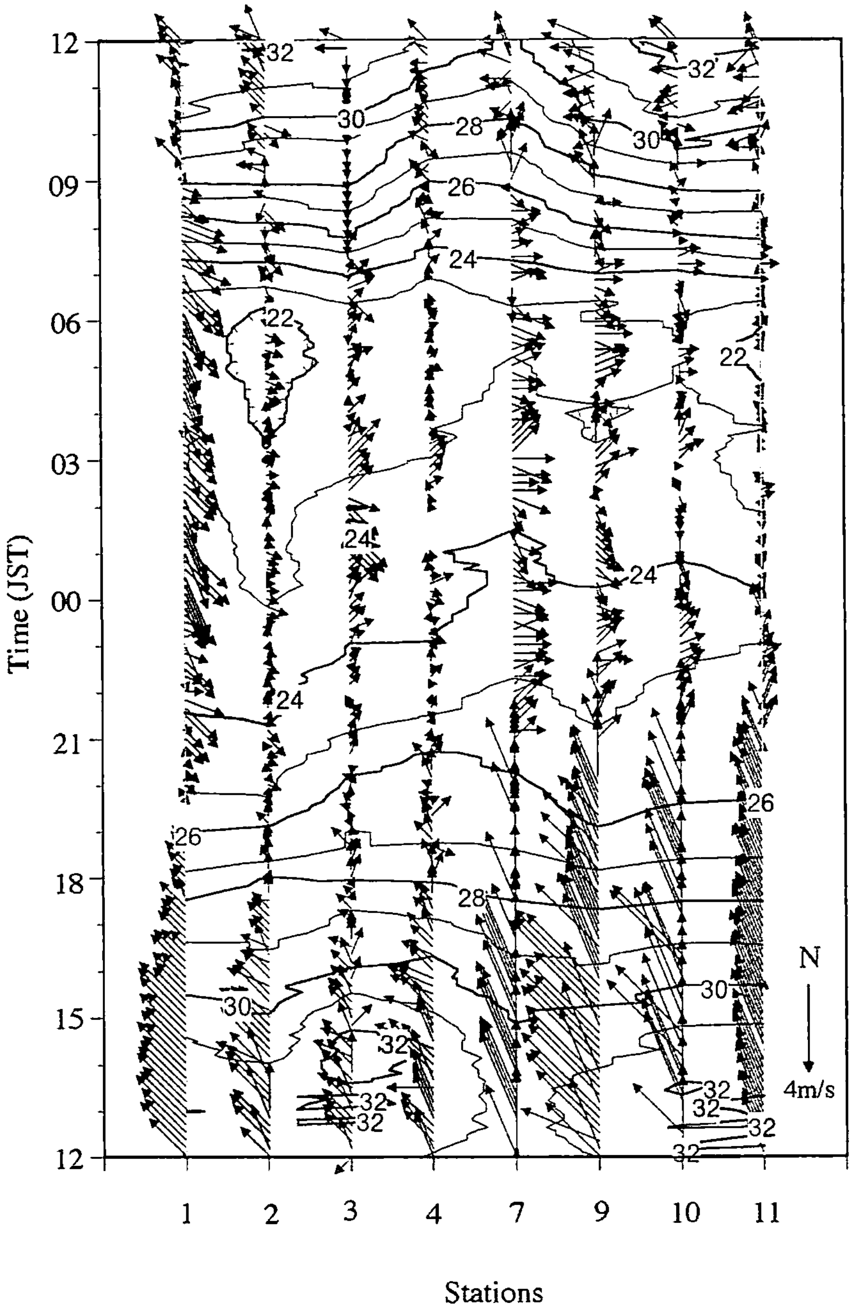

Fig.4 Same as Fig.3 but in August 28-29, 2000.

urban area near Stas. 3 and 4 was relatively warm. The lowest air temperature was found near Sta. 2, which was farther from the river, and the mountain wind was weaker here than at Sta. 1. A temperature inversion was readily generated at Sta. 2, because the mountain wind was weak. If a stable layer was formed with a temperature inversion, this would explain the low air temperatures at Sta. 2. Sato *et al.* (1994) observed the horizontal distribution of air temperature in this area by mobile observation, by which they obtained similar results.

