LOCAL CLIMATOLOGICAL STUDY OF THE NOCTURNAL COLD AIR DRAINAGE ON THE MOUNTAIN SLOPE

by

Keizo NAKAMURA

Submitted in partial fulfillment of the requirements for the degree of Doctor of Science in Doctoral Program in University of Tsukuba

Ibaraki

Japan

June 1983

ABSTRACT

This study is concerned with the cold air drainage which occurs and flows down on the mountain slope at night. In order to make clear the characteristics of the cold air drainage, thirteen micrometeorological observations were carried out since 1973 on the mountain slopes in Sugadaira, Nagano Prefecture and in Engaru, Hokkaido.

In this study, new parameters introduced in order to perceive the source and the drainage areas of cold air. The one of these is "the degrees of inversion", and the other is "the vertical difference of cooling". The study involves two kinds of the analyses of observation data. Firstly, the formation process of ground inversion layer on the slope is analyzed in detail by using these new parameters in addition to net radiation and other data, so that the source and the drainage areas of cold air can be grasped accurately. Secondly, for the understanding of the whole aspect of cold air drainage, the vertical structure of cold air drainage on the mountain slope is described in terms of air temperature, horizontal and vertical wind velocities, and wind direction.

From the micrometeorological observations, from which the general characteristic natures of cold air drainage were grasped, it was found that the cold air drainage is

defined as the air flow having following characters: The relation between air temperature and wind velocity is negatively correlated, and the wind directions converge within $\pm 45^\circ$ of the mean direction, which coincides with the direction of maximum inclination of the slope. On the source area of cold air drainage, the wind velocity is found to be positively correlated with air temperature and to be negatively correlated with "the degrees of inversion".

From the observations on the slope of Mt. Ômatsu (1,648.7 m), Sugadaira, it was found that the ground inversion area is strongly formed on the middle part of the slope of this mountain, so that the cold air drainage occurs within this area of this slope. At night on August 20, 1976, the cold air originated near the point which is 1,320 m a.s.l. and flowed down toward the downward of the slope.

On the mountain slope in Engaru, the downslope wind and the anti-downslope wind were observed. Also, for the air flow of the slope of Mt. Ômatsu, the detail structure of nocturnal air circulation was made clear. From these, it was concluded that the cold air drainage which originates in the ground inversion layer on the middle part of the slope turns its direction to the upward when it attains to upper surface of cold air lake.

Finally, on the basis of these conclusions, the model of nocturnal cold air drainage on the mountain slope was obtained.

CONTENTS

LIST OF FIGURES vii

LIST OF TABLES xii

CHAPTER 1. INTRODUCTION 1

1.1. Purpose of This Study 1

1.2. Literature Review 2

1.2.1. Radiative Cooling 2

1.2.2. Ground Inversion 4

1.2.3. General Characteristics of Cold Air Drainage 6

1.2.4. Velocity of Cold Air Drainage 9

1.2.5. Cold Air Lake and Nocturnal Air Circulation on the Mountain Slope 11

CHAPTER 2. OBSERVATION 18

2.1. Physiographic Outline of the Observation Area 18

2.2. Observation Methods and Weather during the Observations 23

CHAPTER 3. VELOCITY AND TEMPERATURE OF COLD AIR DRAINAGE 34

3.1. General Characteristics of Velocity and Temperature of Cold Air Drainage 34

3.1.1. Relation between Air Temperature and Wind Velocity at Clear, Calm Night 34

3.1.2. Wind Direction and Vertical Distribution of Wind Velocity 38

3.1.3. Definition of Cold Air Drainage and Its Occurrence Frequency 42
3.1.4. Occurrence Periods of Cold Air Drainage 44
3.1.5. Change of Horizontal Distribution of Air Temperature in Association with Cold Air Drainage 48
3.2. Relation between Flowing Distance and Velocity of Cold Air Drainage 52
3.2.1. At the Snow Field 53
3.2.2. At the Cultivated Field 58
3.2.3. Comparison with the Other Empirical Equation 58
3.3. Synoptic Conditions for Cold Air Drainage 61
3.3.1. Relation between Meso-scale Pressure Conditions and Cold Air Drainage 62
3.3.2. Relation between Vertical Air Conditions and Cold Air Drainage 64
3.4. Summary for Chapter 3 70
CHAPTER 4. SOURCE AREA AND DRAINAGE OF COLD AIR 74
4.1. Source and Drainage of Cold Air on the Slope of Mt. Omatsu 74
4.1.1. Air Temperature and Ground Inversion 74
4.1.2. Source and Drainage Areas of Cold Air 79
4.2. Radiative Cooling and Ground Inversion on the Slope of Mt. Ômatsu 87
4.2.1. Economical Net Radiometer 87

4.2.2. Relation between Net Radiation and Air Temperature 91
4.2.3. Relation between Net Radiation and "The Degrees of Inversion" 95
4.2.4. "The Vertical Difference of Cooling" 97
4.3. Summary for Chapter 4 100
CHAPTER 5. VERTICAL STRUCTURE OF COLD AIR DRAINAGE 104
5.1. Vertical Structure of Cold Air Drainage on the Mountain Slope in Engaru 105
5.2. Vertical Structure of Cold Air Drainage on the Slope of Mt. Ômatsu 108
5.2.1. The Case of August 25, 1980 109
5.2.2. The Case of August 28, 1980 115
5.3. Summary for Chapter 5 122
CHAPTER 6. CONCLUSION 124
6.1. Summaries of the observed Results 124
6.2. Conclusion : A proposed Model 128
ACKNOWLEDGEMENTS 141
REFERENCES 142

LIST OF FIGURES

Fig. 1.1 Model of nocturnal air circulation at Ôchô (Mano, 1953).

1.2 Model of nocturnal air circulation on the slope of Mt. Bandai (Mano, 1956).

1.3 Model of nocturnal air circulation on the gentle slope of Kokchetavska, U.S.S.R. (Vorontsov, 1958).

1.4 Model of wind circulation on a clear calm night on the small island, Hakatajima (Kimura, 1961).

2.1 Topographical map of the Sugadaira region.

2.2 Location map of the observed stations on the slope of Mt. Neko.

2.3 Location map of the observed stations on the slope of Mt. Ômatsu.

2.4 Topographical map of the Engaru region.

3.1 Location map of the observed stations on the lower part of the slope of Mt. Neko during the period from August 1973 to September 1975.

3.2 Variations of air temperature and wind velocity observed at heights of 1.0 m and 2.0 m above the ground at a station (Staion No. 6) located on the lower part of the slope of Mt. Neko on August 19 - 20, 1973.

Fig. 3.3 Relation between air temperature falling (ΔT) and wind velocity (U) at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on August 19 - 20, 1973.

3.4 Wind roses of cold air drainage on the gentle slope of Mt. Neko during the time from 21 h 00 m to 24 h 00 m on May 29, 1974.

3.5 Transitions of vertical distribution of wind velocity from the onset to the finish of cold air drainage on the slope of Mt. Neko during the times from 19 h 03 m to 19 h 11 m on May 29 and from 03 h 25 m to 03 h 57 m on May 30, 1974.

3.6 Frequency of cold air drainage on clear, calm nights obtained at a station (Station No. 6) located on the lower part of the slope of Mt. Neko in August 1973.

3.7 Regional differences of the periods of the temperature and the velocity of cold air drainage on the slope of Mt. Neko during the time from 21 h 00 m to 24 h 00 m on May 29, 1974.

3.8 Relation between the peak value of the velocity of cold air drainage and the time after sunset at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on August 12 - 13, 1973.

3.9 Appearance of warm area on the slope of Mt. Neko on May 29 - 30, 1974.

3.10 Transformations of the whole appearance type of warm areas with time on the slope of Mt. Neko on May 29, 1974.

Fig. 3.11 Variations of air temperature and wind velocity at a station (Station C) located on the lower part of the slope of Mt. Neko on December 26 - 27, 1973.

3.12 Relation between α and U_b at a station (Station B) located on the lower part of the uniform slope of Mt. Neko during the time from 7 h 30 m to 8 h 30 m on December 27, 1973.

3.13 Relation between the flowing distance and the velocity of cold air drainage on the slope of Mt. Neko on December 27, 1973 and May 29, 1974.

3.14 Variations of air temperature and wind velocity at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on May 29 - 30, 1974.

3.15 Relation between the deviation of sea level pressure and the drainage time of cold air in Sugadaira.

3.16 Vertical conditions of pressure gradient, wind velocity, air temperature and relative humidity for the drainage time of cold air.

3.17 Relation between relative humidity at the 700 mb level at Wajima and drainage times of cold air on the slope of Mt. Neko during the period from August 1973 to September 1976.

4.1 Isopleths of air temperature on the slope of Mt. Ômatsu at nights on August 19 and 20, 1976.

Fig. 4.2 Isopleths of "the degrees of inversion" on the slope of Mt. Ômatsu at nights of August 18 - 20, 1976.

4.3 Transition of ground inversion on the slope of Mt. Ômatsu at night on August 20, 1976.

4.4 Variations of air temperature and wind velocity on the slope of Mt. Ômatsu at night on August 20, 1976.

4.5 Comparison of air temperature at the three Stations on the slope of Mt. Ômatsu at night on August 20, 1976.

4.6 Construction of economical net radiometer.

4.7 Comparison of the accuracy of economical net radiometer used at a station (Station No. 3) located on the middle part of the observation slope of the Mt. Ômatsu withe that of standard net radiometer.

4.8 Variation of net radiation on the slope of Mt. Omatsu on July 30, 1978.

4.9 Relations between net radiation and air temperature on the slope of Mt. Ômatsu at night on July 30, 1978.

4,10 Relation between net radiation and "the degrees of inversion" on the slope of Mt. Ômatsu at night on July 30, 1978.

4.11 Distribution of "the vertical difference of cooling" on the slope of Mt. Ômatsu at night on July 30, 1978.

Fig. 5.1 Wind direction profile and circulation system on the mountain slope in Engaru at night on July 21 - 22, 1979.

5.2 Air temperature profile on the mountain slope in Engaru at night on July 21 - 22, 1979.

5.3 Cross-section analysis of wind along the slope of Mt. Ômatsu at night on August 25, 1980.

5.4 Estimated circulation system on the slope of Mt. Ômatsu at night on August 25, 1980.

5.5 Temperature profile on the slope of Mt. Ômatsu at night on August 25, 1980.

5.6 Temperature profile and circulation system on the slope of Mt. Ômatsu at night on August 25, 1980.

5.7 Cross-section analysis of wind along the slope of Mt. Ômatsu at night on August 28, 1980.

5.8 Estimated circulation system on the slope of Mt. Ômatsu at night on August 28, 1980.

5.9 Temperature profile on the slope of Mt. Ômatsu at night on August 28, 1980.

5.10 Temperature profile and circulation system on the slope of Mt. Ômatsu at night on August 28, 1980.

6.1 Model of nocturnal cold air drainage on the mountain slope.

LIST OF TABLES

Table 2.1 List of observations.

2.2 Weather of observation periods.

3.1 Seasonal variations of the period and the range of fluctuation of cold air drainage on the slope of Mt. Neko.

3.2 Occurrence frequency of pressure patterns in Central Japan during the nights when cold air flows down on the slope of Mt. Neko.

6.1 Model of nocturnal cold air drainage on the mountain slope.

6.2 Characteristics of the cold air drainage.

CHAPTER 1. INTRODUCTION

1.1. Purpose of This Study

The air layer near the ground on the slope grows cold on clear and calm nights. When the air layer becomes colder than that in the free atmosphere at the same height, the cold air on the slope begins to move to a topographically lower place due to the gravity (Schnelle, 1956; Shôno, 1958; Baumgartner, 1963; Geiger, 1961, 1965; Munn, 1966; Yamamoto, 1976; Yoshino, 1975, 1980). This is called cold air drainage, cold air current, cold air flow, cold air run-off or cold air stream. The terms gravity wind or microadvection (Szász, 1964) also indicate the same cold air motion (Yoshino, 1980).

The cold air down flow formed by gathering of the cold air drainage on the respective slopes in upper tributaries and developed more largely is called downslope wind or Katabatic wind. They become the mountain wind in the middle and lower courses of valley and then become the land breeze on the coastal region (Yoshino, 1975). Lawrence (1954) gave the general name, nocturnal wind, to Katabatic wind and land breeze.

This study deals with the phenomenon that is called cold air drainage. The mechanism of the development of the cold air drainage is explained as mentioned above. The cold air drainage, however, has not been defined accurately. Therefore, it is difficult to determine that the observed air flow is either the cold air drainage, which grows cold and flows down on the slope, or the air stream which comes over the mountain. It is considered that for the definition of the cold air drainage, the drainage state of cold air should be observed continuously at night and the general natures for the meteorological elements of cold air drainage should be made clear by the detail analysis of the results.

The purpose of this study is first to express quantitatively the natures of the cold air drainage. From this result, the cold air drainage may be accurately defined. The second part is to make clear the source area and drainage area of cold air from the analysis of formation process of ground inversion layer on the slope. This is essential to elucidation of the mechanism of the cold air drainage. The third part is to make clear the whole aspect of cold air drainage from the vertical structure of air layer on the mountain slope. Finally, a model of nocturnal cold air drainage on the mountain slope is drawn.

These are main purposes of this study.

1.2. Literature Review

1.2.1. Radiative Cooling

Lake (1956) found that there is the minimum on the temperature profile between 1.5 and 6.0 in. heights above the surface of bare soil, and he thought that direct radiation loss from the air layer is important factor in determing the temperature distribution from the result. In order to explain such a cooling phenomenon, Rikitake (1962) estimated the amount of radiative cooling in the cold air layer in consideration of the reflectivity on the ground surface to the long wave radiation. As the results, it is found that the larger the reflectivity on the ground surface is, the larger the amount of radiative cooling in the air layer near the ground is.

Since radiative cooling rates are generally found to be higher than actual rates, development of the nocturnal inversion near the surface is shown to be predominantly caused by radiation with eddy cooling which is replaced in the lowest layers by eddy warming (Funk, 1960). Further, from the results obtained for the nocturnal cooling in the wheat plants, Saito (1966) reported that the calculated radiative cooling is about 6 times as large as the actual temperature falling. It can be considered that the phenomenon is caused by the heat transfer by turbulence at night.

The radiation chart for the radiative heat transfer of atmosphere was shown by Elsasser (1942), Robinson (1947), Yamamoto (1952, 1954) and other investigaters. However, these charts are not suitable for the application to the air layer near the ground. Therefore, Azuma (1957) calculated the rates of air temperature variation (dT/dt) by use of the equation of thermal conduction which has the gradient of emissivity ($d\varepsilon/du$) in air layer as a variable. The emissivity in this equation was calculated in detail in consideration of the effect of CO_2 on radiation which Deacon (1950) investigated. From the result, it is found that the radiative cooling in the air layer near the ground is effected hardly by the air layer more than 10 m height above the ground, and that it mainly depends on the air condition near the ground. Oke (1970) observed the temperature profile over grass, snow and bare soil surfaces at calm and clear nights. He pointed out that the height from the surface and the intensity of the minimum temperature are strongly correlated with wind velocity, surface roughness and stability.

1.2.2. Ground Inversion

It is considered that ground inversion layer reaches the height that the action of radiative cooling is effecting, and that the cold air drainage is a part of the phenomena in it.

The thickness of the inversion layer in the basin was 50 - 80 m, but on the coast it was about 200 m, according to the observation results at Ôchô villege of Ôsakishimojima Island in the Inland Sea (Setouchi), SW-Japan. The height of the inversion top changes with the time elapsed during the night. The top of inversion layer had a height of 200 m at 20 h 00 m, 90 m at 23 h 40 m and 80 m at 5 h 00 m during the night of December 3 - 4, 1949, in the valley on Ôchô Island (Mano, 1953). Aerological observations of the lower atmosphere were made on the gentle slope of relative elevation 110 m in Tsrikovka Village, the Aruik-Baluiksky region of Kokchetavska, Kazakh SSR, U.S.S.R. in summer, 1955 and 1956 (Vorontsov, 1958). From the results, the ground inversion which is observed under the very dry conditions at the night of june 19 - 20, 1955, begins to be formed from the lower part of the slope at 19 h 24 m, 50 minutes before sunset, and it is formed on the whole slope immediately after sunset. The ground inversion layer is generally dissipated in a short time after sunrise. However, MacHattie (1970) reported that an inversion of 3°F in daily maximum temperature was found in the first 300 ft above the valley bottom in Kananaskis valley in Rocky Mountain, Canada. He thought that this is attributed, with reason, to a difference in evaporation between slope and valley bottom.

Generally, it is said that the occurrence frequencies of inversion layer is high in winter and low in summer (Masatsuka, 1949; Baynton et al., 1965; Yoshino et al., 1981, 1982). According to the result observed at two stations having an altitude difference of 250 m in the basin of Hokkaido, the intensity of ground inversion in midwinter is bigger than that in snow-melting season (Ishikawa and Ishida, 1973 a, 1973 b; Ishikawa, 1977).

1.2.3. General Characteristics of Cold Air Drainage

According to the aforementioned Vorontsov's (1958) observation, the cold air on the gentle slope began to flow down toward the lower part of the slope before 40 - 50 minutes from sunset. This corresponds to the fact that inversion layer is formed on the lower part of the slope before about 50 minutes from sunset. After then, cold air drainage develops on the whole slope, and disappears after 30 - 40 minutes from sunrise on the SE-facing slope and directly after sunrise on the N-NE-facing slope. Furthermore, in the Red Butte Canyon in the Wasatch Range of Northern Utah, U.S.A., the thin film of cold air is formed at 1 - 2 hours before sunset, the wind direction of the air stream in the canyon clearly shifts from upward to downward within about 10 minutes before and after sunset (Thompson, 1967).

It was reported by Nitze (1936), Mano (1953, 1956) and other investigators that the cold air observed at night flows down intermittently. Studying such phenomenon, Küttner (1949) concluded that the instability overcomes the roughness because of the rhythmical alternation of the air-avalanche. Moreover, from the result of micro-meteorological observation on the Hohen Venn, Berg

(1951) reported the fact as follows: The air temperature on the plateau is warmer than that in the basin or valley. Therefore, it is found that the air flowing down from the plateau or the slope doesn't form the cold air lake. However, this air stream is needed to flow the cold air that runs over the cold air lake. If the store and the drainage of cold air in the cold air lake occur periodically, this can be considered to be the cause for the intermittent drainage of cold air.

According to the results summarized on the occurrence time of cold air drainage observed in Japan, for many cases, cold air drainage occurs in the times between 20 h and 21 h, 23 h and 1 h, or 3 h and 4 h, and it occurs mostly with the minimum temperature in the time between 5 h and 7 h (Yoshino, 1960). The frequencies of occurrence time of cold air drainage on the mountain slope in Sugadaira, Nagano Prefecture is higher in winter and lower in summer (Tateishi, 1961).

Spectra of the time series of wind velocities and temperatures observed in the outflow area on a large drainage region in the Geysers area of northern California, U.S.A. were presented by Doran and Horst (1981). Peaks were found in these spectra at frequencies corresponding to periods of oscillation of about 1.5 h.

The flowing types of cold air drainage were reported by Hilkenbaumer et al. (1951), Mason (1958), Sahashi (1962) and other investigators. Especially, Hilkenbaumer et al. explained by using schematic illustrations on the four different flowing types as follows: (1) the cold air drainage from the plateau and the slope of basin and valley wall, and the store of cold air in the river and valley. (2) cold air drainage in the plantation. (3) drainage in the meandering valley. (4) inflow from tributary to main stream.

The thickness of cold air drainage differs greatly from case to case. In week case, it is only 1 - 2 m, but in the stronger case, it develops up to 100 - 200 m. Such a thick drainage might be called a katabatic wind, mountain breeze or mountain wind. Where the valley is narrow, the cold air tend to be dammed up and becomes thicker (Schnelle, 1956). According to the observation results obtained on the Hakatajima Island in the Inland Sea (Setouchi), SW-Japan, the thickness of cold air drainage was 20 - 30 m in the valley where the length is about 770 m and the depth is about 50 m (Imaoka, 1964 a). On the other hand, basing upon the observation results obtained by use of pilot balloons as air parcel trancers on the E-facing slope of Anderson Creek Valley in the Geysers area of northen California U.S.A., Nappo and Snodgrass (1981) reported that the drainage layer thickness grows at the rate of about 80 m per kilometer of flowing distance.

From the result obtained on Hakatajima Island, it was found that the cold air drainage always becomes weak at the time when general wind blows from any directions, and that the relation between the velocities of cold air drainage and general wind is shown by one-dimensional function with positive slope (Imaoka, 1964 b).

1.2.4. Velocity of Cold Air Drainage

The theoretical and experimental equations for the velocity of cold air drainage has been studied by many researchers. The velocity of cold air drainage is dynamically the same as that of the katabatic wind on mountain slopes (Yoshino, 1975). Heywood (1933) presented the equation of the wind velocity as a function of the distance from the sea and the angle of the mountain slope, and Reiher (1936) also obtained the equation, based on the assumption that the cold air flows down due to gravity.

Assuming the compressibility of cold air, Fleagle (1950) attempted to express mean flow velocity of the cooling air layer, theoretically. From the results, it is found that the velocity is proportional to the net outgoing radiation and is in inverse proportion to the thickness of the cold air layer and to the angle of the slope.

Bergen (1969) studied the cold air drainage on a forested mountain slope in the Fraser Experimental Forest, Colorado, U.S.A., and the equation for the local mean velocity was obtained.

Assuming that the air parcel has compressibility and the friction force is proportional to the falling velocity of the parcel, Sahashi (1974) set up the equation of motion of cooled air parcel. The characteristic feature of the solution is that the falling velocity along the slope will chang periodically with the distance from the top of the slope.

Petkovšek and Hočevar (1971) showed the very simple model on the velocity of cold air drainage by use of only the main four parameters, viz. rate of cooling, friction coefficient, steepness of the slope and the lapse rate in the environment of the cooled air layer at the slope. Moreover, Nakamura (1980 b) exposed the relation between flowing distance and velocity of cold air drainage, experimentally.

The numerical model of katabatic winds was constructed by Sakamoto and Ishida (1973), although it is a one-dimensional one. Results obtained from this model agreed fairly well with the observed ones which were obtained by Imaoka (1964 a) on Hakatajima Island in the Inland Sea, SW-Japan.

A numerical simulation of cold air drainage observed in realistic terrain, part of the California Geysers area, U.S.A., has been carried out by means of a three-dimensional mesoscale atmospheric model (Yamada, 1981). The simulated results agree with the observed ones, but the simulated wind velocity near the ground are greater than the observed values.

1.2.5. Cold Air Lake and Nocturnal Air Circulation on the Mountain Slope

The cold air is stored in the topographical hollow, valley or basin. It is called a cold air lake. In other words, the cold air lake is called a clearly developed inversion layer, which is intensified by the topographical situation. The diameters of the lake is several meters to tens kilometers. Wagner (1970) especially named the phenomena in relatively broad area a cold air sea, and these in small hollows such as dolines a cold air pond.

From the observation results in Hohen Venn and its surroundings mentioned above, Berg (1951) reported that the formation of cold air lake in the basin or valley is independent of air flow from the plateaus or slopes. Furthermore, summarizing the observation results on the Ôiso Hill, Kanagawa Prefecture (Iwasaki, 1975), in Sugadaira Basin, Nagano Prefecture (Miura, 1971), and on the many mountain slopes (Saito et al. 1966), the author considered the mechanism for the formation of cold air lake as follows: (1) The air temperature in the basin becomes lower by radiative cooling. (2) The cold air is kept easily in the basin due to weak wind velocity, and then it gradually increases the stability. (3) In this way, cold air lake is formed, and it is never formed by inflow of cold air from the slope.

As for the nocturnal air circulation on the mountain slope, several models have been reported which were based on the observation results. Mano (1953) showed the models of the cold air lake and the nocturnal air circulation as shown in Fig. 1.1, based on observation results in the basin on Ôchô village of Ôsakishimojima Island in the Inland Sea. From this figure, it is found that there is a cold air lake in the lowest layer and the cold air flows down on the slope. Moreover, the warm air invades from free atmosphere at a height of 100 - 250 m a.s.l. to the places where the cold air has run away.

Basing upon the Wargner's model (1938), Mano (1956) presented the model of the nocturnal air circulation on the slope of Mt. Bandai, NE-Japan (Fig. 1.2). The thin advection fog which covers the lake surface ascends over the lake because this flows over the inversion layer on the land towards the mountain. There is general wind over this upwind system, and there is cold air drainage on the slope.

Vorontsov (1958) formed the model of nocturnal air circulation (Fig. 1.3) from the observation results mentioned above. According to the model, the circulation system related to cold air drainage develops over the cold air lake. The thickness (A) of the cold air drainage is expressed by

$$A = (0.20 \sim 0.25)\ H \qquad (1)$$

where H is the difference of height between basin or valley bottom and the surrounding mountain ridges.

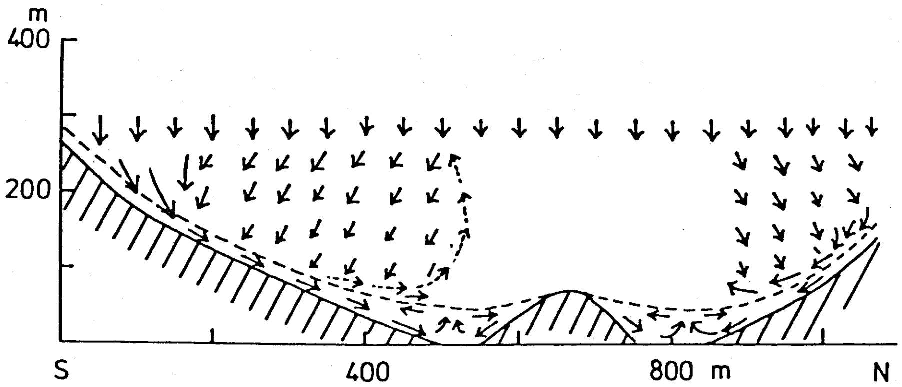

Fig. 1.1 Model of nocturnal air circulation at Ôchô (Mano, 1953).

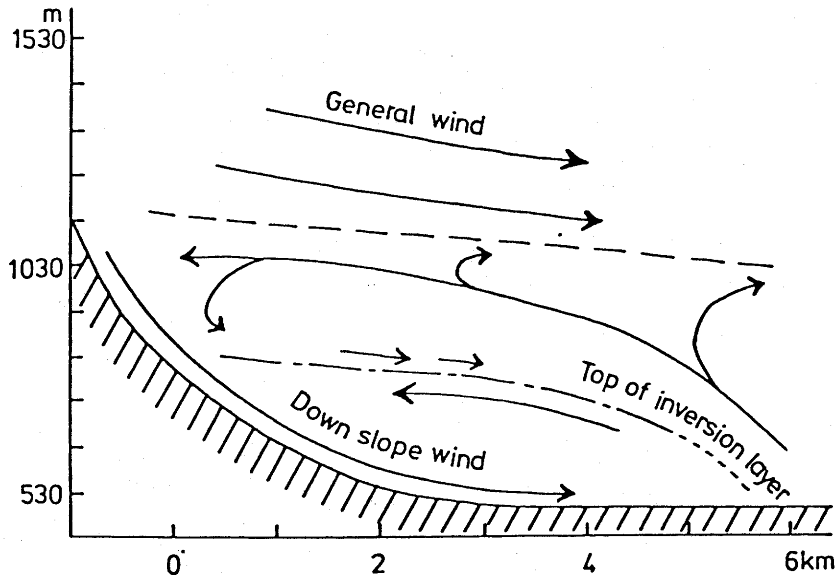

Fig. 1.2 Model of nocturnal air circulation on the slope of Mt. Bandai (Mano, 1956).

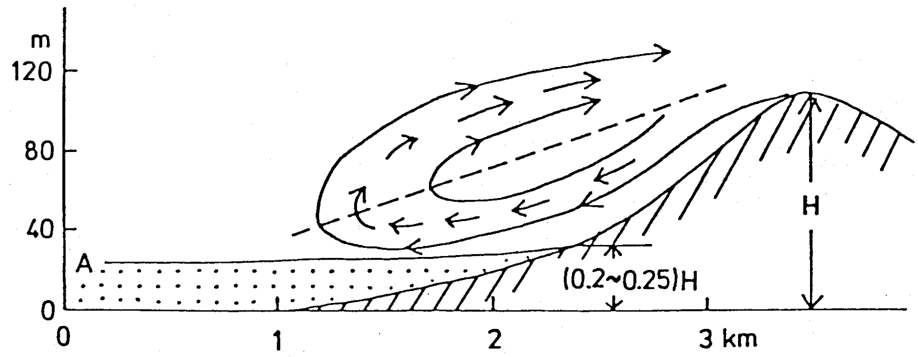

Fig. 1.3 Model of nocturnal air circulation on the gentle slope of Kokchetavska, U.S.S.R. (Vorontsov, 1958).
A shows the upper limit of the cold air lake and H the relative height of the mountain.

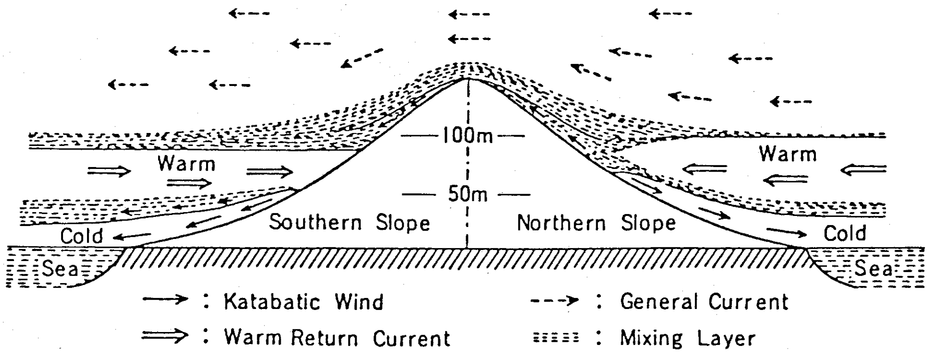

Fig. 1.4 Model of wind circulation on a clear calm night on the small island, Hakatajima (Kimura, 1961).

Kimura (1961) gave an idealized model (N-S section) of the circulation system of cold air drainage based on the observation results obtained in Hakatajima Island, Setouchi region, SW-Japan (Fig. 1.4). The warm anti-downslope wind layer is clearly seen over the cold downslope wind layer on the slope.

Summarizing these results and schematic illustrations mentioned above, one can obtain the following conclusions. (1) The cold air lake is formed on the bottom of the valley or basin. (2) Over the mountain slope, cold air flows down. Over this flow, the ascending air current which is compensating current to downslope wind blows. and the circulation system related to cold air drainage is formed. (3) Over this circulation system, the general upper winds are blowing.

CHAPTER 2. OBSERVATION

2.1. Physiographic Outline of the Observation Area

The topography of Sugadaira, Nagano Prefecture, has been formed from the volcanic slope of Mt. Neko (2,213 m) and Mt. Azuma (2,332.9 m) and the basin located on the west side of the slope (Fig. 2.1).

The observation points distribute on the WSW-facing slope between 1,280 m and 1,550 m a.s.l. (Fig. 2.2). The average inclination of the slope is approximately 4°, the difference of height is about 270 m and the horizontal distance is about 3,000 m. The forests of Larix leptolepis (tree height: 10 - 15 m) distribute in the area ranging from 1,390 m to 1,460 m. The pasture continues to the upper part of these forests, the villas surrounded by the forests to the lower part of the slope to the 1,350 m level, and the vegetable fields under cultivation to the lower part than these villas. The depth of valley is less than 3 m on the upper part than Station No. 8 on the slope. But it reaches 8 - 9 m on the lower part than Station No. 9. This small valley flows into Karasawa River on the lower part of the slope.

The observation points on the NE-facing slope of Mt. Ômatsu (1,648.7 m) locating in south side of the basin

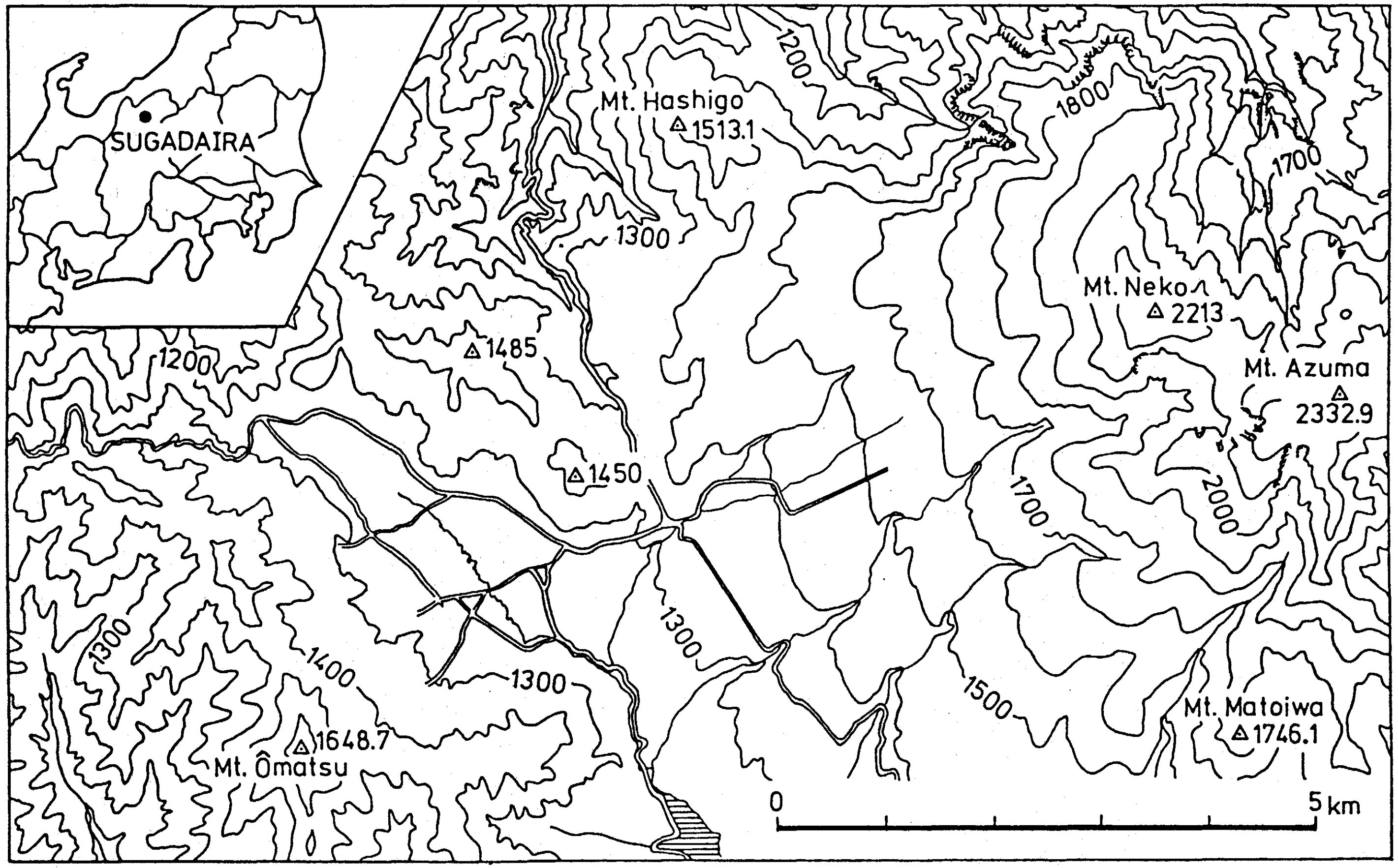

Fig. 2.1 Topographical map of the Sugadaira region.

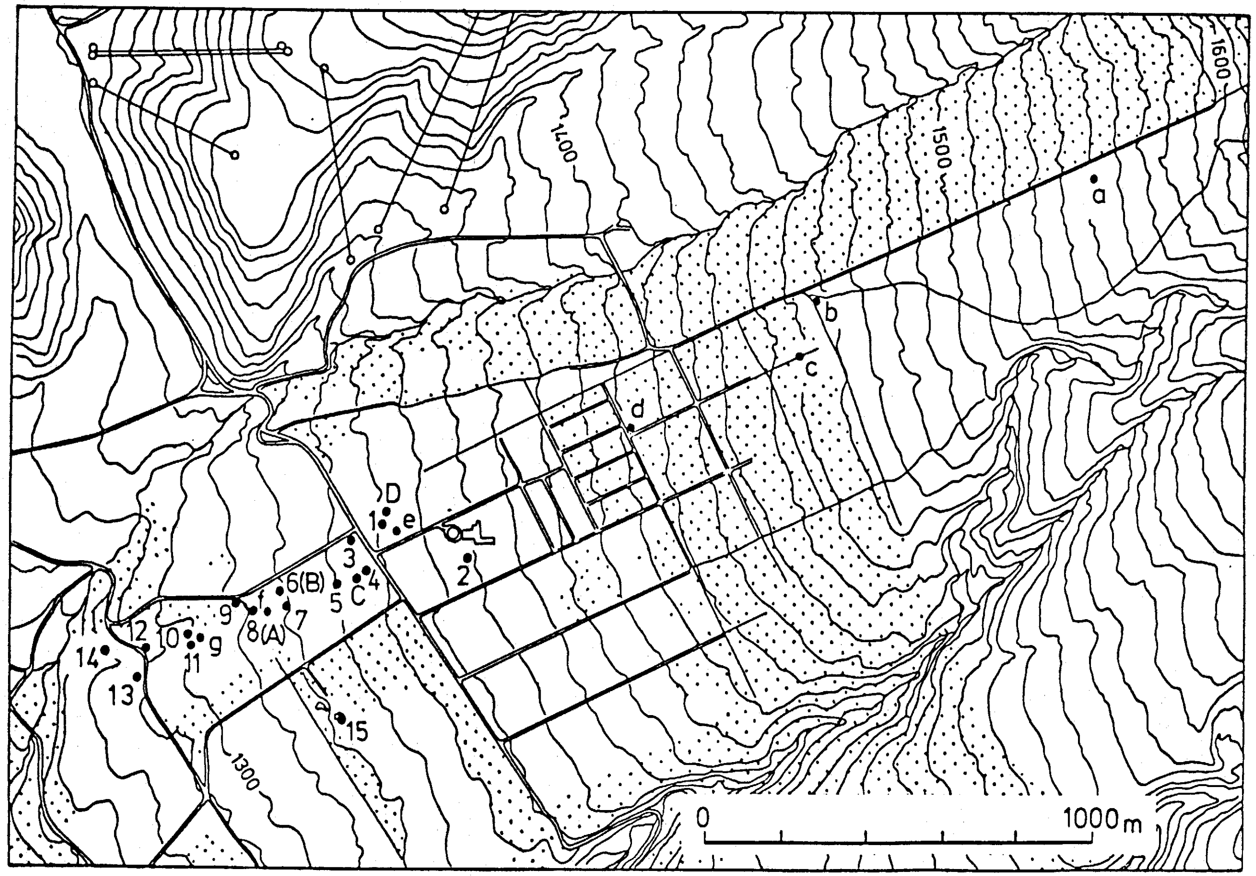

Fig. 2.2 Location map of the observed stations on the slope of Mt. Neko. Shadow shows the forest areas.

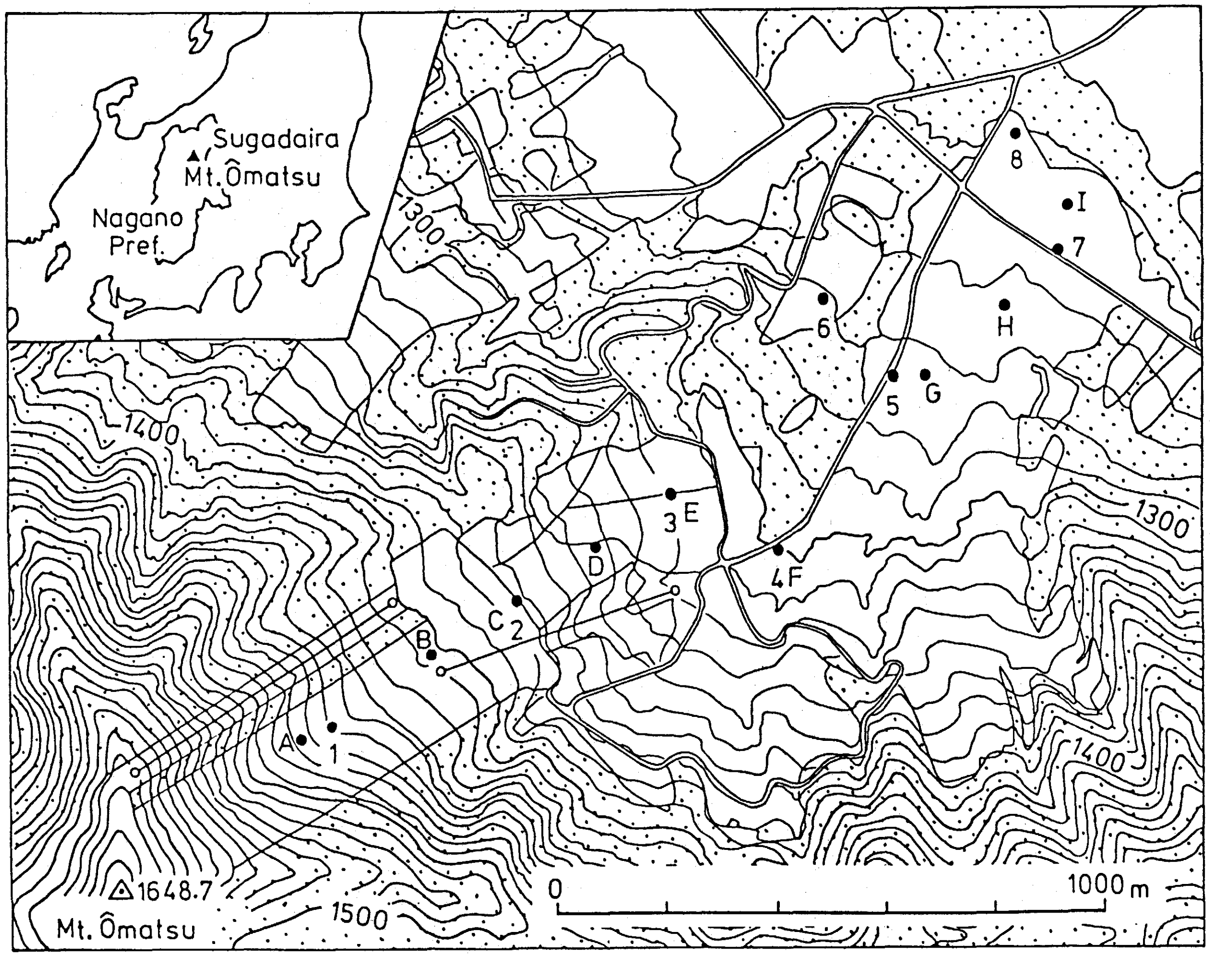

Fig. 2.3 Location map of the observed stations on the slope of Mt. Ômatsu. Shadow shows the forest areas.

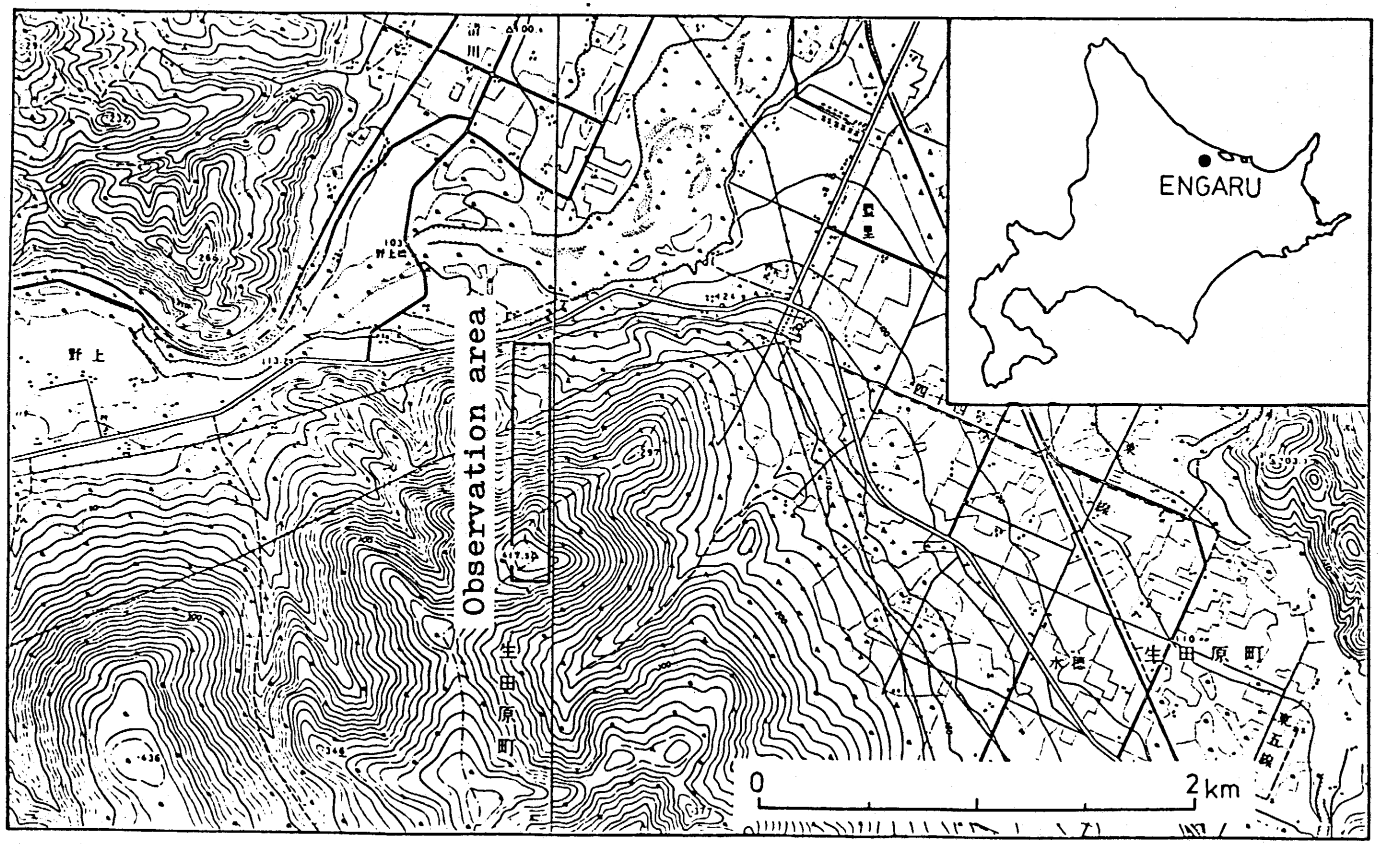

Fig. 2.4 Topographical map of the Engaru region.

distribute in the area ranging from 1,250 m of basin bottom to 1,450 m a.s.l. on the slope as shown in Fig. 2.3. The average inclination of the slope is approximately 7°, the difference of height is about 200 m and the horizontal distance is about 1,600 m. The area in the higher part of the slope than 1,400 m a.s.l. is used as skiing ground in winter, and is overspread with weed in summer. The vegetables fields distribute in the lower part of the slope.