Regional differences of the mountain winds

When a mountain wind blows from the valley mouth to the plain, it is not clear whether the wind continues to blow in the direction of the valley or whether it diverges. We considered this question using data for the autumn of 2000. Figure 5 shows a typical mountain wind on November 4 and 5, 2000. The wind continued at Stas. 8 and 9 throughout the night. By contrast, the wind was very weak at Sta. 6, located on the Tama River, and at Sta. 12, located in the north. Similar nighttime observations were conducted when the weather conditions met the criteria which were defined in Section 3: the observations indicate that when the mountain wind enters the plain, it continues to blow in the direction of the valley.

4. Seasonal Variation of Water Vapor Pressure

Figure 2 shows the seasonal variation of the mountain wind blowing in the valley. The mountain winds resulted from cold air that was formed on the valley slopes. Seasonal variation of the factors regulating atmospheric cooling should explain the seasonal variation in the velocity of the mountain wind. Kondo (1994) pointed out that the humidity of the atmosphere is one of the factors regulating the cooling of air. When the humidity is high, radiative cooling is weak.

Therefore, we examined the seasonal average humidity in the valley. The seasonal average water vapor pressure was calculated using the air temperature and relative humidity at Sta. 1 on days when mountain winds were clearly recognized (see Section 3). Figure 6 shows the seasonal variation of water vapor pressure at Sta. 1: the lowest values occurred in winter and the highest in summer. This trend almost paralleled the seasonal variation in mountain wind velocity (Fig. 2). Therefore, the development of mountain winds is related to the amount of water vapor in the atmosphere. Moreover, the diurnal variation of the water vapor pressure showed seasonal trends. The water vapor pressure increased around sunset, and then decreased over time.

The weak mountain winds in summer resulted from the high water vapor pressure, which controlled radiative cooling of the atmosphere. Conversely, radiative cooling is more rapid in winter, when the atmospheric water vapor pressure is low. Therefore, mountain winds are very strong in winter.

In addition, Iijima and Shinoda (2000) reported that the water vapor pressure is high in the mountains of central Japan in summer. When the wind was weak on a synoptic scale, the circulation caused water vapor to converge in this area, which weakened the radiative