Engaru, Hokkaido, is situated in the place which is about 20 km from Okhotsk coast along the valley of the Yûbetsu River. The observation area is located on the N-facing slope of the small mountain (417.5 m) situated near the meeting point of the Yûbetsu River and the Ikutawara River (Fig. 2.4). The observation points distribute in the area ranging from 150 m to 350 m a.s.l., and the horizontal distance of the area is about 1,000 m. This slope is used as skiing ground in winter. The gentle slope lower than 190 m a.s.l. is used as golf course in summer.

2.2. Observation Methods and Weather during the Observations

The observational items with specifications are summarized in Table 2.1. Also, the weather during the observation is shown in Table 2.2.

Table 2.1 List of observations

No.	Period observed	Place of observation	Elements observed	Instruments used (measurement levels, m)	Stations of observation
1	Aug. 11 - 20, 1973	Nb	Air temp. Wind veloc. Wind direc.	Ta (0.5, 1.0 & 1.5 m) Tr (1.0 m) Vh (1.0, 1.5, 2.0, 3.0 & 5.0 m) Vb (1.2 m) & Smok	Sts. 6 & 8 Sts. 6 & 8 Sts. 6 & 8 St. 8
2	Dec. 25 - 27, 1973	Nb	Air temp. Wind veloc. Wind direc.	Tt (0.5, 1.0, 1.5 & 2.0 m) Vh (0.5, 1.0 & 2.0 m) Sv (1.0 m)	Sts. A - D Sts. A - D Sts. A - D
3	Mar. 28, - Apl. 1, 1974	Nb	Air temp. Wind veloc. Wind direc.	Tt (0.5 & 2.0 m) Tm (1.0 m) Vh (0.5 & 2.0 m) Vb (1.2 m)	Sts. A - F Sts. H - Q Sts. A - E Sts. A - E
4	May 28 - 30, 1974	Nb	Air. temp. Wind veloc. Wind direc.	Ta (0.5 m) Tm (1.0 m) Tr (1.0 m) Tt(f) (0.5, 1.0, 2.0, 3.0 & 5.0 m) Vh (0.5, 1.0, 2.0, 3.0 & 5.0 m) Vb (1.2 m) & Sv	Sts. 1 - 13 Sts. 1 - 13 Sts. 6 & 11 St. 6 Sts. 6 & 11 Sts. 1 - 13

Table 2.1 (continued)

5	Aug. 5, 1974	Nb	Air temp.	Tt(f) (0.0, 0.5, 1.0, 2.0, 3.0 & 5.0 m)	Sts. 6 & 14
			Wind veloc.	Vb (1.2 m)	Sts. 6 & 14
			Wind direc.	Vb (1.2 m)	Sts. 6 & 14
6	Aug. 11 - 16, 1975	Nb	Air temp.	Tt (0.5 & 5.0 m)	Sts. 1, 6, 11 & 14
			Wind veloc.	Tr (1.0 m)	St. 6
				Vr (0.5, 2.0, 4.0, 6.0 & 8.0 m)	St. 6
				Vb (1.2 m)	Sts. 1, 6, 11 & 14
			Wind direc.	Vb (1.2 m)	Sts. 1, 6, 11 & 14
				P	St. 6
7	Sep. 26 - 30, 1975	Nb	Air temp.	Ta (0.2 & 1.2 m)	Sts. 1, 4, 6, 11 & 14
				Tr (1.0 m)	Sts. 1, 4, 6, 11 & 14
			Wind veloc.	Vh (2.0 m)	Sts. 1, 4, 6, 11 & 14
				Vb (1.0 m)	Sts. 1, 4, 6, 11 & 14
			Wind direc.	Vb (1.0 m)	Sts. 1, 4, 6, 11 & 14

Table 2.1 (continued)

8	Aug. 18 - 20, 1976	O	Air temp. Wind veloc. Wind direc.	Ta (0.3 & 1.3 m) Vh or Vm (1.0 m) Vm or Vb (1.0 m)	Sts. 1 - 7 Sts. 1 - 7 Sts. 1 - 7
9	Sep. 15 - 16, 1976	Na	Air temp. Wind veloc. Wind direc.	Ta (0.3 & 1.3 m) Tr (1.0 m) Vh (2.0 m) Vb (1.0 m)	Sts. a - g Sts. a - g Sts. a - g Sts. a - g
10	Jul. 29, - Aug. 1, 1978	O	Air temp. Relat. humid. Wind veloc. Wind direc. Net radiation	Ta (0.3 & 1.3 m) Ha (0.3 & 1.3 m) Vh or Vm (1.0 m) Vm or Vb (1.0 m) Rs (1.0 m) Re (1.0 m)	Sts. 1, 2, 3, 5 & 7 Sts. 1, 2, 3, 5 & 7 Sts. 1, 2, 3, 5 & 7 Sts. 1, 2, 3, 5 & 7 St. 3 Sts. 1, 2, 3, 5 & 7
11	Jul. 21 - 22, 1979	E	Air temp. Wind veloc.	Ta (0.5 m) Tt(F)-b-mo (5, 10, 20, 30, 40, 50, 60, 70, 80 & 85 m) Vb (1.0 m) Vm-b-mo (5, 10, 20, 30, 40, 50, 60, 70, 80 & 85 m)	Sts. 1 - 4 Sts. 1 - 4 Sts. 1 - 4 Sts. 1 - 4

Table 2.1 (continued)

11			Wind direc.	Vb (1.0 m) Sv-b-mo (5, 10, 20, 30, 40, 50. 60, 70, 80 & 85 m)	Sts. 1 - 4 Sts. 1 - 4
12	Aug. 10 - 11, 1979	0	Air temp.	Ta (0.5 m) Ta-mo (0.5 m) Tt(f)-b-mo (2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	St. F Sts. A - E & G - I Sts. A - I
			Wind veloc.	Vb (1.0 m) Vb-mo (1.0 m) Vm-b-mo (2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	St. F Sts. A - E & G - I Sts. A - I
			Wind direc.	Vb (1.0 m) Vb-mo (1.0 m) Sv-b-mo (2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	St. F Sts. A - E & G - I Sts. A - I
13			Air temp.	Ta (0.5 m) Tt(f)-b-mo (2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m) Tr (1.0 m)	Sts. C, F, G & I Sts. C, F, G & I Sts. C & F

Table 2.1 (continued)

13	Aug. 25 - 28, 1980	O	Wind veloc.	Vm-r (2.0 m)	St. F
				Vm-mo (1.0 m)	Sts. C, F, G & I
				Vm-b-mo (2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	Sts. C, F, G & I
				Vv-b-mo (2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	Sts. C, F, G & I
			Wind direc.	Vm-mo (1.0 m)	Sts. C, F, G & I
				Sv-b-mo (2, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 & 100 m)	Sts. C, F, G & I
			Net radiation	Rs (1.0 m)	St. F

Na: On the slope of Mt. Neko

Nb: On the lower part of the slope of Mt. Neko

O : On the slope of Mt. Ômatsu

E : On the mountain slope of Engaru

Ta: Assmann ventilated psychrometer

Tt: Thermistor thermometer

Tr: Recording thermograph

Tm: Minimum mercury thermometer

Vh: Photo-electronic anemometer

Vm: Magnetic contact wind vane and anemometer

Vb: Biram's anemometer

Vv: Vertical anemometer

Rs: Standard net radiometer

Re: Economical net radiometer

Sv: Vinyl string

r : Recording

(f): with fan

b : Captive balloon

P : Pilot balloon

mo: Mobile observation

Table 2.2 Weather of observation periods.

No.	Period observed	Description of weather
1	Aug. 11 - 20, 1973	Honshu was overcasted with Ogasawara anticyclone until Aug. 14, and clear and calm days continued in Sugadaira during this periods. Scowling days continued under the influence of typhoon No. 10 in Sugadaira during the periods from the evening on 14th day to that on 18th day. Sugadaira region was covered with Ogasawara anticyclone, and it was clear and calm on 19th and 20th days.
2	Dec. 25 - 27, 1973	The distribution of atmospheric pressure that the high pressure area lies to the west and the low pressure area to the east developed during this periods. It was fine and calm in Sugadaira.

Table 2.2 (continued)

3	Mar. 28-Apl. 1, 1974	Japan has begun to be overcasted with traveling anticyclone from afternoon on 28th day, and it was fine both 29th and 30th days. However, weather began to break on 31th day because cyclone with front came nearer to Japan, and it rained on next day.
4	May. 28 - 30, 1974	The 28th day was fine day like midsummer because Baiu front leaved to far the south sea. The Baiu front moved slightly to east, the center of anticyclone got away to east, and rain began to fall in the western region of Kyûshû on 30th day. It was cloudy in Sugadaira.
5	Aug. 5, 1974	The whole of japan was overcasted with anticyclone with exception of North Japan. Sugadaira was also clear and calm day.
6	Aug. 11 - 16, 1975	The whole of Japan was overcasted with anticyclone until 15th day, and fine weather continued. However, the weather on 16th day was quite changeable under the influence of typhoon No. 5 which went up to north over the south sea of Japan.

Table 2.2 (continued)

7	Sep. 26 - 30, 1975	The traveling anticyclone that overcasted the whole of Japan on 25th day, advanced to the east sea on 26th day. Continuously, cyclone with front came nearer to Japan, and the weather on 27th day broke. After then, as this front lied to south coast of Japan, bad weather continued until the morning on 29th day. Japan began to be overcasted with traveling anticyclone from the afternoon on 29th day, and it was fine on 30th day.
8	Aug. 18 - 20, 1976	Japan was overcasted broadly with anticyclone that jutted out from Okhotsk direction, and fine and calm weather continued until 20th day of final observation in Sugadaira.
9	Sep. 15 - 16, 1976	Japan was overcasted with the anticyclone which jutted out from continent to Japan on 15th day, and the whole of Japan had fine weather. Sugadaira had also fine weather on both days of 15th and 16th.
10	Jul. 29-Aug.1, 1978	Japan was overcasted with Ogasawara anticyclone during this periods, and weather in Sugadaira was fine.

Table 2.2 (continued)

11	Jul. 21 - 22, 1979	Trough moved in close to northern and southern parts of Hokkaido, but the eastern part of Hokkaido at the night on 21th day was clear and calm.
12	Aug. 10 - 11, 1979	The whole of Japan was overcasted broadly with Ogasawara anticyclone on both days of 10th and 11th, and it was fine all over the country.
13	Aug. 25 & 28, 1980	Japan was overcasted with Okhotsk anticyclone on both days of 25th and 28th. It was also fine in Sugadaira.

CHAPTER 3. VELOCITY AND TEMPERATURE OF COLD AIR DRAINAGE

3.1. General Characteristics of Velocity and Temperature of Cold Air Drainage

It was tried first to observe the drainage states of cold air on the slope at night continuously and in detail and to make clear their general features. Secondly, by use of these results, it was tried to express quantitatively cold air drainage and also to make clear the general relations between the meteorological elements of cold air drainage. From these results, the cold air drainage is defined.

The discussion in this Section is based upon the results which was obtained from the observation on the WSW-facing gentle slope of Mt. Neko (Fig. 3.1) in August 1973, December 1973 and May 1974.

3.1.1. Relation between Air Temperature and Wind Velocity at Clear, Calm Night

Fig. 3.2 shows the air temperature variations with time at a height of 1.0 m and the wind velocity variations with time at a height of 2.0 m above the ground of Station

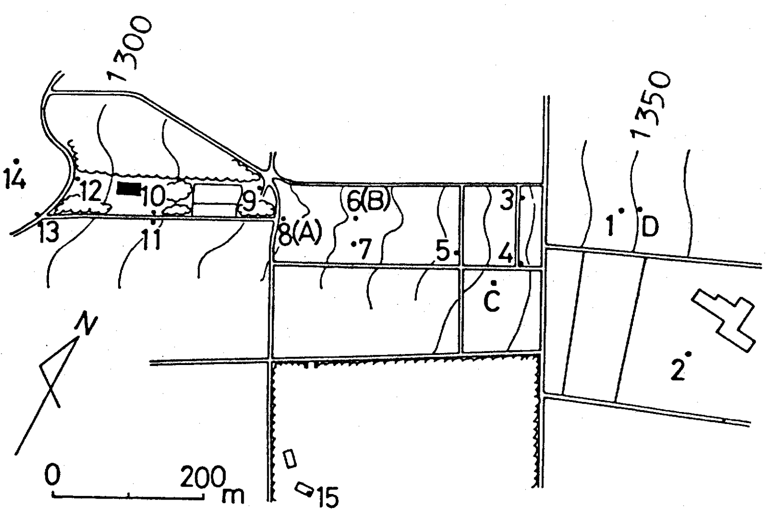

Fig. 3.1 Location map of the observed stations on the lower part of the slope of Mt. Neko during the period from August 1973 to September 1975.

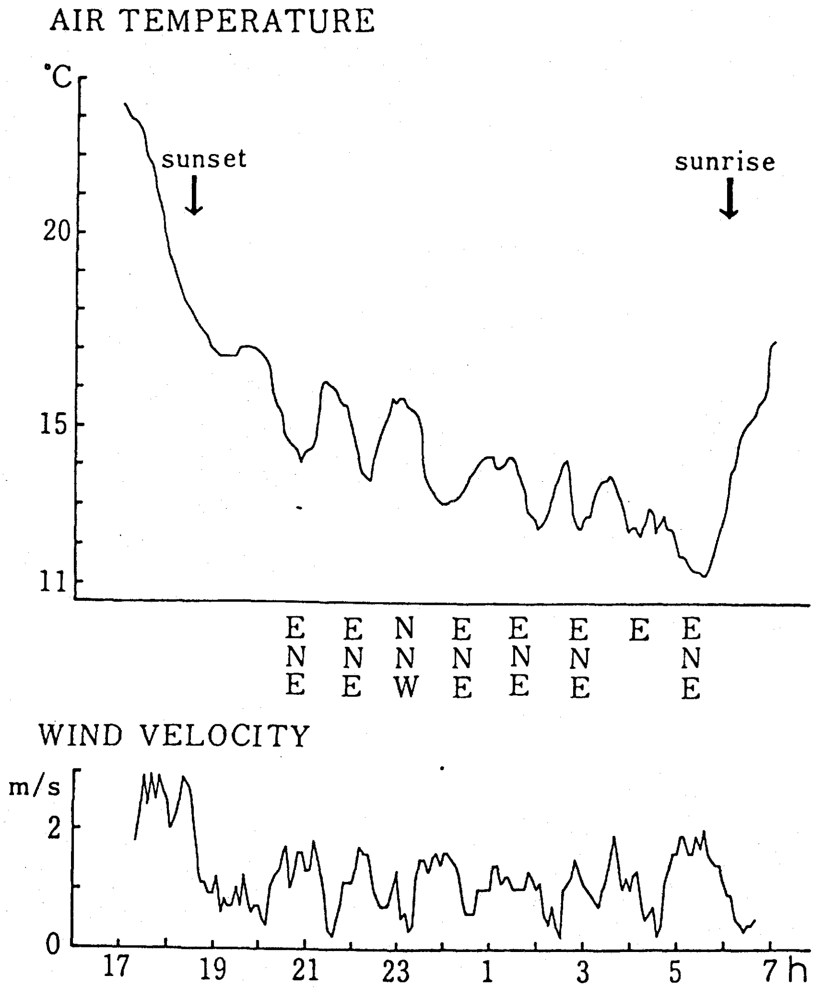

Fig. 3.2 Variations of air temperature and wind velocity observed at heights of 1.0 m and 2.0 m above the ground at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on August 19 - 20, 1973.

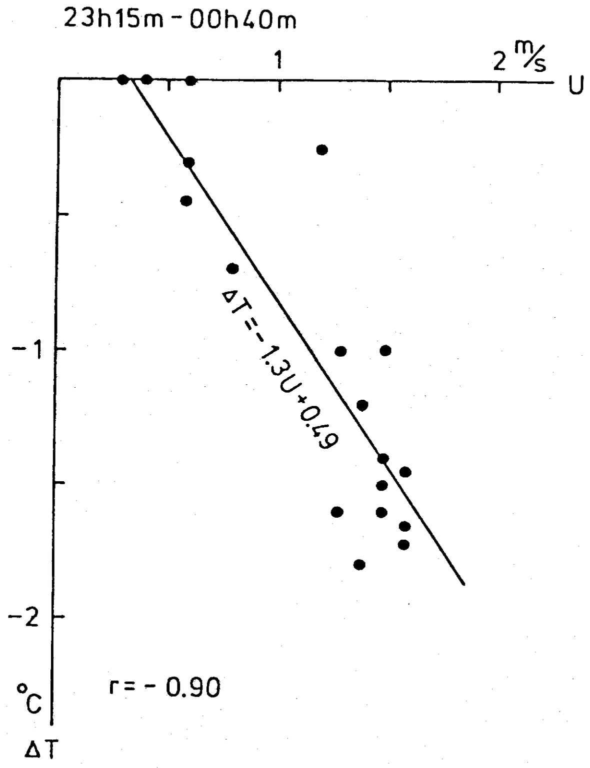

Fig. 3.3 Relation between air temperature falling (ΔT) and wind velocity (U) at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on August 19 - 20, 1973.

No. 6 at night on August 19 - 20, 1973. Air temperature and wind velocity have inverse relation; namely, wind velocity increases as air temperature decreases. In order to express this relation in detail, the decreasing amounts of air temperature to the values of wind velocity were obtained from air temperature variation curve expressed in Fig. 3.2, and then these were correlated. Fig. 3.3 shows the relation between these values during the time 23 h 15 m to 00 h 40 m. The coefficient of the correlation is - 0.90 and the significance level is below 0.05.

As the result, it is found that the decreasing amount of air temperature due to cold air drainage shows high negative correlation with wind velocity. In the analysis mentioned above, it is postulated that the decreasing amount of air temperature is shown by the deviation from straight line which joins the peaks of air temperature variation curve, since air temperature at clear night has a tendency to decrease gradually until immediately before sunrise.

3.1.2. Wind Direction and Vertical Distribution of Wind Velocity

Since cold air flows down on the slope as a density current, it must flow down to the direction of maximum inclination of the slope, if there are no other factors for it. In the fact, however, as the cold air drainage is affected by upper wind, ground state and so on, its direction may be varied within a certain range. Fig. 3.4 is the wind roses which are illustrated from observation results obtained at Stations No. 1 to No. 13 during the time from 21 h 01 m to 24 h 00 m on May 29, 1974. As the cold air drainage appears almost every-time, the data obtained are most suitable for the investigation on the direction of cold air drainage.

If the average values of directions of cold air drainage with respect to all Stations are taken into account, 90.3 % fraction of the wind directions distributes within the $\pm 22.5^{\circ}$ angular range centering the most probable wind direction, that is approximately ENE. Otherwise, 97 % fraction of these falls within the $\pm 45^{\circ}$ angular range from ENE, The most probable direction of the cold air drainage coincides with the mean direction of maximum inclination on whole observation area.

Consequently, it can be said that the direction of cold air drainage ranges within $\pm 45^{\circ}$ from the axis of direction of maximum inclination of the slope.

Next, in order to capture the microchanges of wind velocity every minute during the period from the start to the end of cold air drainage, the vertical distributions of wind velocity were obtained. Some examples of the results, which were obtained during the times from 19 h 03 m to 19 h 11 m on May 29 and from 03 h 25 m to 03 h 57 m on May 30, 1974, are shown in Fig. 3.5. From this figure, it is found

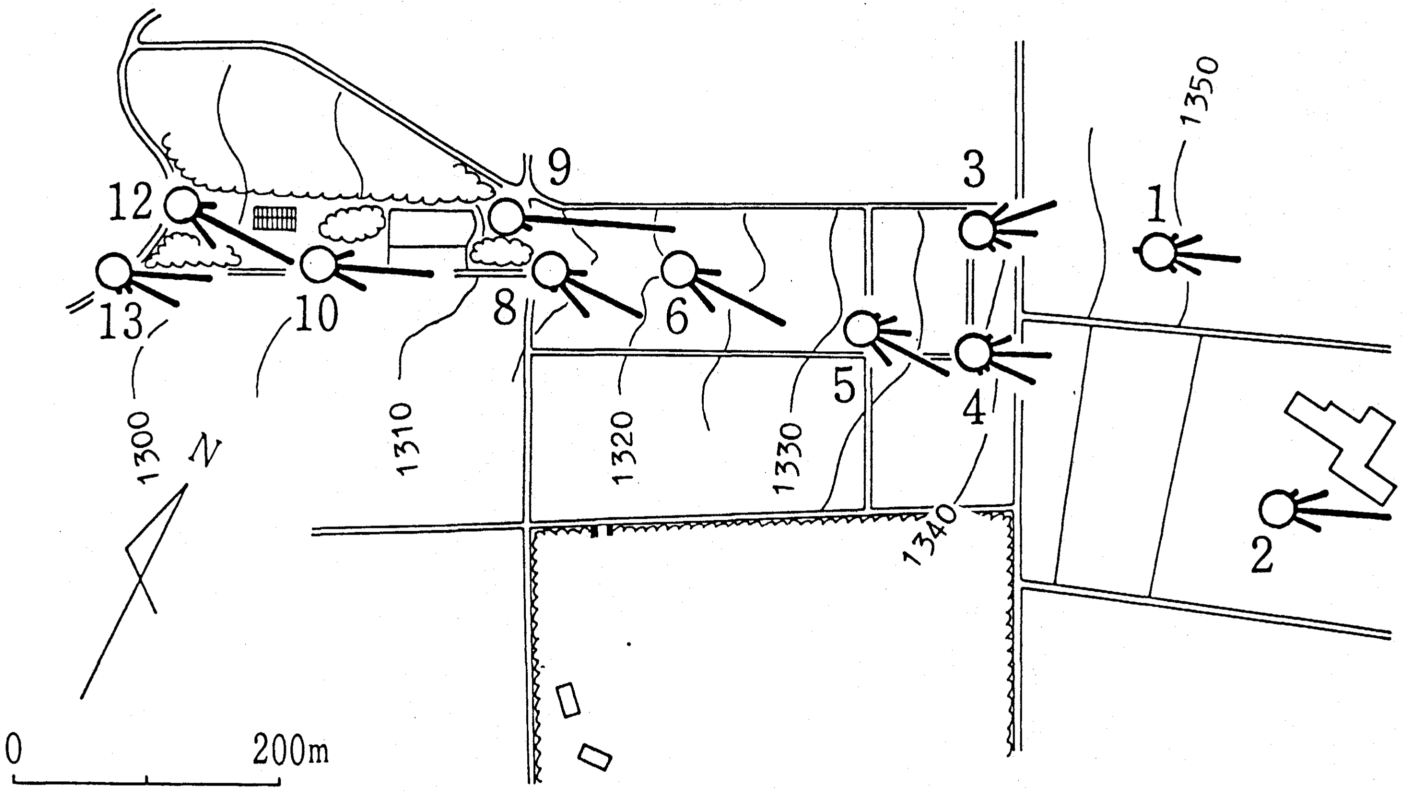

Fig. 3.4 Wind roses of cold air drainage on the gentle slope of Mt. Neko during the time from 21 h 00 m to 24 h 00 m on May 29, 1974.

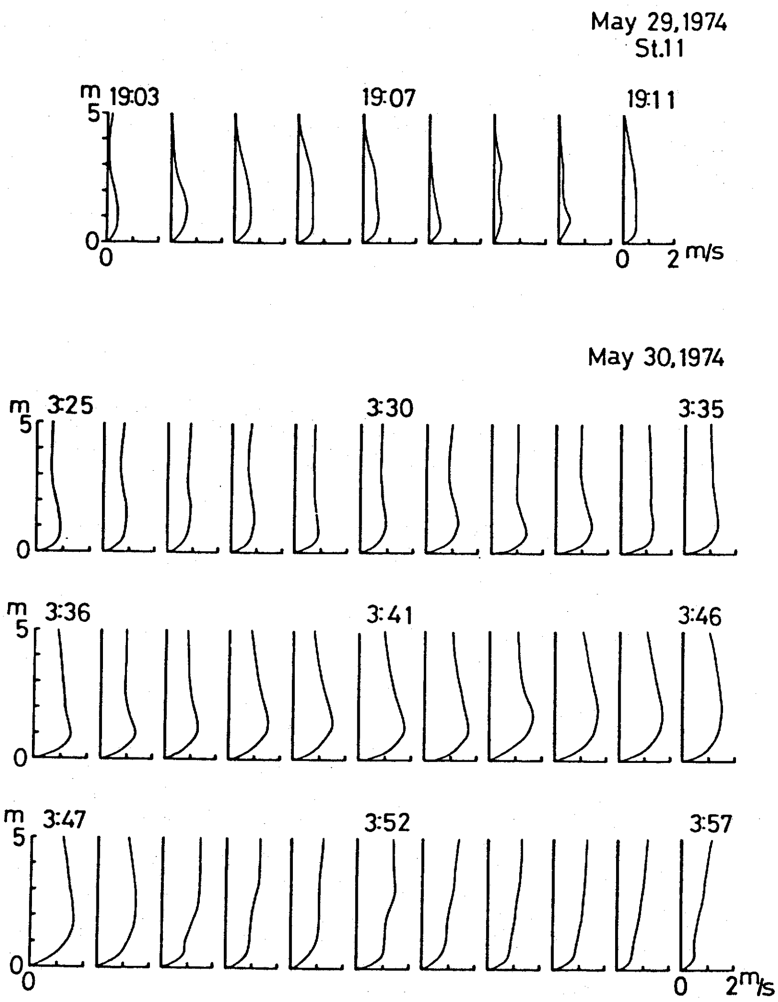

Fig. 3.5 Transitions of vertical distribution of wind velocity from the onset to the finish of cold air drainage on the slope of Mt. Neko during the times from 19 h 03 m to 19 h 11 m on May 29 and from 03 h 25 m to 03 h 57 m on May 30, 1974.

Each profile is expressed in every minute.

that tha profiles of cold air drainage are as follows; Firstly, increasing gradually the velocity and the thickness, cold air drainage flows down on the slope. After this, these values reach maximum ones and then decrease. Finally, the cold air drainage diminishes. On May 29, because the layer of the drainage was thin, it was possible to capture the whole image of the cold air drainage. The thickness of this layer was about 5 m. Then maximum wind velocity in this layer was about 0.5 m/s.

3.1.3. Definition of Cold Air Drainage and Its Occurrence Frequency

From the analytical results of the relation between air temperature and wind velocity, and of the wind direction, the characteristic natures exhibiting between these elements can be expressed quantitatively. In this study, the air flow which has the following two characters can be defined as cold air drainage (Nakamura, 1976).

(1) The air temperature correlates negatively with the wind velocity.

(2) The wind directions are within the range of $\pm 45°$ from the center axis of direction of maximum inclination of the slope.

In accordance with this definition, the occurrence time of cold air drainage was calculated from the observation results obtained at the calm and clear nights

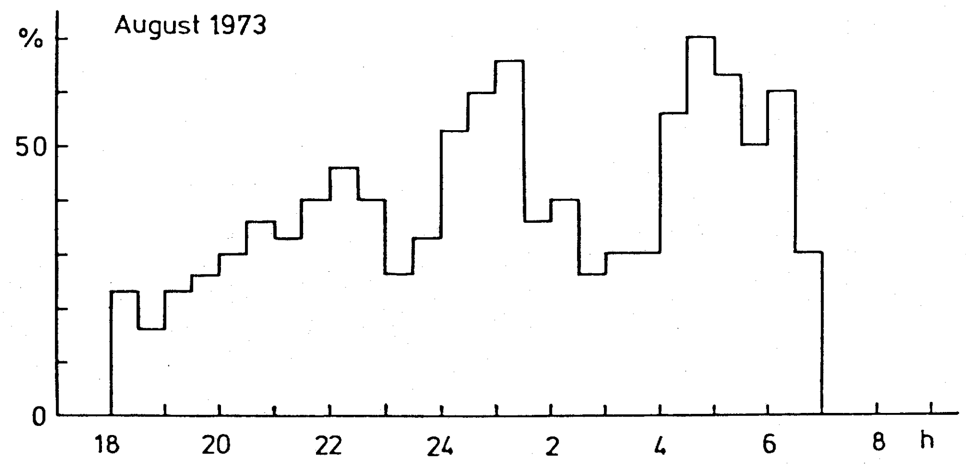

Fig. 3.6 Frequency of cold air drainage on clear, calm nights obtained at a station (Station No. 6) located on the lower part of the slope of Mt. Neko in August 1973.

of August 11 to 14, 18 to 20, 1973, December 25 to 27, 1973, and May 28 to 30, 1974. From these results, the frequencies of the occurrence of cold air drainage were obtained every 30 minute between 17 h 00 m and 9 h 00 m. In the case of August, the major three peaks appeared at 21 h 30 m to 23 h 00 m, 24 h 00 m to 1 h 30 m and 4 h 00 m to 6 h 30 m as shown in Fig. 3.6. In all cases tested, other peak appeared at 19 h 30 m to 21 h 00 m in addition to these times, so that there were 4 peaks in all. The peak values of the frequencies increased with the time elapsed, and the values of final peak became about 70 %.

3.1.4. Occurrence Periods of Cold Air Drainge

The periods are found on the variations of the temperature and the velocity of cold air drainage. It was tried to make clear the dependency of time and location on the slope of Mt. Neko on the period. The period was calculated from the data obtained every minute by using the method of periodgram analysis.

Fig. 3.7 shows the local differences of the periods of air temperature (0.5 m height) and wind velocity (1.2 m height) along the slope which were observed during the three hours from 21 h 00 m to 24 h 00 m of May 29, 1974 in the area of Stations No. 1 to No. 13 where ground surface coverage is relatively uniform. These periods show large values within the deep valley on the lower part of the slope than Station No. 6. As the reason for

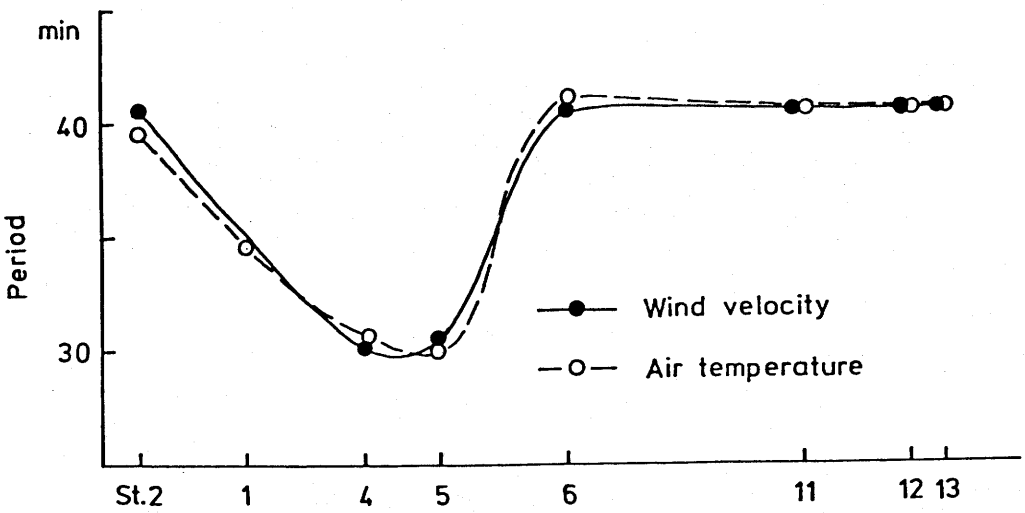

Fig. 3.7 Regional differences of the periods of the temperature and the velocity of cold air drainage on the slope of Mt. Neko during the time from 21 h 00 m to 24 h 00 m on May 29, 1974.

Table 3.1 Seasonal variations of the period and the range of fluctuation of cold air drainage on the slope of Mt. Neko.

Season	Observation day	Period	Range of fluctuation
Winter	Dec. 25-26, 1973	295 min	5.0 °C
	26-27,	450	7.5
	Average	373	6.3
Spring	May 28-29, 1974	173	3.5
	29-30,	130	1.6
	Average	152	2.6
Summer	Aug. 11-12, 1973	112	1.9
	13-14,	84	2.3
	18-19,	98	2.0
	19-20,	88	3.0
	Average	96	2.3

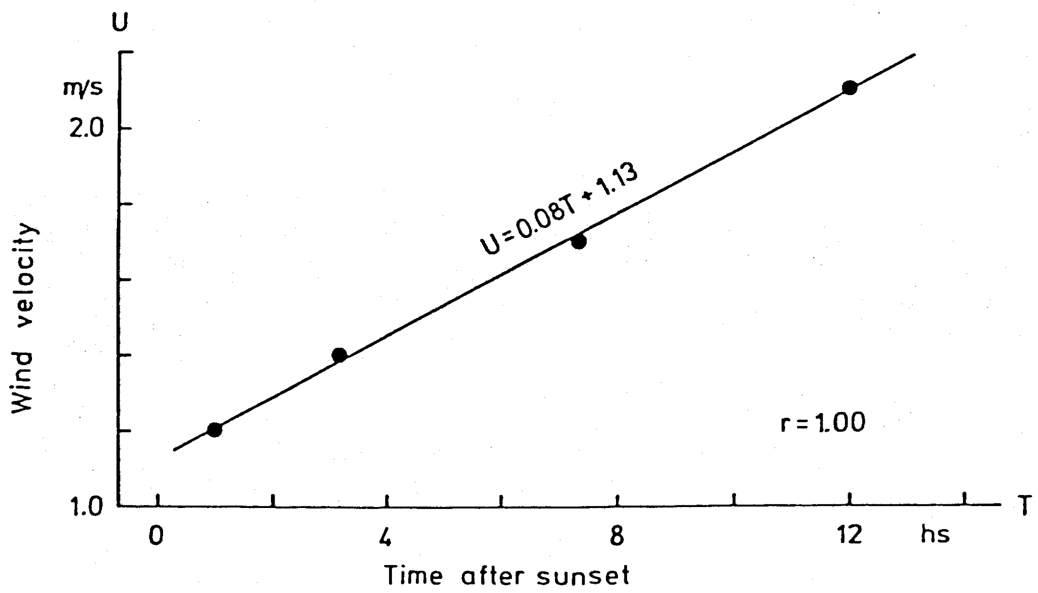

Fig. 3.8 Relation between the peak value of the velocity of cold air drainage and the time after sunset at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on August 12 - 13, 1973.

this, it is considered that cold air drainage within shallow valley is influenced by upper general wind more than that within deep valley.

The periodical fluctuation of velocity and temperature of cold air drainage and the range of the fluctuation are different seasonally. Of the data of air temperature and wind velocity obtained every minute at Station No. 6 in winter (December 1973), in spring (May 1974) and in summer (August 1973), eight examples, from which the period can be found clearly, were selected to obtaine the average values of the periods and the range of fluctuation. These are summarized in Table 3.1. It is found from this Table that the periods and the range of fluctuation decrease according to seasons, that is, winter to summer. Furthermore, it is found that the range of fluctuation for the wind velocity have a tendency to increase with respect to time elapsed after sunset. Fig. 3.8 shows the typical example of these on August 12 - 13, 1973. In this figure the abscissa represents the time elapsed after sunset and the ordinate the values of five minutes mean wind velocity at each peak of wind velocity variation curve. The relation between them is expressed by a positive linear relation.

3.1.5. Change of Horizontal Distribution of Air Temperature in Association with Cold Air Drainage

The cold air on the slope of Mt. Neko started to flow down soon after sunset on May 29, 1974. From the data of air temperature, wind velocity and direction observed every minute during time from 21 h 00 m to 24 h 00 m in the area ranging from Stations No. 1 to No. 13, the horizontal distributions of these elements were drawn every minute. It is found from these diagrams that air temperature distribution along the slope is complex and warm areas appear at various places in this observation region. Therefore, warm areas were classified into 5 types, that is, following three types and two intermediate types of these, according to the appearance sites of the warm area (Nakamura, 1976).

Type A: The center of warm area is located near Station No. 2.

Type B: The center of warm area is located near Station No. 4 (Fig. 3.9).

Type C: The center of warm area is located near Station No. 13.

The transitions of appearance time of each type are shown for the time duration from 21 h 00 m to 24 h 00 m in Fig. 3.10. In this figure, each type arranges alphabetically from the upper part to the lower part of the slope. The distance between the locations of Type A and Type C is about 900 m. It is found that the appearance time of each type becomes to be late along the direction from the location of Type C to it of Type A, namely, warm areas travel toward from lower part to

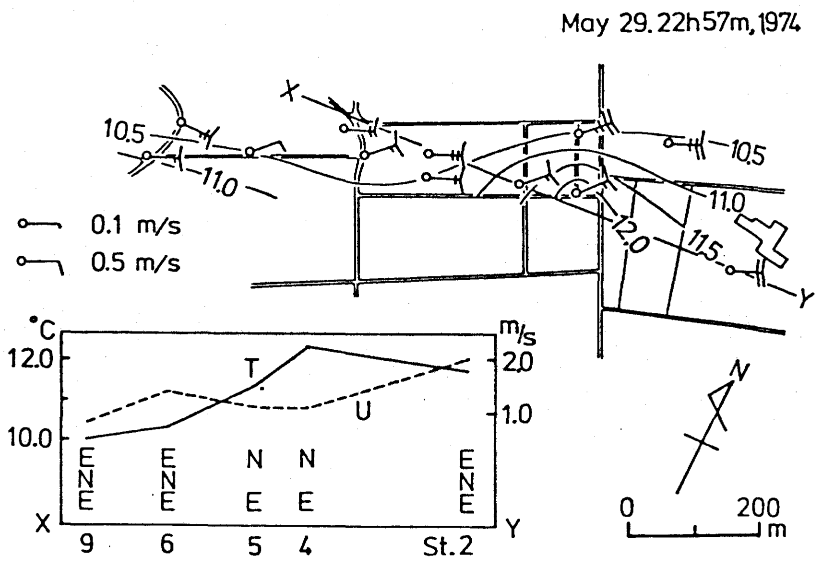

Fig. 3.9 Appearance of warm area on the slope of Mt. Neko on May 29 - 30, 1974. Lower diagram shows the air temperature (T), the wind velocity (U) and the its direction on the X - Y section of upper diagram. Solid line is air temperature and broken line wind velocity.

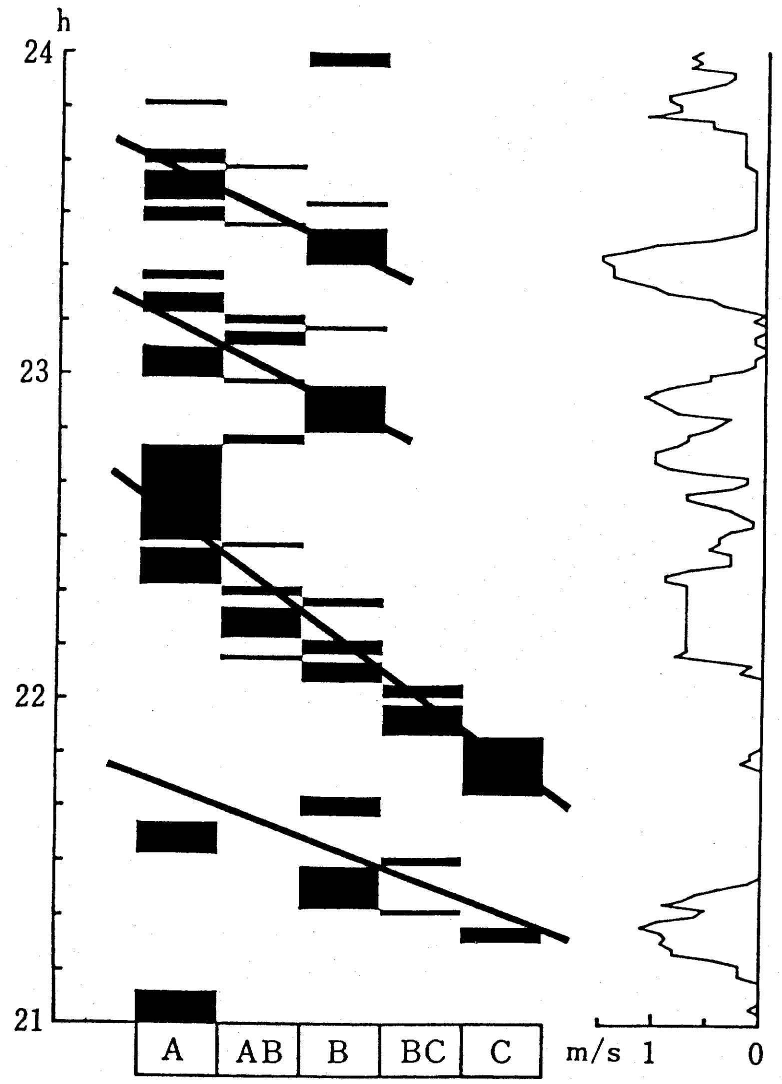

Fig. 3.10 Transformations of the whole appearance type of warm areas with time on the slope of Mt. Neko on May 29, 1974.
A, AB, B, BC, and C showing the location of warm area are arranged in this order from upper part to lower part along the slope. The distance from A to C is about 900 m. Right side of the figure shows the wind velocity at 10 m height above the ground at Station No. 15.

upper part of the slope. 20 to 60 minutes are needed in one cycle of them, so that the warm areas move toward the upper slope with the velocity of about 0.3 - 0.8 m/s. The wind velocities at a height of 10 m at Station No. 15 shown at right side in this figure give 0.0 m/s during 55 minutes equivalent to about one - third of all observation time. However, the temperature distribution of each type also appears during this time. The moving ranges of warm area don't reach lower slope in the latter half time when upper wind velocity increases gently.

It is considered that the appearance of these warm areas is caused by inflow of warm air from upper air layer as compensating stream of cold air drainage.

3.2. Relation between Flowing Distance and Velocity of Cold Air Drainage

As seen in Chapter 1, the velocity of cold air drainage has been studied by many investigators. Reiher (1936) set up the equation for the velocity of cold air drainage based on the assumption that cold air flows down on the slope by gravity. Taking account of the compressibility of cold air, Fleagle (1950) and Sahashi (1974) expressed theoretically the wind velocity of cold air drainage. Introducing the radiative cooling effect of air layer and the effect of heat advection with flow-down into Prandtl's theory (1942), Koresawa (1961) tried the accommodation of this theory to the small scale downslope wind (cold air drainage). Sakamoto and Ishida (1973) constructed the one dimensional model of downslope wind, considering the heat balance on the ground surface of the slope.

Although many of these theories are very complicate, they don't predict the velocity of cold air drainage accurately. Therefore, in this Section, it is tried to expose the relation between flowing distance and velocity of cold air drainage, experimentally.

3.2.1. At the Snow Field

Micrometeorological observations on the snow surface (about 50 cm snow depth) on the slope of Mt. Neko, were carried out at nights during the period from December 25 to 27, 1973. The observations of air temperature (by thermistor thermometer) and wind velocity (by photo-electronic anemometer) were conducted at 0.5, 1.0, and 2.0 m heights above the snow surface at Stations A to D (Fig. 3.1). However, since the condition of observation was so wrong that a few instruments did not work completely, only Stations B and C were available for the observations. For the investigation on the relation between flowing distance and wind velocity of cold air drainage, it is necessary that the inclination of the slope, vegetations and other ground conditions on the slope are uniform.

Stations B and C were satisfied with these conditions, approximately. The wind velocities investigated were that at 2.0 m height above the surface.