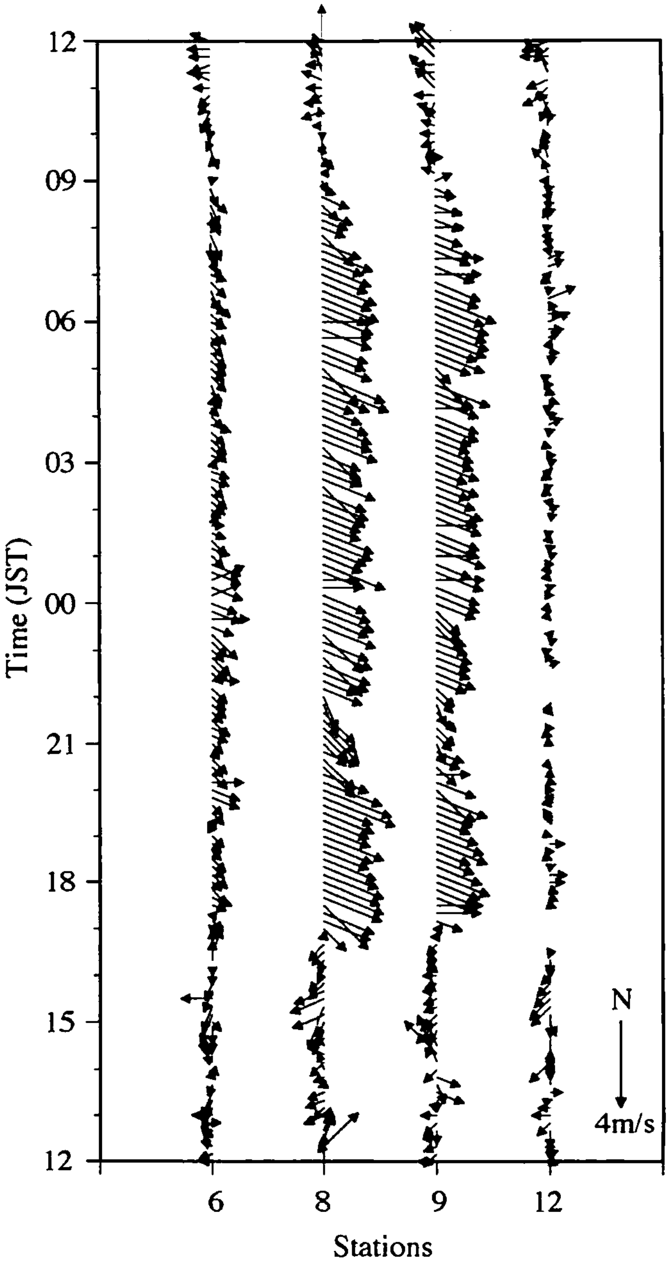

Fig.5 Regional difference of the mountain wind (November, 4 – 5, 2000). The downward arrow indicates the northerly wind.

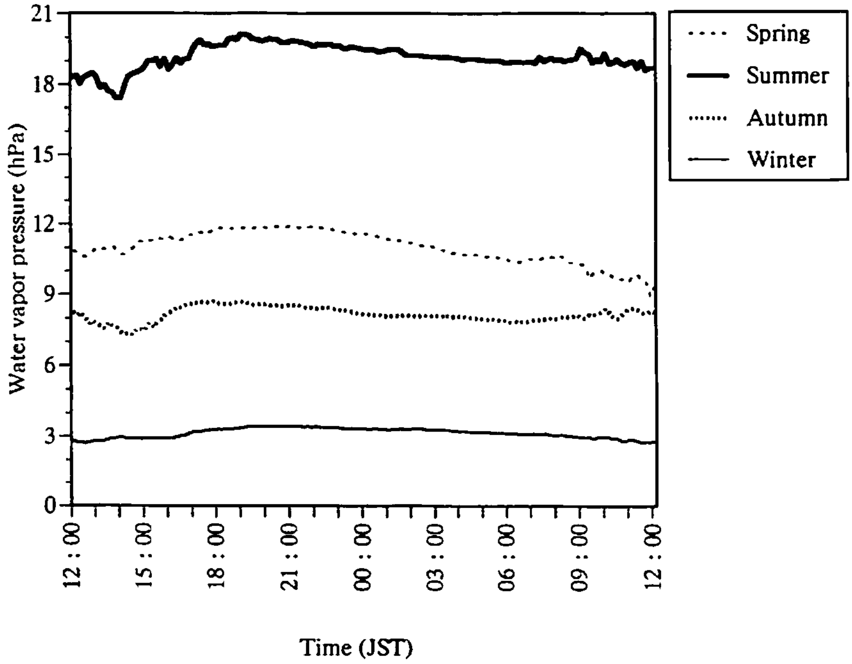

Fig.6 Seasonal variations of water vapor pressure at Station 1.

cooling. By contrast, the absolute water vapor pressure in the atmosphere was very low in winter, even if there was convergence of flows formed with local circulation. Thus, there were seasonal differences in atmospheric cooling. In summer, the water vapor content in the study area increased as a result of sea breezes from Sagami Bay, weakening mountain winds in this area.

These facts imply that the water vapor content affects radiative cooling of the air, resulting in seasonal variation of mountain winds. The mountain winds are weak when the absolute vapor content is high, and strong when it is low.

5. Seasonal Variability in the Duration of Mountain Winds

Urfer-Henneberger (1970) found that, in 90% of cases or larger, the transition from mountain wind to valley wind occurred within one hour. Reiter *et al.* (1983) compared the start times of valley winds at a valley mouth and those in the valley. A stable layer in the valley delayed the start of a valley wind.

In this section, we discuss the duration of mountain winds and its seasonal variation. The criteria used to determine mountain winds were defined in Section 3. The duration and seasonal variation of mountain winds at each site were compared. Figure 7 shows the average times when mountain winds started, and ended, in each season for Sta. 1 (valley), Sta. 3 (valley), Sta. 7 (valley mouth), and Sta. 10 (plain). This figure shows that the duration of mountain winds changed each season, especially at the eastern site which is located to the

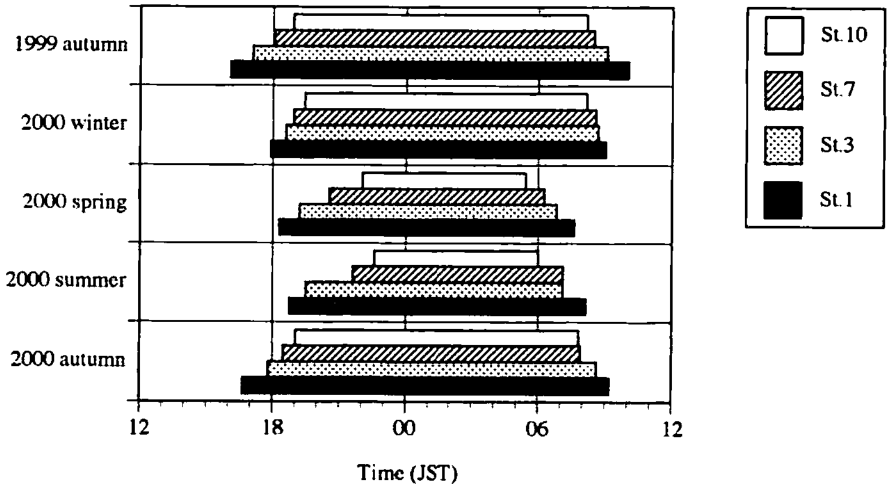

Fig.7 Duration hours of mountain wind in valley and around valley mouth.
(Valley: Station 1, Valley mouth: Stations 3 and 7, Easterly part: Station 10)

leeward (Stas. 7, 10). The winds lasted longer in winter and shorter in summer. The start times at the sites differed by 1.5 to 3 hours, while the end times differed by 0.5 to 1.5 hours. At Sta. 10, which is located in the plain, the start of the mountain wind delayed by about 3.5 hours in summer, as compared with Sta. 1. The duration of the mountain winds at each station differed by 2 to 4 hours. During the cold season, the differences of the start and end times among the sites were smaller than those in summer.

6. Vertical Distribution of Temperature and Wind within the Valley

We observed the vertical distribution of temperature and wind in the valley on November 5 and 6, 1999, at Sta. 1 (valley), and at Sta. 4 (valley mouth). It was only possible to carry out synchronous observations at the two sites immediately after sunset, because the wind was very strong in the valley. Figure 8 shows the vertical distribution of potential temperature and wind at Stas. 1 and 4.

Immediately after sunset, at 17:02, a northwesterly mountain wind was recognized at Sta. 1 from the ground (224 m ASL [above sea level]) to around 330 m ASL. Although the wind near the ground was weak, the mountain wind began at around 240 m ASL, at Sta. 4. At 17:30, the mountain wind began to blow near the ground at Sta. 4, while a strong southeasterly wind still existed in the upper layer. At 18:00 a very strong WNW wind was found at Sta. 1, which exceeded 5 m/s, while the southeasterly wind in the upper layer, at Sta. 4, weakened at this time.

In the vertical profile of potential temperature from 17:00 to 18:00, the potential temperature at Sta. 4 were 1~2°C higher than those at Sta. 1. At Sta. 1, a boundary layer was found at 300 m ASL, and an inversion was generated: the lower layer was 1~2°C cooler than the upper layer. Moreover, the wind direction differed in the two layers. Landforms