The cold air drainage which started due to a sudden falls in temperature (about 6 °C) at 1 h 30 m December 27, continued during 7 hours until 8 h 30 m (Fig. 3.11). The velocity of cold air drainage decreased gradually during one hour from 7 h 30 m to 8 h 30 m, which was suitable to use for evaluating the flowing distance of cold air drainage.

Fig. 3.12 is drawn in order to calculate the ratios (α) of 5 minutes mean wind velocity at Station C (No. 4) to this (U_b) at Station B (No. 6). α is expressed by following equation.

$$\alpha = -0.30\, U_b^2 + 0.98\, U_b + 0.05 \qquad (2)$$

It is assumed that as the distance from Stations B to C is 200 m, the wind velocity at any point distanced 200 m from the base point is calculated by use of the α. Namely, following equation is assumed to be used to obtain the wind velocity at any point.

$$U_{n+1} = \alpha U_n \quad , (n = 1, 2, 3 \cdots\cdots) \qquad (3)$$

where U is wind velocity and suffix n represents Station. The relation between flowing distance (L) and wind velocity (U) obtained by this method is shown by black circles in Fig. 3.13, and this is also expressed by following equation.

$$U = 1.48\, L^{1.57} \qquad (4)$$

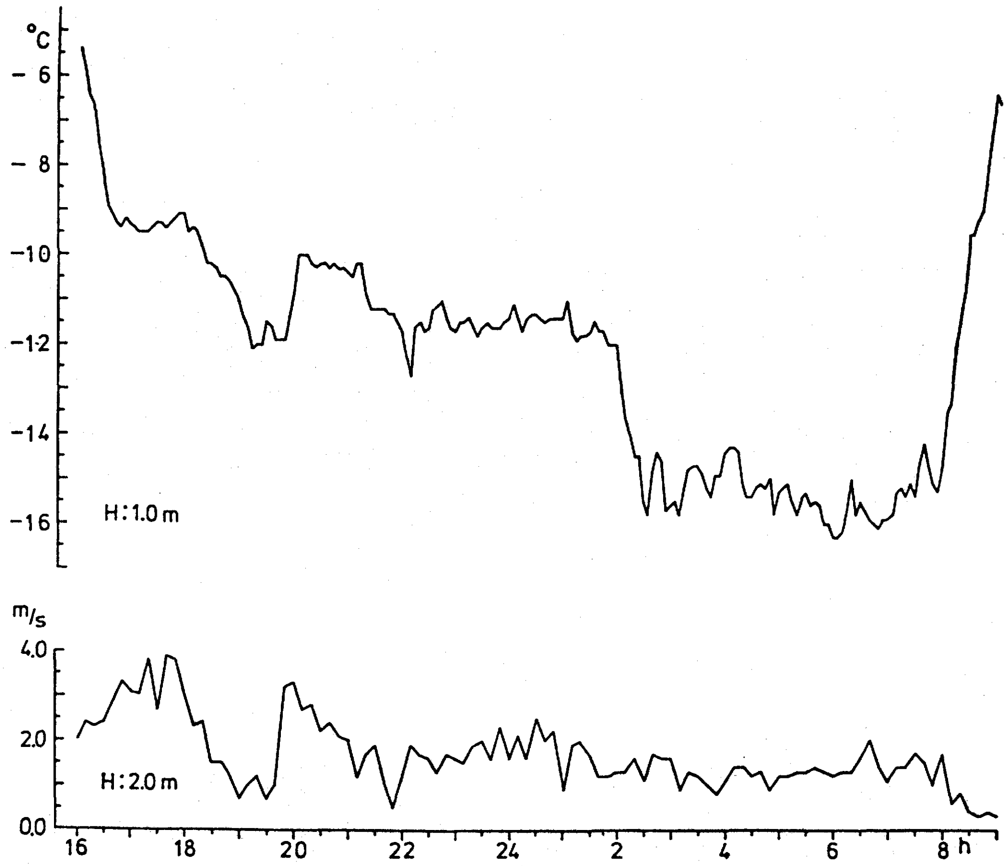

Fig. 3.11 Variations of air temperature and wind velocity at a station (Station C) located on the lower part of the slope of Mt. Neko on December 26 - 27, 1973.

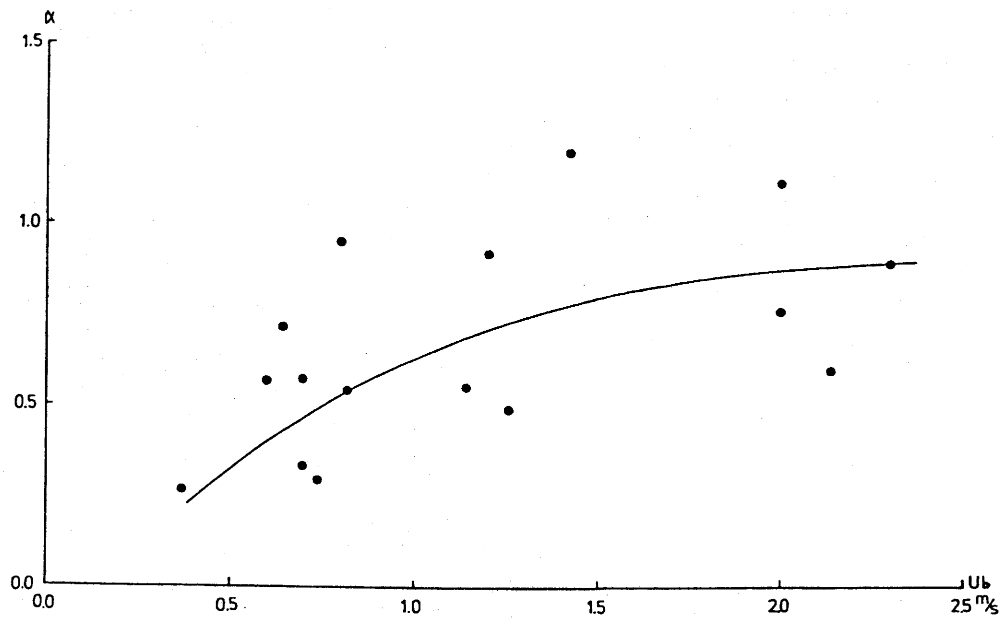

Fig. 3.12 Relation between α and U_b at a station (Station B) located on the lower part of the uniform slope of Mt. Neko during the time from 7 h 30 m to 8 h 30 m on December 27, 1973.
$\alpha = U_c/U_b$, U_b = velocity at Station B,
U_c = velocity at Station C.

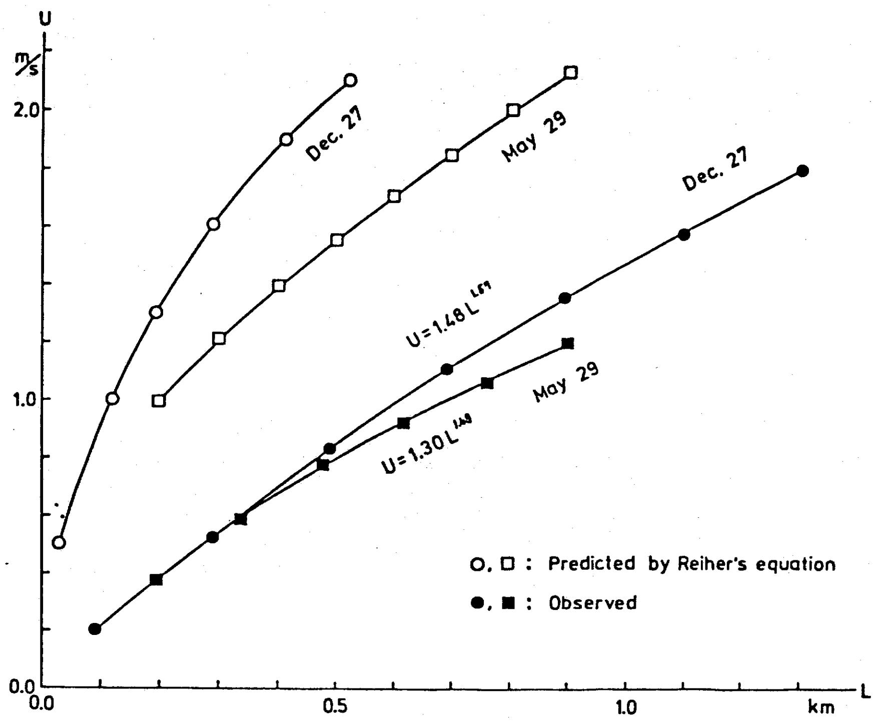

Fig. 3.13 Relation between the flowing distance and the wind velocity of cold air drainage on the slope of Mt. Neko on December 27, 1973 and May 29, 1974.

3.2.2. At the Cultivated Field

The cultivated field in the observation area was in the state of bare soil on May 28 - 30, 1974. The main purpose of this observation was to grasp the horizontal distribution of cold air drainage. However, in this Section, the observation results only at Stations No. 6 (B) and No. 4 (nearest C) are used for the comparison of the relation between flowing distance and wind velocity on the snow field with that on the cultivated field.

Cold air flowed down almost continuously during the 3 hours from 21 h 00 m to 24 h 00 m May 29 (Fig. 3.14). Therefore, the observation results during this time was analyzed by use of same method as previous one. The relation between flowing distance (L) and wind velocity (U) on the cultivated field is shown by black squares in Fig. 3.13, and also expressed by following equation.

$$U = 1.30\ L^{1.49} \qquad (5)$$

3.2.3. Comparison with the Other Empirical Equation

When the relation between flowing distance and wind velocity on the snow field was compared with that on the cultivated field, the difference between the both was so small that one could not detect it to the firest 300 m of flowing distance (Fig. 3.13)

However, the difference began to spread from 300 m.

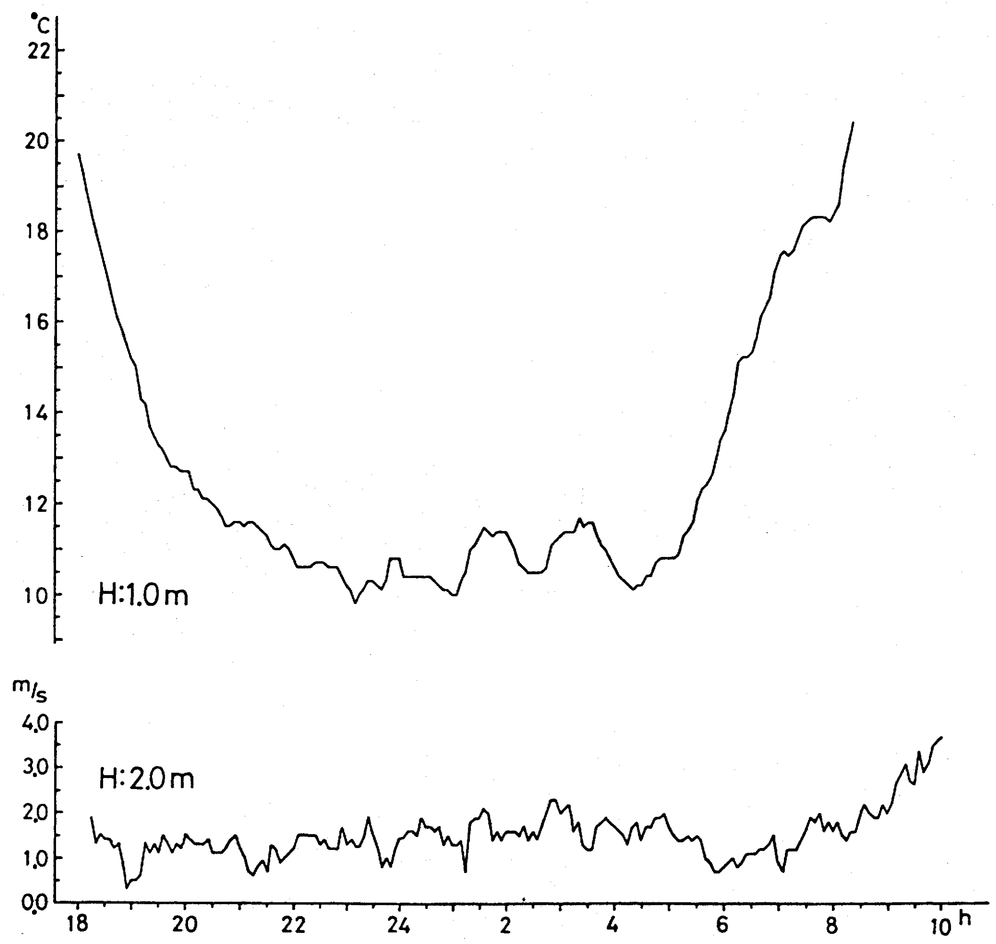

Fig. 3.14 Variations of air temperature and wind velocity at a station (Station No. 6) located on the lower part of the slope of Mt. Neko on May 29 - 30, 1974.

For example, flowing distance of cold air on the cultivated field which needs to obtain wind velocity 1.0 m/s was 700 m. It is 100 m longer than that on the snow field.

Next, it is tried to compare the observed results with that calculated by the Reiher's (1936) equation. His equation is:

$$U = \sqrt{2h \frac{T - T'}{T'} \cdot g} \qquad (6)$$

where U is the velocity of cold air drainage, h is difference of height, T is the absolute temperature of cold air, T' is the absolute temperature of air around the cold air, and g is the acceleration of gravity. The relation between flowing distance and wind velocity calculated by the Reiher's equation is shown in Fig. 3.13. The values of T and T' are calculated from the top and bottom of temperature curve by means of the same method with Tateishi (1961), respectively.

According to the results observed, the wind velocities on the snow and cultivated field per flowing distance 500 m show 0.84 m/s and 0.78 m/s, respectively. On the other hand, the velocities calculated by the Reiher's equation give 2.05 m/s and 1.55 m/s, respectively. These are 2.0 to 2.4 times larger than the observed values. It is considered that the discrepancy is caused by the use of Reiher's equation in which friction term is not contained.

The factors affecting the velocity of cold air drainage on the slope may be as follows:

(1) The velocity and direction of general wind in

the upper air layer.

(2) The intensity of inversion in the surface air layer.

(3) The friction effect of the ground surface.

(4) The angle of inclination of the slope.

As the both observations were carried out on the same slope, the cold air drainages on the both fields have equal condition with respect to (4). This was also same with respect to (1), because the wind velocities and directions at the 850 mb level in Wajima at 9 h December 27, 1973 and 21 h May 29, 1974 were WSW 8 m/s and WSW 10 m/s, respectively. The mean values of the difference (ΔT) between air temperature ($T_{2.0}$) at 2.0 m height and that ($T_{0.5}$) at 0.5 m height at Station B (No. 6) showed 0.3°C at night on December 27 and 0.2°C on May 29, respectively. This signifies that the intensities of inversion on the both days were also nearly equal. Therefore, it can be considered that the difference between the rates of wind velocity to the flowing distance on the snow field and on the cultivated field is due to the difference of the friction effects under the conditions of these fields.

3.3. Synoptic Conditions for Cold Air Drainage

Cold air flows down on the slope at clear and calm night covered with anticyclone (Lawrence, 1954), and then a sudden rise of nocturnal temperature occurs. The cold air drainage appears intermittently (Nitze, 1936; Küttner, 1949; Mano, 1953, 1956). According to unpublished data observed (by Kanamaru) in the Nasu region, Tochigi Prefecture, Japan, the rise of temperature in this region occurred when the wind velocity at the 1,000 mb level at Tateno, Ibaraki Prefecture is less than 10 KTS and less than half of the wind velocity at the 800 mb level. It may be necessary for the cold air drainage that pressure gradient is small and wind velocity at the lower air layer is weak, so that the cold air flows down at night when the ground inversion due to radiative cooling is formed actively. The low humidity of atmosphere is also necessary, so that the latent heat is so less that the radiative cooling is forced (Lawrence, 1954).

Therefore, an attempt was made to study the relation between these synoptic conditions and cold air drainage.

3.3.1. Relation between Meso-scale Pressure Conditions and Cold Air Drainage

After the daily observation data of Japan Meteorological Agency, the daily charts of local weather for the Central Japan were obtained. These are charts for the times of 21 h and 3 h at which the observations of cold air drainage were carried out on the slope of Mt. Neko during the period from August 1973 to September 1976. Table 3.2 shows the 11 examples of pressure pattern for the cases of 21 h and 3 h. In this table L denotes the local anticyclone, H the

Table 3.2 Occurrence frequency of pressure patterns in Central Japan during the nights when cold air flows down on the slope of Mt. Neko.

Type \ Time		21 h		3 h	
L	m	4	% 55	7	% 100
	c	2		2	
	t	0		2	
H		5	45	0	0
Total		11	100	11	100

L denotes the local anticyclone, H the anticyclone without local anticyclone, m the maritime anticyclone, c the continental anticyclone and t the travelling anticyclone.

anticyclone without local anticyclone, m the maritime anticyclone, c the continental anticyclone, and t the travelling anticyclone. Local anticyclones are found on the all examples at 3 h, although they are found on the only 55 % of 11 examples in all at 21 h.

Subsequently, it is tried to investigate the relation between the pressure gradient in Sugadaira and its vicinity and the drainage time of cold air in there. The method used is as follow: firstly, mean values of deviations of sea level pressure between Nagano and Takada and between Nagano and Matsumoto at 21 h and 3 h are calculated. The drainage time of cold air is determined from the relation between air temperature and wind velocity. The relation between the mean values of deviations of sea level pressure and the drainage time of cold air is calculated (Fig. 3.15). By use of this method, it is found that the smaller the pressure deviation is, namely the smaller the pressure gradient is, the longer the drainage time is. Since the distances from Nagano to Takada and to Matsumoto are about 50 km, respectively, the drainage time is about 6 hours when the pressure gradient is 1.0 mb/ 100 km, and is about 4.5 hours when this 2.0 mb/ 100 km.

3.3.2. Relation between Vertical Air Conditions and Cold Air Drainage

In order to make clear the effect of the vertical

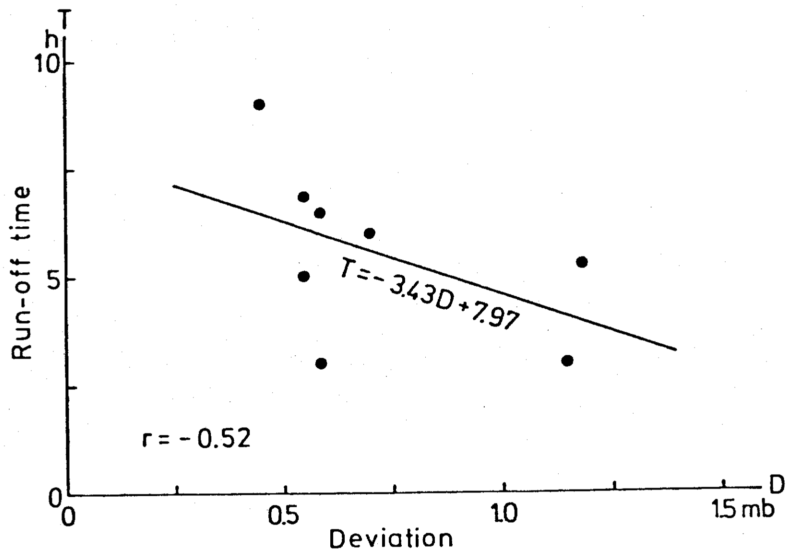

Fig. 3.15 Relation between the deviation of sea level pressure and the drainage time of cold air in Sugadaira.
The deviation is the mean value of the sea level pressure differences which were obtained between Nagano and Takada, and between Nagano and Matsumoto at 21 h and 3 h August and December 1973, and May 1974.

conditions of pressure gradient, velocity, temperature and relative humidity on cold air drainage, the diagrams of these were obtained to the 500 mb level by use of Aerological Data. Fig. 3.16-a and 3.16-b show typical examples of these. The former is that for the case in which the drainage time of cold air is more than 6 hours. The latter is that for the case in which the time is less than 2 hours. The observation area in Sugadaira is located at a height of the 850 to 900 mb level at the central portion of the distance between Wajima and Tateno. The distances from the central portion to these are about 150 km.

The drainage time of cold air is long when the difference of isobaric surface height at the 850 - 900 mb level between Wajima and Tateno is less than 18 m (6 m/ 100 km) or, in other words, when the wind velocity in the air layer lower than the 850 mb level is less than 10 m/s. Especially, this wind velocity is less than 5 m/s at the 1,000 mb level. In this time, the atmosphere at the 850 - 900 mb level indicates stability or conditional instability. Also, the values of the relative humidity decrease with increasing height up to the 500 mb level, and those are less than 50 % at the 800 mb level and 14 - 44 % at the 500 mb level.

On the other hand, the drainage time of cold air is less than 2 hours when the difference of isobaric surface height reaches more than 20 m (7 m/ 100 km) at the 850 - 900 mb level and when the wind velocities show more than 10 m/s at this level, and more than 5 m/s at the 1,000 mb

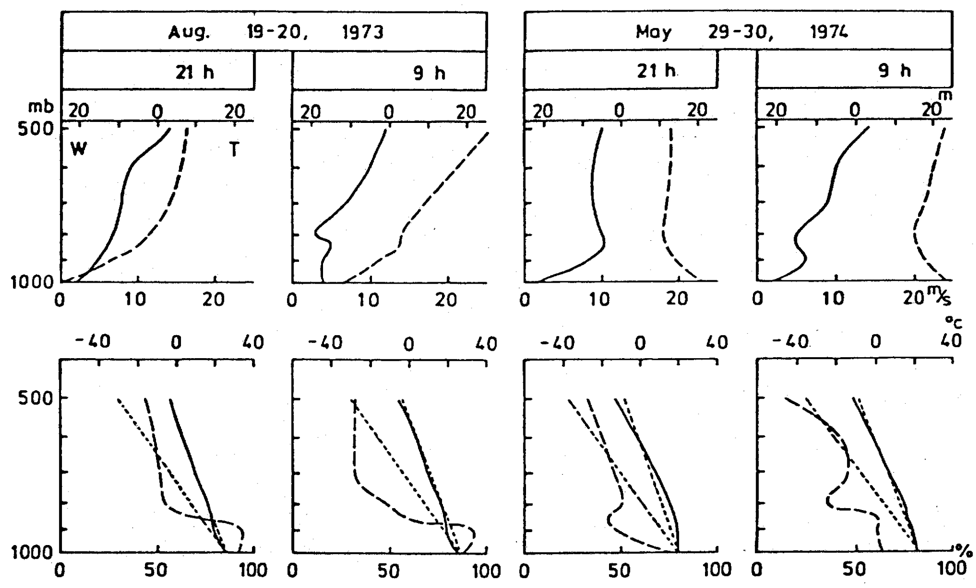

Fig. 3.16-a Vertical conditions of pressure gradient, wind velocity, air temperature and relative humidity for the case of longer drainage time of cold air.