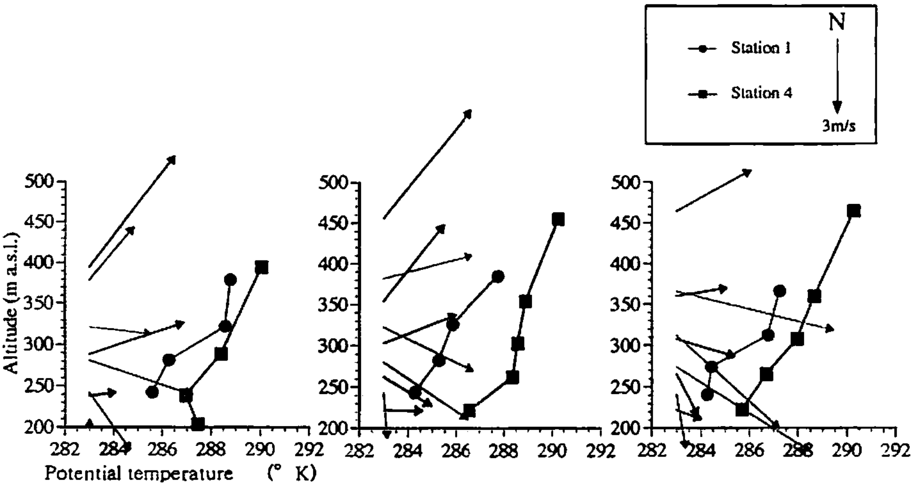

Fig.8 Vertical profiles of potential temperature and wind at Stations 1 and 4 (November 5, 1999). The downward arrow indicates the northerly wind.

near Sta. 1 probably caused katabatic drainage from the valley north of Sta. 1 to the lower layer at Sta. 1.

The vertical profiles of potential temperature, specific humidity, and wind at Sta. 4 are shown in Fig. 9. After sunset, a westerly wind generally prevailed at Sta. 4. Before midnight, the prevailing wind shifted to northerly and this wind continued until early morning at heights greater than 350 m ASL. This altitude corresponds to the top of the nearby topographical ridge. The temperature and humidity also differed at the boundary formed at this height. The air temperature within the valley was lower than that of the region above the level of the valley, and the vertical distribution of air temperature within the valley was uniform. It was clear that vertical mixing resulted from the very strong wind within the valley. This is quite different from the result of Whiteman (1982), who observed an inversion layer throughout the entire valley. The difference may be caused by the size of the valley. Namely, Whiteman (1982) studied a big valley (relative elevation: 700 m), while we studied a small one (relative elevation: 300 m). The inversion layer was formed at the bottom of the large valley, indicating that mountain winds are less likely to blow in an inversion layer. By contrast, a mountain wind blew throughout the valley in our study area because there was no inversion layer in the valley.

The specific humidity also changed with height, and affected the air temperature. The specific humidity was greater in the valley than that above the level of the valley. The specific humidity temporarily decreased before midnight, and then increased again before sunrise. The vertical distribution of specific humidity remained stable throughout the night. These observations indicate that the mountain winds in the valley regulate the vertical distribution of air temperature and specific humidity.

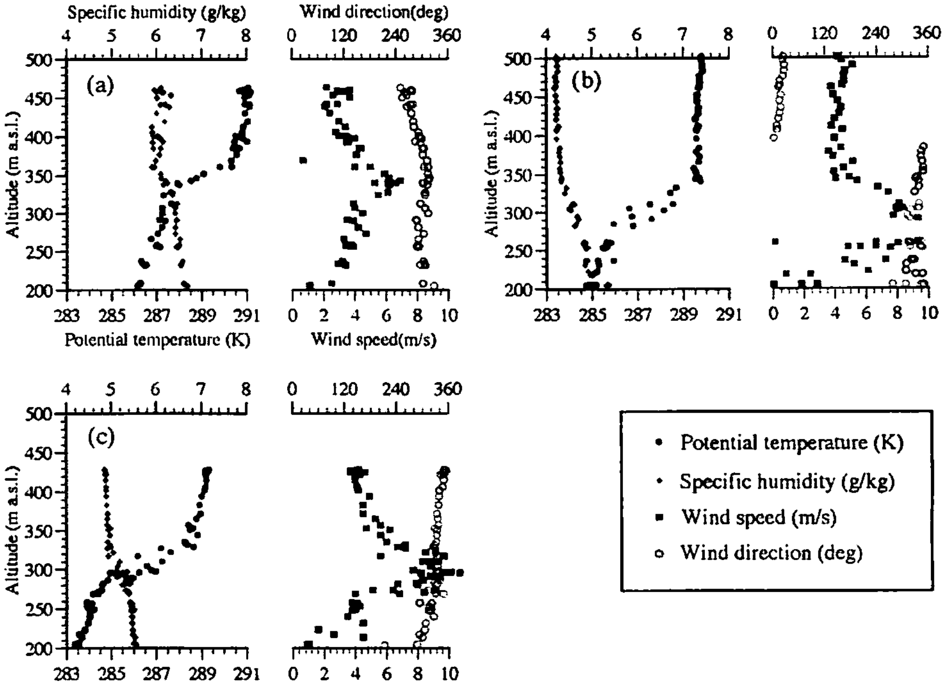

Fig.9 Vertical profiles of air temperature, specific humidity and wind at Station 4 (November 5-6, 1999 (a) 18:55-19:19, (b) 22:55-23:24, (c) 04:35-04:54). 0 (360) degrees show the north.

7. Concluding Remarks

We found the followings:

1. In the valley, mountain winds blew at night. The local circulation around the valley mouth changed seasonally, from easterly to westerly winds in cold season, and from southerly to westerly winds in warm season.
2. In comparison with warm season, the transition of winds occurred earlier in the evening and later in the morning.
3. The air temperature variations at night near the valley mouth stations differed from one another. Radiative cooling began earlier in the valley than it did at the east of the valley mouth.
4. The mountain wind velocity was strong in winter, and lasted longer than in summer. There appeared to be a relationship between the development of mountain winds and water vapor in the atmosphere.
5. Strong mountain winds in the valley produced a uniform vertical distribution of atmospheric temperature. The temperature at Sta. 4, which was located in an urban area, was higher than that at Sta. 1.

Acknowledgments

We would like to express our thanks to the Department of Geography. Tokyo Metropolitan University and many other people for helping us during the field observations. A part of this study was reported at the annual meeting of the Association of Japanese Geographers. in March 2000 and 2001.

References

Aoyama. T. 1984. On the development processes of the ground inversion and the nocturnal wind system in Inawasiro Basin, Northeast Japan. *Bull. Yamagata Univ., Nat. Sci.* **11**: 109-119. **

Defant. F. 1951. Local winds. In *Compendium of Meteorology*, ed. T. F. Malone. 655-672. Boston: *Amer. Meteor. Soc.*

Iijima. Y., and Shinoda. M. 2000. Seasonal changes in the cold-air pool formation in a subalpine hollow, central Japan. *Int. J. Climatol.* **21**: 1471-1483.

Kikuchi, R. 1990. Areal classification according to the diurnal change of wind in summer in southern Kanto. *Ann. Tohoku Geogr. Assoc.* **42**: 59-72.

Kondo, J. ed. 1994. *Meteorology of the Water Environment -Water and Heat Balance of the Earth's Surface-*. Tokyo: Asakura Shoten. *

Kuwagata, T. and Kimura, F. 1995. Daytime boundary layer evolution in a deep valley. Part I : Observations in the Ina valley. *J. Appl. Meteor.* **34**: 1082-1091.

McNider, R. T., and Pielke R, A. 1984. Numerical simulation of slope and mountain flows. *J. Climate Appl. Meteor.*, **23**: 1441-1453.

Nakamura, K., and Takayama, H. 1995. Characteristics of mountain winds in the upper and middle course of the Obitsu River. *J. Env. Studies* **3**: 105-112. **

Nakamura. K.. and Takayama. H. 1996. Characteristics of mountain winds in the upper and middle course of the Obitsu River (2). *J. Env. Studies* **4**: 45-56. **

Reiter. R., Müller, H.. Sladkovic. R.,und Munzert, K. 1983. Aerologische Untersuchungen der tagesperiodischen Gebirgswinde unter besoderer Berückssichtigung der Windfeldes im Talquerschnitt. *Meteor. Rdsch.* **36**: 225-242. ***

Sato, N., Kanou. M.. and Ogawa. N. 1994. An investgation into the urban heat island in Oume City. Tokyo. *Japanese Progress in Climatol.* 1994. 89-98.

Urfer-Henneberger. C. 1970. Neure Beobachtungen über die Entwicklung des Schöwetterwindsystems in einem V-förmigen Alpental (Dishmatal bei Davos). *Arch. Meteor. Geoph. Biokl.*. **18B**: 21-42. ***

Whiteman, C. D. 1982. Breakup of temperature inversions in deep mountain valleys: Part 1. Observations. *J. Appl. Meteor.* **21**: 270-289.

Whiteman, C. D.. Bian. X., and Sutherland, J. L. 1999. Wintertime surface wind pattern in the Colorado river valley. *J. Appl. Meteor.* **38**: 1118-1130.

(* : in Japanese. ** : in Japanese with English abstract. *** : in German with English abstract)