Upper diagram : solid line is the wind velocity at Wajima and broken line the pressure gradient based on the pressures at Wajima and Tateno.

Lower diagram : solid line is the air temperature at Wajima, broken line the relative humidity at Wajima, and thin broken line the dry and wet adiabatic lapse rates.

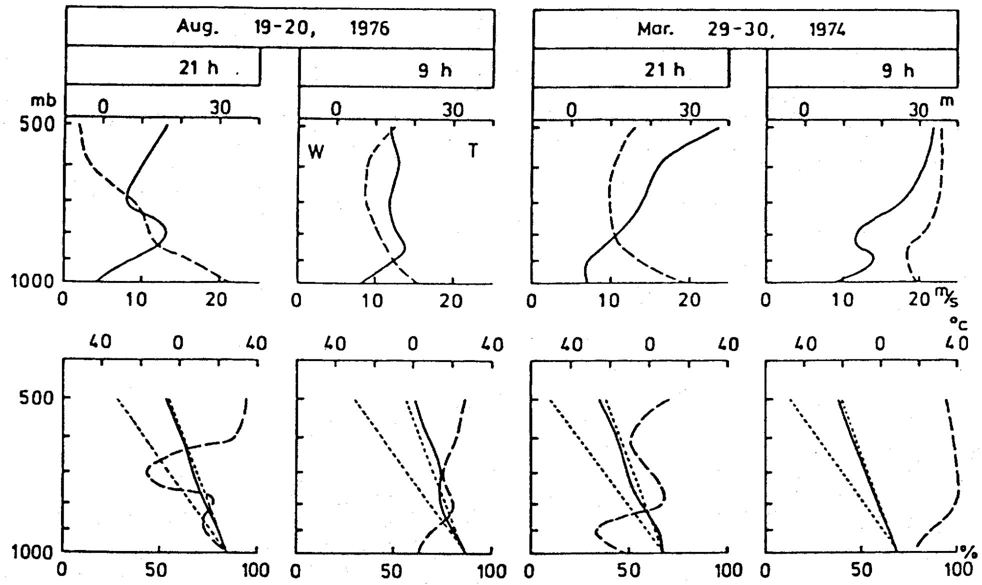

Fig. 3.16-b Vertical conditions of pressure gradient, wind velocity, air temperature and relative humidity for the case of shorter drainage time of cold air.

Upper diagram : solid line is the wind velocity at Wajima and broken line the pressure gradient based on the pressures at Wajima and Tateno.

Lower diagram : solid line is the air temperature at Wajima, broken line the relative humidity at Wajima, and thin broken line the dry and wet adiabatic lapse rates.

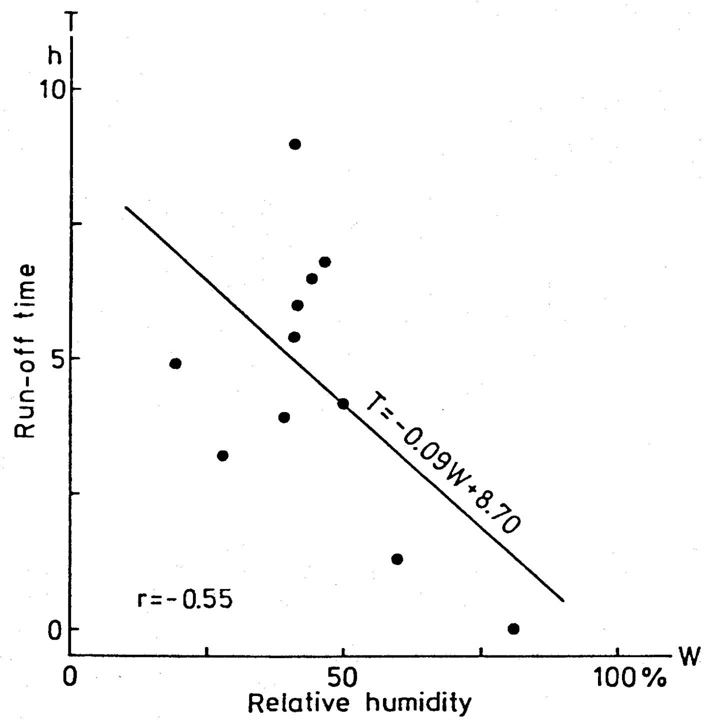

Fig. 3.17 Relation between relative humidity at the 700 mb level at Wajima and drainage times of cold air on the slope of Mt. Neko during the period from August 1973 to September 1976.

level. The atmosphere at the 850 - 900 mb level shows conditional instability, mostly. In contrast with the case that the drainage time of cold air is long, the relative humidity up to the 500 mb level tends to increase with increasing height. Further, it shows the values more than 50 % and 70 % at the air layer higher than the 800 mb level and at the 500 mb level, respectively. The relation between the drainage time of cold air and the mean values of relative humidity at 21 h and at 9 h on the 700 mb level negatively correlates in Fig. 3.17. In this figure, the drainage times reach 7 hours, 4 hours and 0 hour when relative humidities are the values of 30 %, 50 % and 80 %, respectively.

3.4. Summary for Chapter 3

It was tried to observe continuously the cold air drainage on the slope of Mt. Neko, and to make clear the general relation between the meteorological elements of this drainage. The definition of cold air drainage based on these results and the characteristics of cold air drainage can be summarized as follows:

1. The air flow which has following characteristic natures will be defined as cold air drainage. (1) The air temperature correlates negatively with the wind velocity. (2) The wind directions are within the range of $\pm 45^\circ$ from the center axis of direction of maximum inclination of the slope.

2. From the frequency of the occurrence of cold air drainage based on this definition, it is found that in the case of August, major three peaks appear at time duration, 21 h 30 m to 23 h 00 m, 24 h 00 m to 1 h 30 m and 4 h 00 m to 6 h 30 m, respectively. The absolute values of these peaks increase with time elapsed, and final peak is about 70 %.

3. Cold air drainage has the periodicity which is changeable due to location. The drainage has the tendency that the period shows a small value within the shallow valley on the upper part of the slope and a large one within the deep valley on the lower part of the slope. The seasonal difference is also detected on the period and on the range of fluctuation of cold air drainage. These values decrease according to seasons, that is to say winter to summer. Further, the range of fluctuation on the velocity of cold air drainage increases linearly with the time elapsed from just time after sunset.

4. During the time when cold air flowes down on the slope at calm and clear night, its air temperature varies along the slope, and warm areas appear at various places on the slope. The warm areas move from the lower part to the upper part of the slope with 0.3 - 0.8 m/s wind velocity.

Furthermore relation between flowing distance and velocity of cold air drainage on the slope of Mt. Neko and synoptic conditions for cold air drainage are summarized as follows:

1. The relation between the flowing distance (L) and wind velocity (U) on the snow field and on the cultivated field are expressed by following equations, respectively.

$$U = 1.48\ L^{1.57}$$

$$U = 1.30\ L^{1.49}$$

2. It is considered that the difference between the rate of the wind velocity on the snow field and that on the cultivated field to the flowing distance expresses the difference of the friction effect on each field.

3. The drainage times of cold air at Sugadaira correlate negatively with the mean values of the gradient of sea level pressure between Nagano and Matsumoto, and between Nagano and Takada. The times reach about 6 hours and 4.5 hours when pressure gradient shows 1.0 mb/ 100 km and 2.0 mb/ 100 km, respectively.

4. The drainage times of cold air on the slope of Mt. Neko (2,213 m) reach more than 6 hours, when the atmospheres at the 850 - 900 mb level (the same level with the observation area) at Wajima and Tateno have stability or conditional instability. Wind velocity shows the value less than 10 m/s at the 850 mb level, and less than 5 m/s at the 1,000 mb level. Further, the relative humidity decreases with increasing height, and the values are less than 50 % at the level higher than the 800 mb level and 14 - 44 % at the 500 mb level.

5. The drainage times of cold air can't reach 2 hours, when the atmospheres at the 850 to 900 mb level have conditional instability. The wind velocity shows the values more than 10 m/s at the air layer higher than the 850 mb level, and more than 5 m/s at the 1,000 mb level. The relative humidity tends to increase with increasing height, and its values show more than 50 % at the air layer higher than the 800 mb level, and more than 70 % at 500 mb level.

6. The relative humidity at the 700 mb level has negative correlation with the drainage time of cold air.

CHAPTER 4. SOURCE AREA AND DRAINAGE OF COLD AIR

4.1. Source and Drainage of Cold Air on the Slope of Mt. Ômatsu

The survey of the source area of cold air drainage is very important to elucidate the mechanism of the development of cold air drainage (Nakamura, 1978). The results of an observation carried out on the gentle slope in Kokchetavska of Kazakh SSR, U.S.S.R., show that cold air drainage begins from lower part of the slope before about 50 minutes of sunset (Vorontsov, 1958).

In this part of the present study, the author tried to find the areas where cold air is originated and flows down, pursuing the movement of the distribution of ground inversion on the slope of Mt. Ômatsu after sunset. Since the scale of the cold air drainage is so small after sunset that it can be grasped easily, the author especially chose these times as the observation time.

4.1.1. Air Temperature and Ground Inversion

The mean wind velocities at a height of 1 m above the ground were 2.7 m/s, 1.8 m/s and 0.3 m/s at Station No. 7 during the time of observation (sunset: about 17 h

55 m) on August 18, 19 and 20, 1976, respectively. For the understanding of the dependency of the wind strength on the air temperature variations on the slope after sunset, the isopleths of the air temperatre at a height of 0.3 m along the slope were made for the cases of August 18, 19 and 20. The isopleths at August 19 and 20 are shown in Fig. 4.1. The temperature distribution pattern at August 18 is very similar to that at August 19, so that its isopleths is omitted.

On August 19, when the mean wind velocity showed 1.8 m/s at Station No. 7, the isothermal lines are almost distributed vertically from Stations No. 3 to No. 7 on this figure, and the air temperature decreases with increasing height. However, only at the Stations between No. 2 and No. 3, the temperature increases with increasing height.

On the other hand, on August 20, when the mean wind velocity showed 0.3 m/s at Station No. 7, the isothermal lines distribute horizontally. This indicates that the air temperature changes are more largely depended on the time rather than on the height of the slope.

It is presumed that the cold air drainage is originated on the area where the air above the ground is cooled by nocturnal radiation and then ground inversion occurs strongly. The difference (ΔT) between air temperature ($T_{1.3}$) at 1.3 m height and that ($T_{0.3}$) at 0.3 m height was used to express the intensity of ground inversion. Hereinafter, this is referred to "the degrees of inversion"

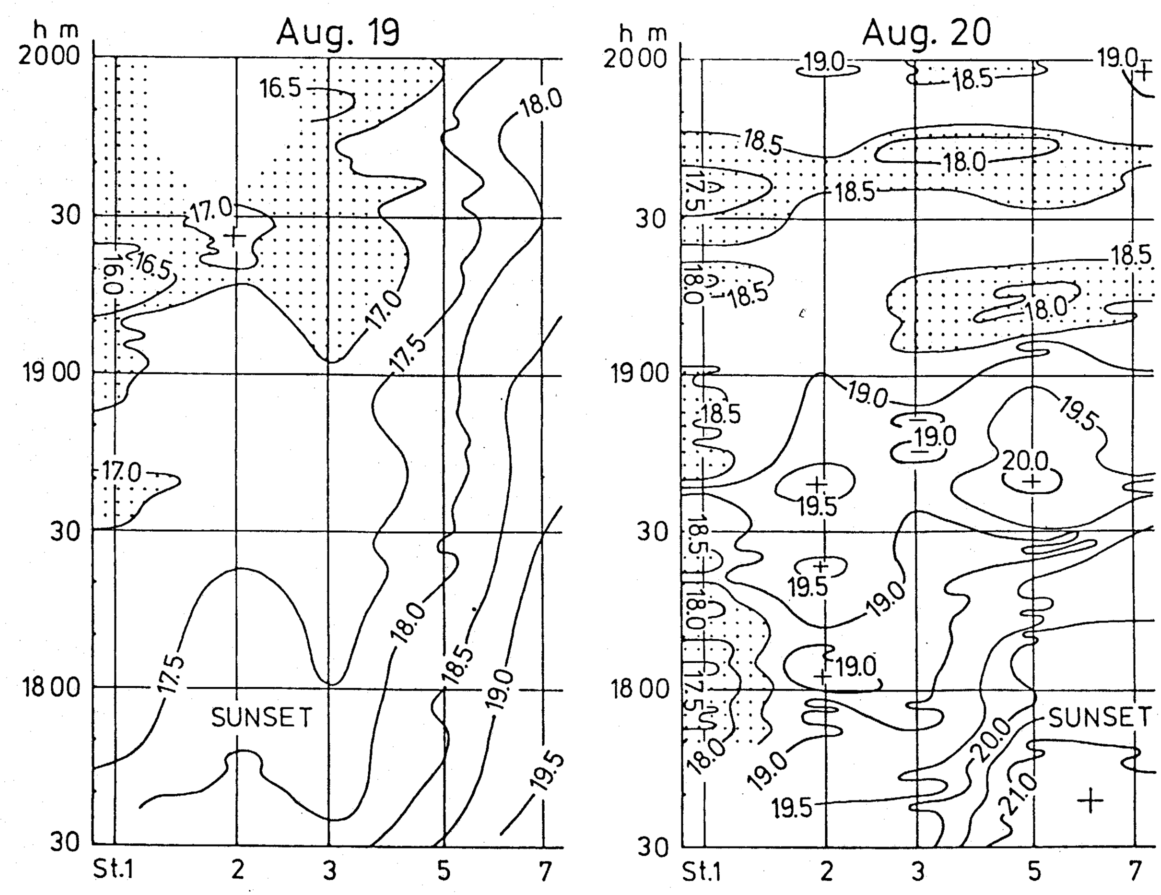

Fig. 4.1 Isopleths of air temperature on the slope of Mt. Ômatsu at nights on August 19 and 20, 1976.

in this study. The positive value of "the degrees of inversion" means the occurrence of the ground inversion on the slope.

In order to show the air temperature distributions along the slope on August 18, 19 and 20. the isopleths of "the degrees of inversion" were prepared in Fig. 4.2. According to Fig. 4.2, at the area from Stations No. 3 to No. 5 on August 18, the ground inversion is found but it is weak. On the upper and lower parts of this slope, the negative inversions appear. The inversion on August 19 is found in the area from Stations No. 3 to No. 5 as same as that on August 18 and the area spreads toward the upper and lower directions on the slope. After 18 h 15 m, the inversion of which "the degrees of inversion" is more than + 0.5 °C appears frequently in this area. Small scale inversions appear at Station No. 3 and its vicinity, and large one at the area from Stations No. 3 to No. 5. On August 20, the inversion area is also spread to Station No. 7. "The degrees of inversion" shows larger value than that of 18 th and 19 th, and the value of + 1.5 °C is obtained at Station No. 5. Further, new inversion area also appears at Station No. 1 and its vicinity, and "the degrees of inversion" at this area is about + 0.5 °C. Nevertheless, the inversion has not been appeared at Station No. 2.

Because "the degrees of inversion" defined in this study is the air temperature difference between 1.3 m and

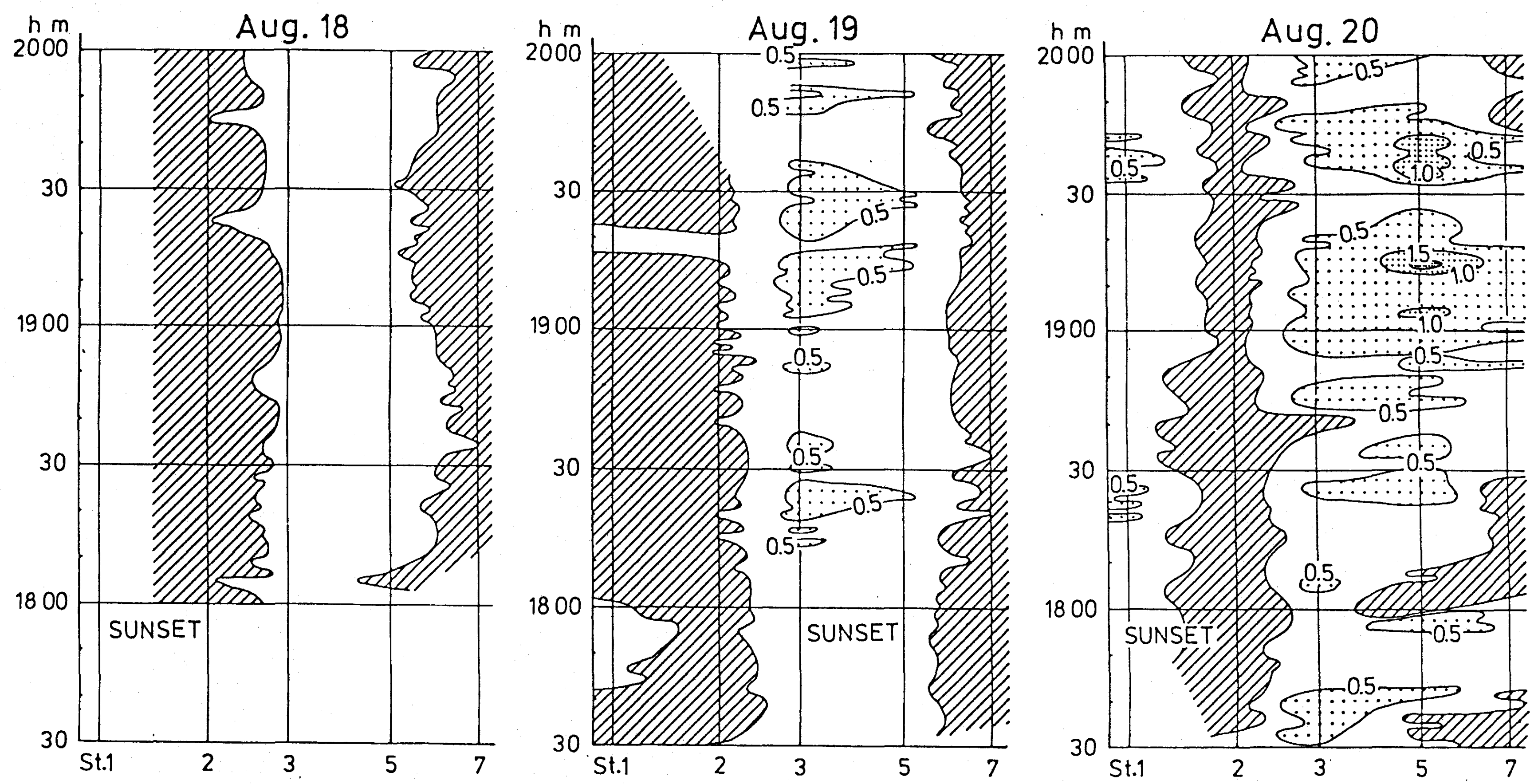

Fig. 4.2 Isopleths of "the degrees of inversion" on the slope of Mt. Ômatsu at nights of August 18 - 20, 1976. The areas of oblique lines in the figure show the negative values of "the degrees of inversion". Mean wind velocities at Station No. 7 are 2.7 m/s on August 18, 1.8 m/s on August 19 and 0.3 m/s on August 20.

0.3 m height, the inversion must be also formed when warm air flows into above the air layer near the ground. Therefore, for the determination of the area exhibiting the ground inversion caused by air cooling on the ground surface, "the degrees of inversion" and the air temperature near the ground should be taken into account. On the ground inversion area, the former is positive and the latter falls. However, since the air temperature may be increase as the ground inversion gradually diminishes, the area where "the degrees of inversion" is positive and air temperature is low on the isopleth is determined as ground inversion area. In order to express the variation of ground inversion with time on the slope on August 20, the isopleths of air temperature at 0.3 m height and of "the degrees of inversion" were superimposed mutually, and the areas where air temperature is less than 19.0°C and "the degrees of inversion" is more than + 0.5°C were defined as the strong ground inversion area, for convenience. These are shown in Fig. 4.3. It is considered that in these areas, cold air is originated and flows down.

4.1.2. Source and Drainage Areas of Cold Air

It is assumed that cold air drainage is originated on the area where ground inversion is formed strongly and "the degrees of inversion" correlates negatively with wind velocity. On the other hand, it is considered that air

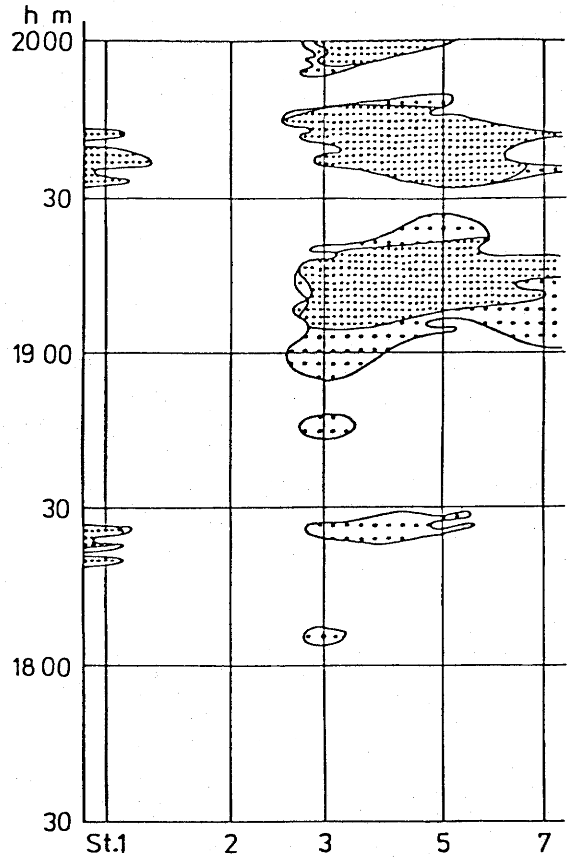

Fig. 4.3 Transition of ground inversion on the slope of Mt. Ômatsu at night on August 20, 1976. This figure is obtained from Fig. 4.1 and Fig. 4.2 for August 20, 1976. Deep shadow shows the strong inversion that air temperature is less than 18.5 °C at 0.3 m height.

temperature has a negative correlation with wind velocity on the drainage area of cold air and that the cold air flows down on the slope.

Therefore, the areas which have following characteristics can be defined to be the source area or drainage area of cold air on the slope at night.

Source area : The area where (1) "the degrees of inversion" has positive value, (2) the air temperature at a height of 0.3 m correlates positively with the wind velocity at a height of 1.0 m, (3) "the degrees of inversion" correlates negatively with the wind velocity at a height of 1.0 m, and (4) A drainage area of cold air exists on the lower part of the slope.

Drainage area : the area where (1) "the degrees of inversion" has positive value, (2) the air temperatures at a height of 0.3 m correlate negatively with the wind velocities at a height of 1.0 m, (3) the wind velocities at a height of 1.0 m are less than 3.0 m/s, and (4) a fall-wind is observed.

In these definitions, the most remarkable difference between the source area and the drainage area of cold air is in the point whether air temperature correlates positively or negatively with wind velocity. From Fig. 4.3, it is considered that the source and drainage areas of cold air observed on August 20 are ranging from Stations No. 3 to No. 5 where ground inversion develops most strongly. In order to understand the source and drainage areas of the cold air, the variations of the air temperature and wind velocity on the whole Stations (except Stations No. 4 and No. 6 for observation miss) with time during the time from 17 h 30 m to 20 h 00 m are shown in Fig. 4.4. According to this figure, the negative correlations between air temperature and wind velocity are found during the following times ; (1) from the starting time of the observation to 18 h 19 m at Station No. 1, (2) from 19 h 26 m to 19 h 41 m at Station No. 1, and (3) from 19 h 14 m to 19 h 27 m at Station No. 5.

The time of (3) corresponds to the time when the ground inversion area was formed strongly in the area ranging from Stations No. 3 to No. 7 in Fig. 4.3. The wind was direct from SSE to SSW, namely from the upper part of the slope to the lower one. From these facts, it is considered that the cold air originated by strong ground inversion flowed down during the time from 19 h 05 m to 19 h 27 m, especially 19 h 14 m to 19 h 27 m. At Station No. 3 located on the upper part of the slope than Station No. 5, a well of the air temperature variation curves with time is during the time from 19 h 00 m to 19 h 20 m. "The degrees of inversion" during this time shows the values more than + 0.5 C. However, the air temperatures at a height of 0.3 m have positive correlation with the wind velocities at a height of 1.0 m. Therefore, it is found that cold air drainage didn't exist at Station No. 3 during the time from 19 h 00 m to 19 h 20 m. From the fact that there was the

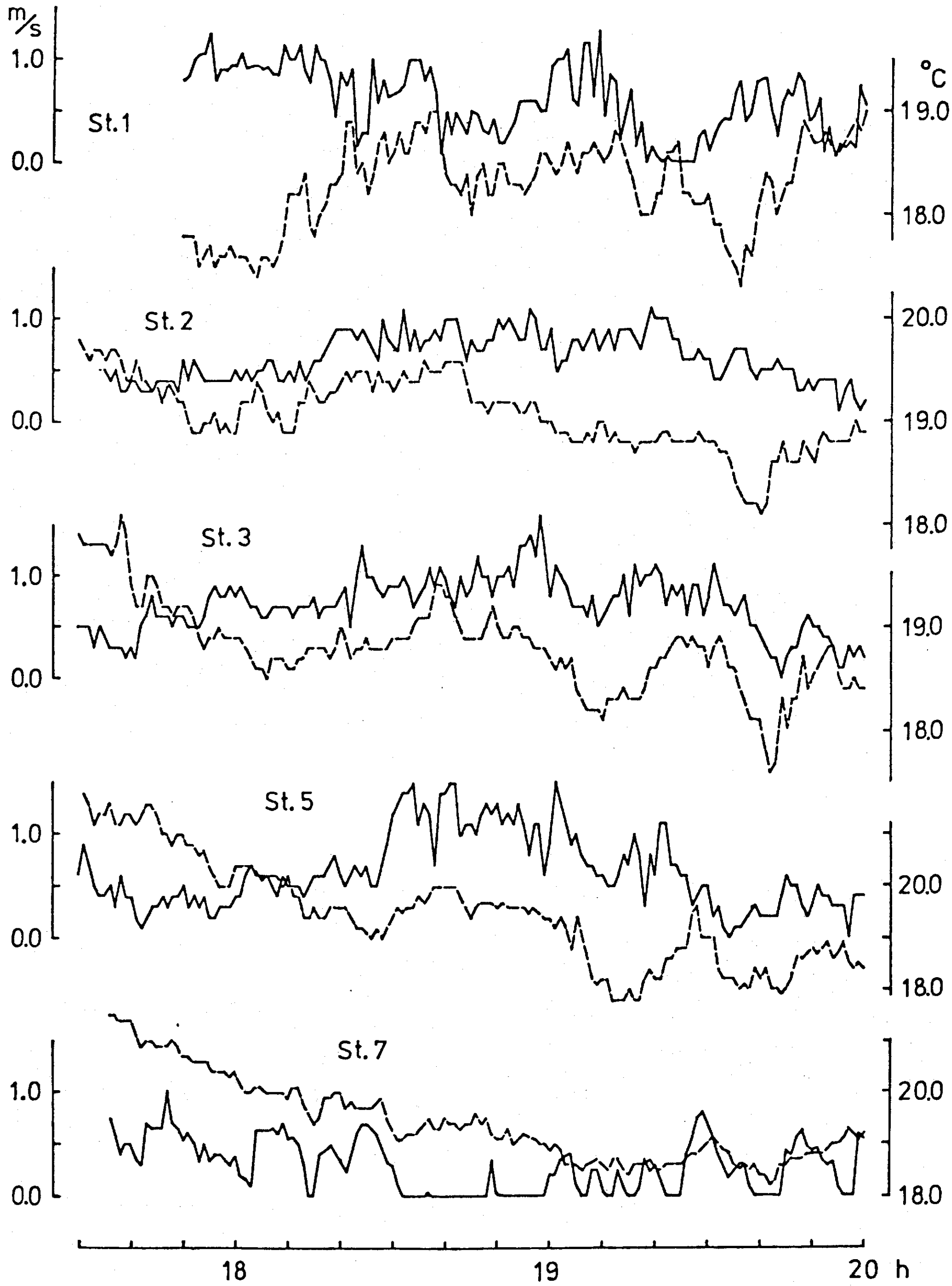

Fig. 4.4 Variations of air temperature and wind velocity on the slope of Mt. Ômatsu at night on August 20, 1976.

Solid line is the wind velocity at 1.0 m height and broken line the air temperature at 0.3 m height.

drainage area of cold air on the lower part of the slope than Station No. 3, it is considered that the source area of cold air drainage should be at Station No. 3 and its vicinity.

On the other hand, for the case of (1), it is likly from the shape of isothermal line of 19.0 °C in Fig. 4.1, that inthe direction from Stations No. 1 to No. 5, namely from upper part to lower part on the slope, cold air flows down. However, air temperatures don't correlate negatively with wind velocities at Stations No. 2, No. 3 and No. 5. A few greater values of "the degrees of inversion" (namely more than + 0.5 °C) are found here and there around Stations No. 1, No. 3 and No. 5, and "the degrees of inversion" at Station No. 2 shows always negative values after 17 h 34 m. On this time, the black cloud which was consiered to be due to inflow of the air from opposite slope of Mt. Ômatsu spread over this mountain, and the air stream from mountain top was observed. It is concluded from these facts that the air stream observed during the time is different from the cold air drainage originated on the slope.

The time of (2) seems likly to correspond to the time when the ground inversion appears strongly in the area ranging from Stations No. 3 to No. 5 during the time 19 h 32 m to 19 h 50 m in Fig. 4.3. However, air temperatures correlate positively with wind velocities at Stations No. 3 and No. 5, and the cold air drainage is not detected.

Furhter, at whole Stations from No. 1 to No. 7, air temperatures decrease at the approximately same time. Nevertheless, the wind velocities at all Stations are less than 1.0 m/s at this time. Although "the degrees of inversion" at Station No. 1 is somewhat over + 0.5 °C, that at Station No. 2 have been - 0.4 - 0.0 °C yet. From these facts, it can be clear that the air stream observed during this time is also different from the cold air drainage which is formed by cooling of the air near the ground and flows down from the upper part of the slope.

Furthermore, in order to make clear the cooling state of the air near the ground (0.3 m height above the ground), the variation curves of air temperature which standardize the values at 19 h 00 m are traced from the results of observation during the time from 19 h 00 m to 19 h 30 m at whole stations (Fig. 4.5). Although the values at Station No. 2 vary within the range of $\pm$ 0.1 °C, at Stations No. 3 and No. 5, especially at Station No. 5, the values show extremely sharp decrease rate.

From these facts, it is concluded that the air near the ground was cooled at Station No. 3 and its vicinity and that the cold air flowed downward to Station No. 5 on the slope. In this manner, the source and drainage areas of cold air after sunset on the slope of Mt. Ômatsu was found. In next Section, from the direct observation of net radiation on the slope, it is tried to make clear the cause that radiative cooling progresses strongly in these

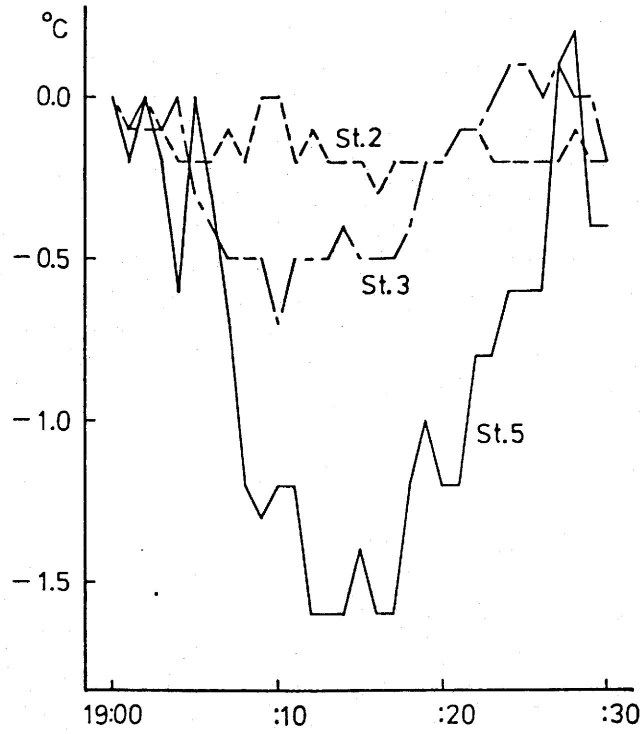

Fig. 4.5 Comparison of air temperature at the three Stations on the slope of Mt. Ômatsu at night on August 20, 1976.

areas.

4.2. Radiative Cooling and Ground Inversion on the Slope of Mt. Ômatsu

It is considered that the cold air drainage originates in the area where ground inversion is formed strongly by radiative cooling on the slope. In accordance with this consideration, in Section 4.1, the author tried to grasp the area where ground inversion is formed strongly on the slope of Mt. Ômatsu, and to divide this area into the source and the drainage areas of cold air. In order to understand the ground inversion area considered in the previous sections more accurately, the ground inversion formed by radiative cooling on the slope must be confirmed by the direct observation of net radiation (Nakamura, 1980). Therefore, from the detailed analyses for the relation between net radiation and "the degrees of inversion", and for "the vertical difference of cooling", it is tried in this part of study to grasp more accurately the areas where the formation of ground inversion occurs strongly. The radiative cooling in this paper means the temperature falling with the cooling of ground surface.

4.2.1. Economical Net radiometer

The polyethylene-shielded net radiometer has a simple structure, and it is posible to construct easily so that it can be conveniently used for the field investigation of the distribution of net radiation (Suomi and Kuhn, 1958; Tanner et al., 1960; Saito, 1964). However, the polyethylene film covering the senser surface becomes wet with dew at night, and this causes the error on the observation. In order to decrease the error due to the partial influence on the surface, the economical net radiometers which have extremely wind surface of senser (10 × 20 cm) were made without the covering of polyethylene film, and these were used for the observation at Stations No. 1, No. 2, No. 3, No. 5 and No. 7. The structure of this net radiometer is shown in Fig. 4.6.

For the examination of the economical net radiometers, the comparative observations with standard net radiometer (by Funk-type) were conducted at Station No. 3 which was situated in the center of the observation area. According to the result, it is found that the high accuracy could not be obtained by means of the economical net radiometer at nights of July 31 and August 1, since the dews put on the surface of senser of this radiometer. However, on the observations carried out during the time from 17 h 30 m to 20 h 00 m, July 30, dews were not put on the surface of the senser of the economical net radiometer at every Station. So extremely high accuracy that the coefficient of correlation is 0.930 and the standard error is 0.012 ly/min was confirmed at Station No. 3, when the net radiation observed by using

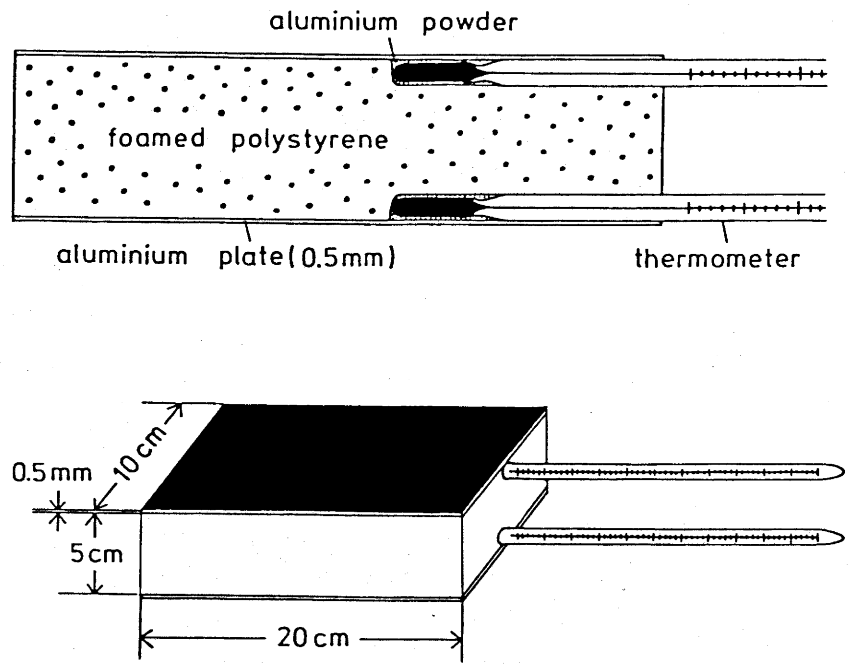

Fig. 4.6 Construction of economical net radiometer.

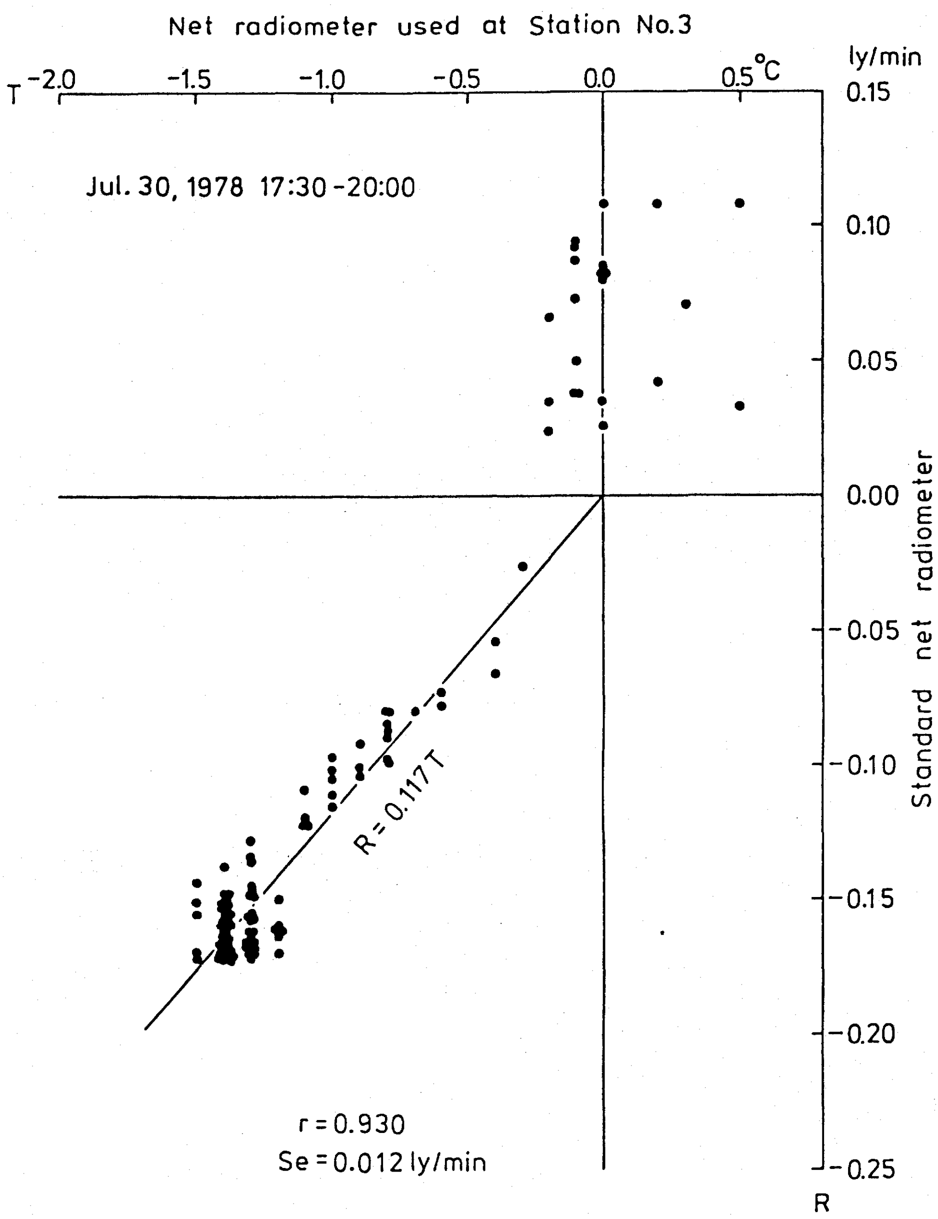

Fig. 4.7 Comparison of the accuracy of economical net radiometer used at a staion (Station No. 3) located on the middle part of the observation slope of the Mt. Ômatsu with that of standard net radiometer.

the standard net radiometer showed negative values (Fig. 4.7). The instrumental errors of economical net radiometers at each Station compared with that at Station No. 3 were + 0.023 ly/min (+ 0.2 °C) and - 0.012 ly/min (- 0.1 °C) at Stations No. 2 and No. 7, respectively, and 0.000 ly/min (0.0 °C) at the other Stations.

From the facts mentioned above, the analysis in this study is conducted only on the observation result obtained during the time from 17 h 30 m to 20 h 00 m on July 30, 1978.

4.2.2. Relation between Net Radiation and Air Temperature

Fig. 4.8 shows the difference depending upon the location for the variations of net radiation with time on the slope. In this figure, the net radiation decreases rapidly until about 18 h 30 m, and reaches constant values after 40 to 70 minutes from the time when the value changes to negative. After then, the net radiation on the slope shows the minimum value at Station No. 7 located on the lowest place, and the secondarily small value appears at Station No. 1 before this Station is influenced by air stream coming over the mountain. The large values appear at Stations No. 3 to No.5 which are located in the middle of the observation area, especially the maximum value appears at Station No. 3.

Air temperature falls rapidly with prompt decrease of

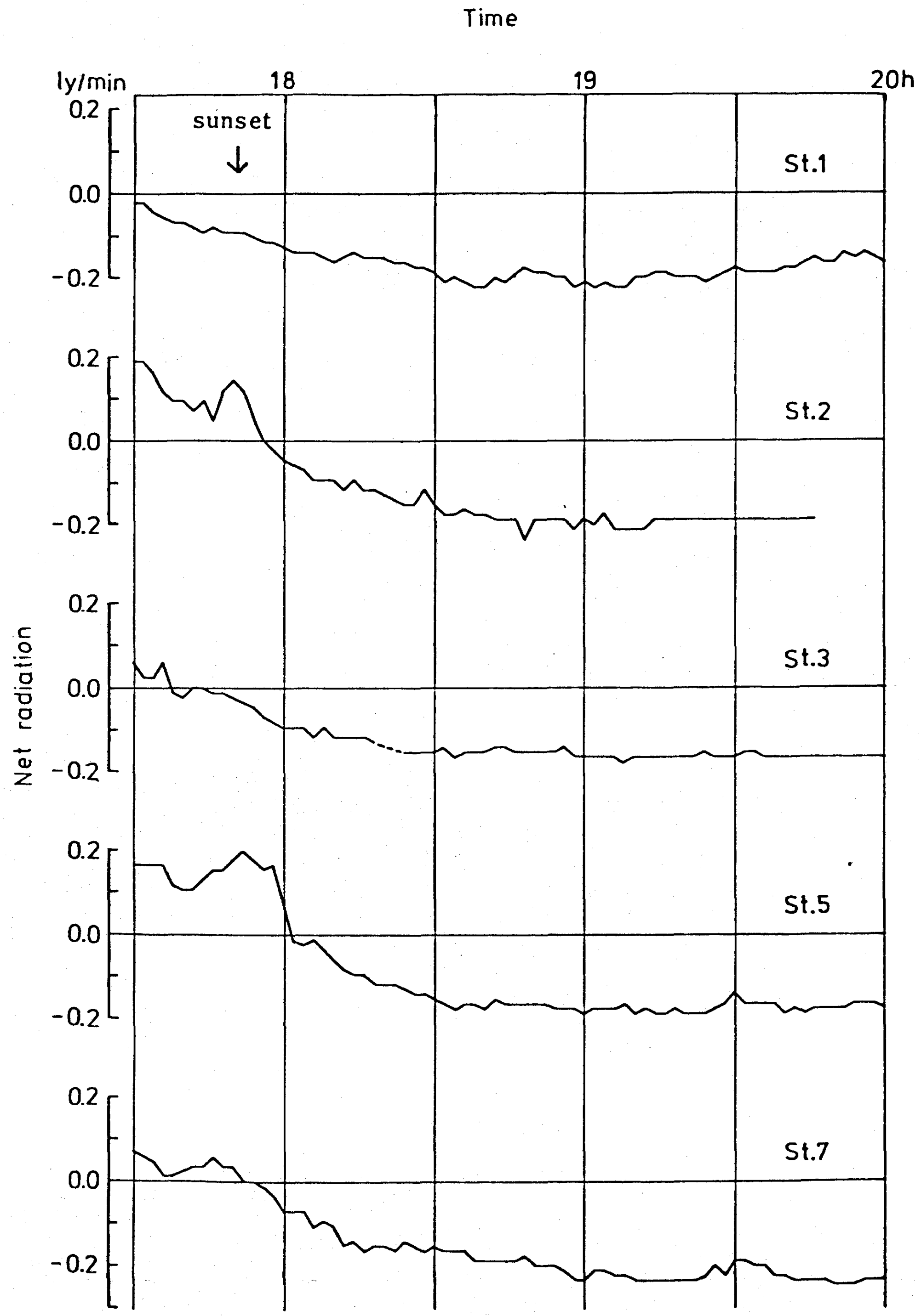

Fig. 4.8 Variation of net radiation on the slope of Mt. Ômatsu on July 30, 1978.

net radiation until 2 or 3 hours after sunset. In order to investigate the relations between the net radiation and air temperature at heights of 0.3 m and 1.3 m at every Station during the observation time from sunset to 20 h 00 m (sunset: about 17 h 50 m), Fig. 4.9 is made. On this figure, although Station No. 7 locats on the lowest part of the slope, the air temperatures at 0.3 m height at this Station show smaller value than that at Stations No. 3 and No. 5 until the net radiation reaches - 0.16 ly/min. After the time that the net radiation decreases to less than - 0.16 ly/min, the air temperature at Station No. 7 shows the highest value of these in every Station. The air temperature at 0.3 m height at Station No. 3 gives the highest value among the stations until the net radiation reaches - 0.15 ly/min. The net radiation at Stations No. 1 and No. 2 have the minimum values when they reach - 0.21 ly/min and - 0.20 ly/min, respectively, and increase after then. Its tendency is more remarkable at Station No. 1 than at Station No. 2. Then, on the relation between the net radiation and the air temperature at a height of 1.3 m, the air temperaure at Station No. 3 also tends to show the high value in comparison of height until the net radiation reaches - 0.15 ly/min. The air temperatures at the other Stations distribute according to the heights of the slope. The net radiation at Stations No. 3 and No. 5 reaches minimum values at - 0.16 ly/min and - 0.18 ly/min, respectively.

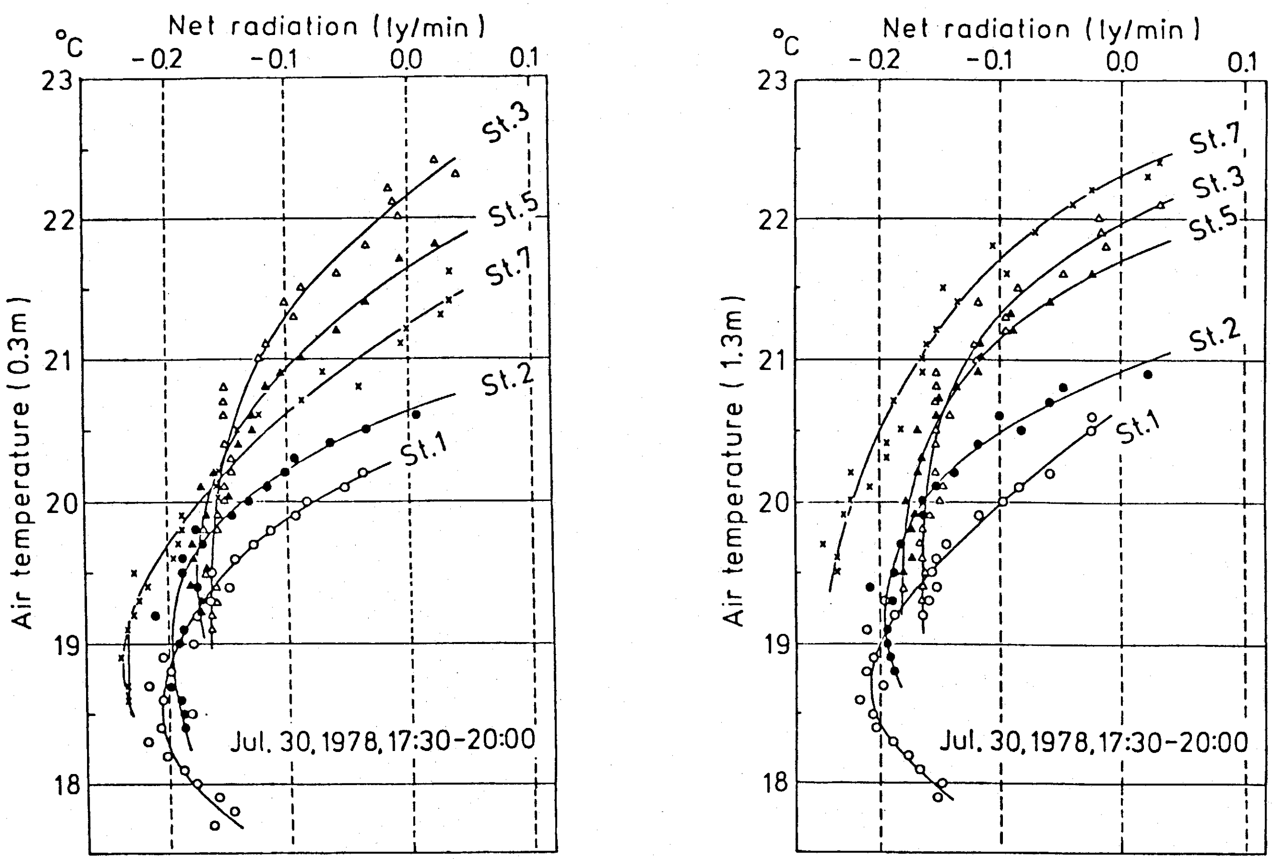

Fig. 4.9 Relations between net radiation and air temperature on the slope of Mt. Ômatsu at night on July 30, 1978.

That at Stations No. 1 and No. 2 shows the minimum values of - 0.21 ly/min and - 0.20 ly/min, respectively, and increase after then. These phenomena show the same tendency with the case of the relation between the net radiation and the air temperature at a height of 0.3 m.

4.2.3. Relation between Net Radiation and "The Degrees of Inversion"

Fig. 4.10 is given for making clear the area where the formation of ground inversion is progressing from the relation between net radiation and "the degrees of inversion". According to this figure, same tendency is found at Stations No. 3 and No. 5. "The degrees of inversion" decreases with the increase of the net radiation. "The degrees of inversion" at Station No. 1 decreases only with the increase of the net radiation. On the other hand, at Station No. 7 where "the degrees of inversion" shows the extremely large positive value, "the degrees of inversion" increases with the increase of the net radiation. Namely, it is found from this fact that the ground inversion becomes weak with the increase of outgoing radiation at Station No. 7. "The degrees of inversion" at Station No. 2 shows the positive value, and the variation of it with the increase of net radiation is hardly found.

"The degrees of inversion" decreases with the increase of net radiation in the area where the formation of ground

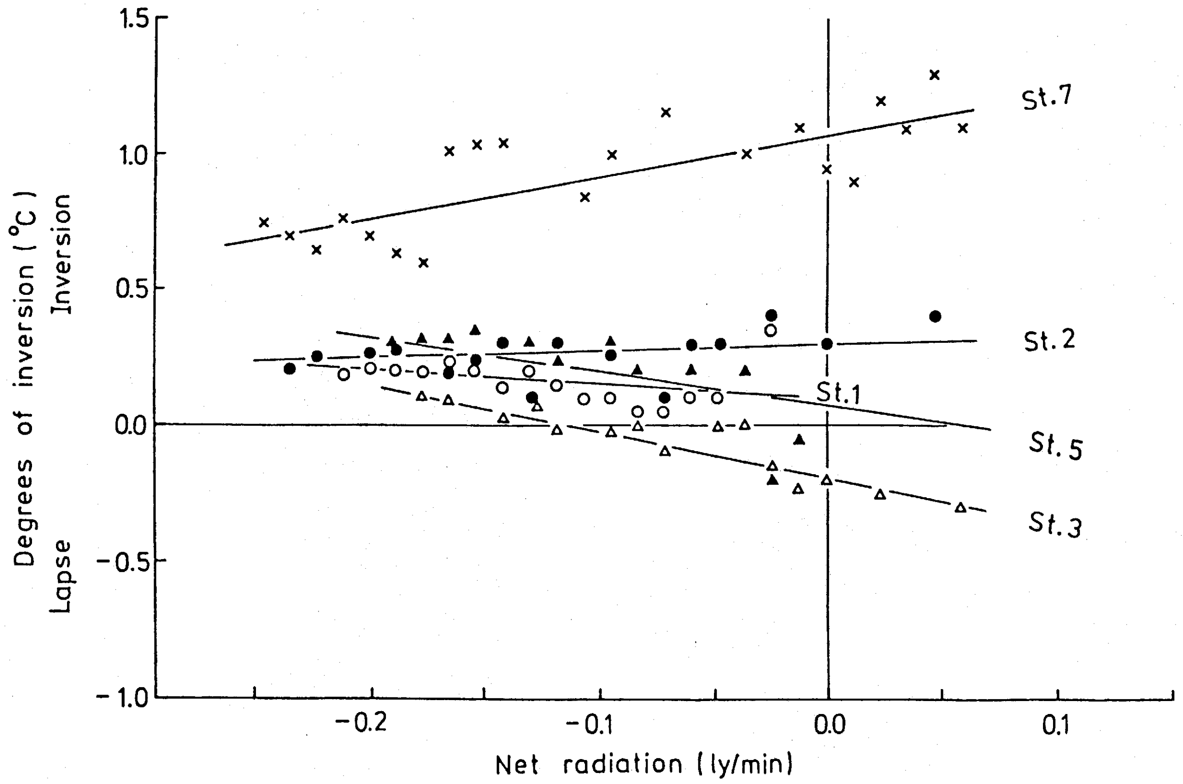

Fig. 4.10 Relation between net radiation and "the degrees of inversion" on the slope of Mt.. Ômatsu at night on July 30, 1978.

inversion is progressing. Therefore, it is considered that the formation of ground inversion with radiative cooling is progressing only in the area ranging from Stations No. 3 to No. 5.

4.2.4. "The Vertical Difference of Cooling"

It was assumed from the consideration on the previous section that the formation of ground inversion with radiative cooling developes especially at the area ranging from Stations No. 3 to No. 5. As "the degrees of inversion" is calculated from the temperature difference between 1.3 m and 0.3 m above the ground, it is possible that it shows the positive value not only when ground inversion occurs, but also when the air temperature increases only at a height of 1.3 m. Essentially, when the ground inversion is formed, the ground surface is cooled firstly, and then the cooling effects reach the higher layer. That is, the closer the air layer near the ground surface is, the faster it is cooled, in other words, its cooling rate should increase more than that of upper air layer. Therefore, it is necessary to confirm this for the recognition of the ground inversion.

In order to investigate more exactly on this cooling condition, this is analyzed by using "the vertical difference of cooling" (C) given by following equation:

$$C_t = \Delta T - \Delta T' \qquad (7)$$

where C_t is "the vertical difference of cooling" at time t, ΔT the difference between air temperatures (°C) at time t - Δt and time t at a height of 0.3 m and $\Delta T'$ the same temperature difference at a height of 1.3 m.

"The vertical difference of cooling" at every 30 minutes during the two and half hours from 17 h 30 m to 20 h 00 m is calculated at every Station. Fig. 4.11 shows the distribution of this on the slope.

The total values of "the vertical difference of cooling" at Stations No. 3 and No. 5 which are located on the center portion of the observation area have the positive greater value, whcih represents that the surface air is cooled from lower layer during the observation time. The maximum value of this at Station No. 3 shows + 0.4°C at 18 h 00 m and that at No. 5 shows + 0.3°C at 18 h 30 m. After then, these values decrease, and "the vertical difference of cooling" reaches - 0.1°C and 0.0°C at Stations No. 3 and No. 5 at 19 h 00 m, respectively. Namely, it is concluded that the rapid cooling from the lower air layer progresses until about one hour after sunset (sunset time : 17 h 50 m).

At Stations No. 1 and No. 2 located at the upper part of the observation area, the values change within the range from - 0.2°C to 0.0°C except the fact that + 0.1°C appears at 19 h 00 m and 19 h 30 m at Station No. 2. The total values of "the vertical difference of cooling" at Stations No. 1 and No. 2 give - 0.2°C and - 0.1°C, respectively.

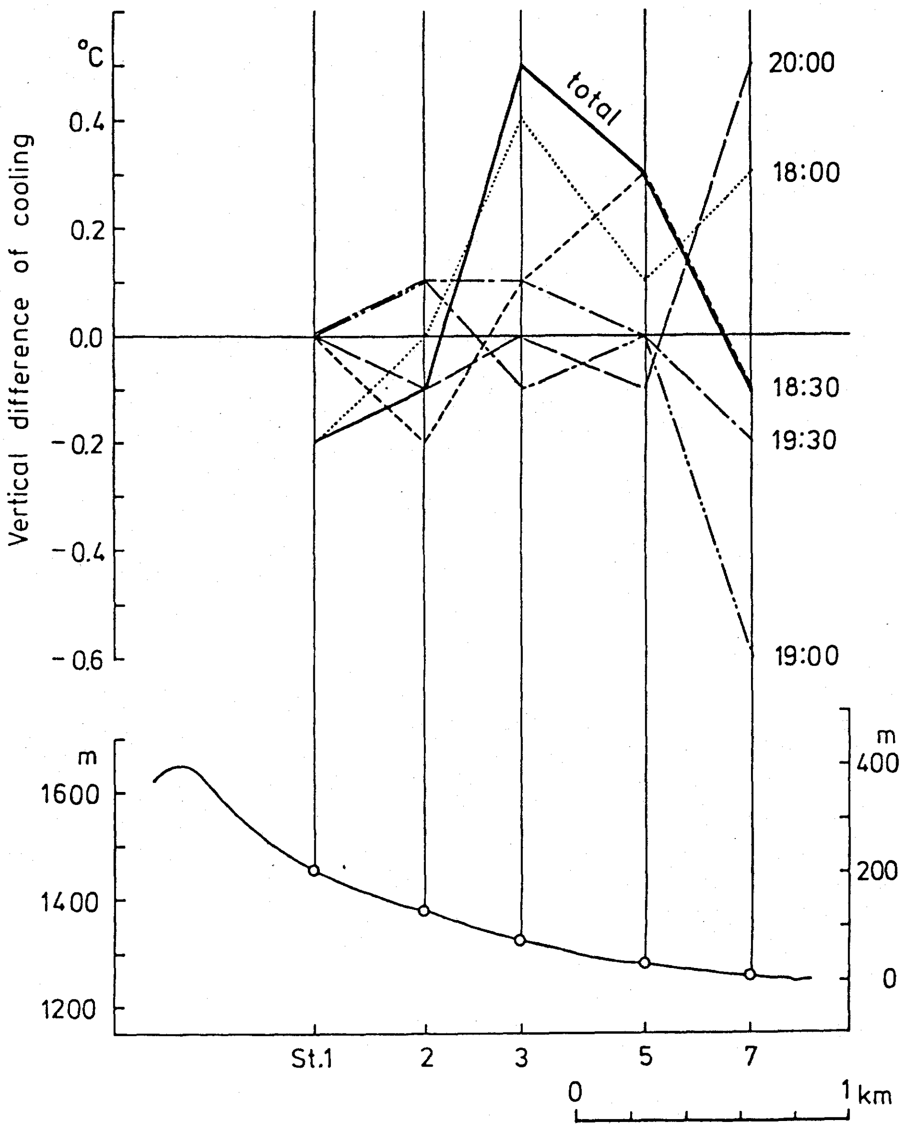

Fig. 4.11 Distribution of "the vertical difference of cooling" on the slope of Mt. Ômatsu at night on July 30, 1978.

On the other hand, "the vertical difference of cooling" at Station No. 7 shows + 0.3 °C at 18 h 00 m. However, the value decreases to - 0.1 °C at 18 h 30 m, and decreases to - 0.6 °C at 19 h 00 m. After then, "the vertical difference of cooling" begins to increase, and it reaches - 0.2 °C at 19 h 30 m and + 0.5 °C at 20 h 00 m. The maximum and minimum values of all of these appear at Station No. 7, and the difference between the maximum and the minimum values amounts to + 1.1 °C. It is considered that the cause of such drastic change is as follows: (1) The air near the ground at Station No. 7 is cooled from lower layer due to the largest outgoing radiation of the all Stations. (2) However, since this Station is located at the lowest part on the slope, the advection air from the out side of the slope destroys the inversion layer, and increases the temperature of lower air layer.

These considerations lead to the following conclusion: In the area ranging from Stations No. 3 through No. 5, the lower part of the slope of Mt. Ômatsu, the ground inversion developed strikingly during the time from 17 h 30 m to 20 h 00 m.

4.3. Summary for Chapter 4

In order to make clear the mechanism of development of cold air drainage, it was tried to investigate the source and drainage areas of cold air by understanding the variation of the distributions of air temperature and "the degrees of inversion" with time along the slope of Mt. Ômatsu diring the time from 17 h 30 m to 20 h 00 m on August 18 - 20, 1976. Furthermore, from the detailed analyses on the relation between net radiation and "the degrees of inversion", and on "the vertical difference of cooling" on the slope of Mt. Ômatsu during the time from 17 h 30 m to 20 h 00 m on July 30, 1978, the area where the formation of ground inversion is being progressed strongly by radiative cooling was investigated.

The results are summarized as follows:

1. Air temperature at 0.3 m height on the slope of Mt. Ômatsu during the time from 17 h 30 m to 20 h 00 m falls with increasing height when the wind velocity is about 2 - 3 m/s at Station No. 7 (1,250 m). This, however, is not found at a calm night or a night with light wind.

2. The values of "the degrees of inversion" are always positive at Stations No. 3 (1,320 m) and No. 5 (1,275 m) when the general wind velocities are less than about 3 m/s. The weaker the general wind is, the more the increase of "the degrees of inversion" is. So far as the observations during this period are concerned, the extreme value of "the degrees of inversion" runs into + 1.5 °C.

3. Around the Station No. 2 (1,370 m), the air temperature at 0.3 m height shows relatively high value and "the degrees of inversion" gives always negative values. The lowest air temperature is found around the Station No.

1 (1,450 m). It is, however, pointed out that "the degrees of inversion" is negative at this Station when the general wind is strong and, on the contrary, is positive when it is weak.

4. It is concluded that during the time from 17 h 30 m to 20 h 00 m on August 20, 1976, a cold air was formed around Station No. 3 during the time from 19 h 00 m to 19 h 20 m and spread downward to Station No. 5 during 19 h 14 m to 19 h 27 m.

5. "The degrees of inversion" on the slope of Mt. Ômatsu during the time from 17 h 30 m to 20 h 00 m decreases with the increase of net radiation at Stations No. 3 (1,320 m) and No. 5 (1,275 m), namely, the larger the outgoing radiation is, the larger "the degrees of inversion" is. On the other hand, "the degrees of inversion" at Station No. 7 (1,250 m) which is located at the lowest part of the slope increases with the increase of net radiation.

6. During the time from 17 h 30 m to 20 h 00 m, the total values of "the verticl difference of cooling" indicate the high positive value (Max. + 0.5°C) at the area ranging from Stations No. 3 to No. 5. It is thought from this that the surface air layer in this area is cooled from lower layer by radiative cooling. On the other hand, the total values of "the vertical difference of cooling" indicate negative at Stations No. 1, No. 2 (upper part of the observation area), and No. 7 (lower part of that). It is considered from this fact that the cooling from the

lower air layer is being prevented by advection air from the outside of the slope.

CHAPTER 5. VERTICAL STRUCTURE OF COLD AIR DRAINAGE

In Chapter 4, the source and drainage areas of cold air on the slope of Mt. Ômatsu were made clear. This investigation was conducted by micrometeorological observation up to 1.3 m height above the ground. Therefore, in order to grasp the whole aspect of cold air drainage, it is necessary to observe by using captive balloon the meteorological elements in the further upper air layer.

As mentioned in Section 1.2.5, the several kinds of models of nocturnal air circulation on the mountain slope have been reported based on the observation results in the basin of Ôchô village of Ôsaki-Shimojima Island in the Inland Sea, SW-Japan (Mano, 1953, Fig. 1.1), on the slope of Mt. Bandai, NE-Japan (Mano, 1956, Fig. 1.2), on the gentle slope of relative elevation 110 m in Tsrikovka Village of Kokchetavska, Kazakh SSR, U.S.S.R. (Vorontsov, 1958, Fig. 1.3), on Hakatajima Island, Setouchi region, SW-Japan (Kimura, 1961, Fig. 1.4) and so on.

From these reports, it is concluded that the circulation system related to cold air drainage certainly exists on the slope, although there are some problems with respect to observation accuracy and the number of the station for observation (Nakamura, 1982).

Therefore, in this Chapter, elucidation on the whole aspect of cold air drainage is tried by analyzing the vertical structure of air layer on the mountain slope in detail.

5.1. Vertical Structure of Cold Air Drainage on the Mountain Slope in Engaru

The meteorological observations were carried out at four stations on the N-facing mountain slope in Engaru, Hokkaido, at the clear and calm night from 22 h 05 m July 21 through 00 h 12 m July 22, 1979. The mobile observations of the air temperature and the wind velocity and direction at 5, 10, 20, 30, 40, 50, 60, 70, 80 and 85 m heights were conducted in series from Staion No. 4 (150 m) to No. 1 (350 m) by use of thermistor thermometer with fan, the micro-anemometer and vinyl string for the detecting the wind direction loaded on the captive balloon.

The wind velocity on the slope couldn't be measured by micro-anemometer because of very weak wind. Therefore, only the observation result of wind direction is shown in Fig. 5.1. As the slope faces N, the air stream from the direction within the range of SE to SW can be called downslope wind. Similarly, an opposed air stream will be called anti-downslope wind. The downslope wind develops in the first 15 m above the ground at Stations No. 1 and No. 4, in the first 5 m at Station No. 2 and in the first 10 m at Station No. 3, respectively. In the

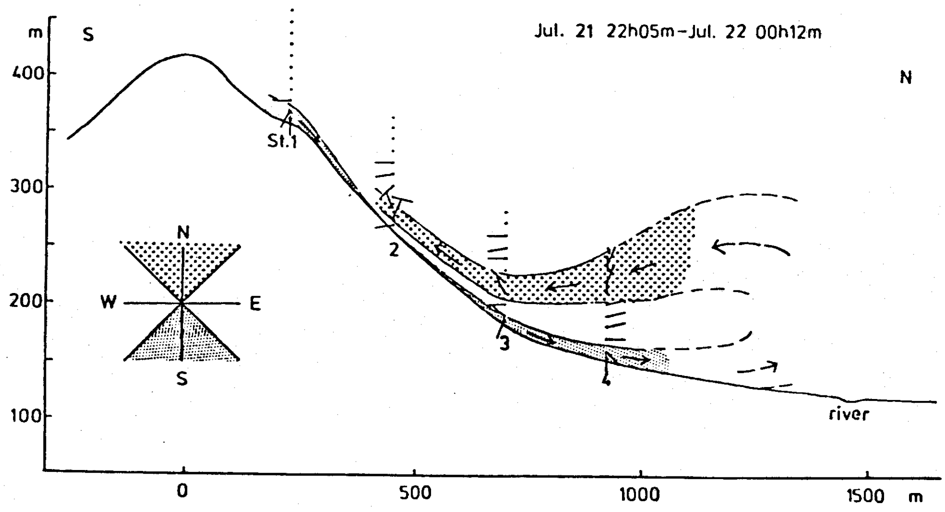

Fig. 5.1 Wind direction profile and circulation system on the mountain slope in Engaru at night on July 21 - 22, 1979.

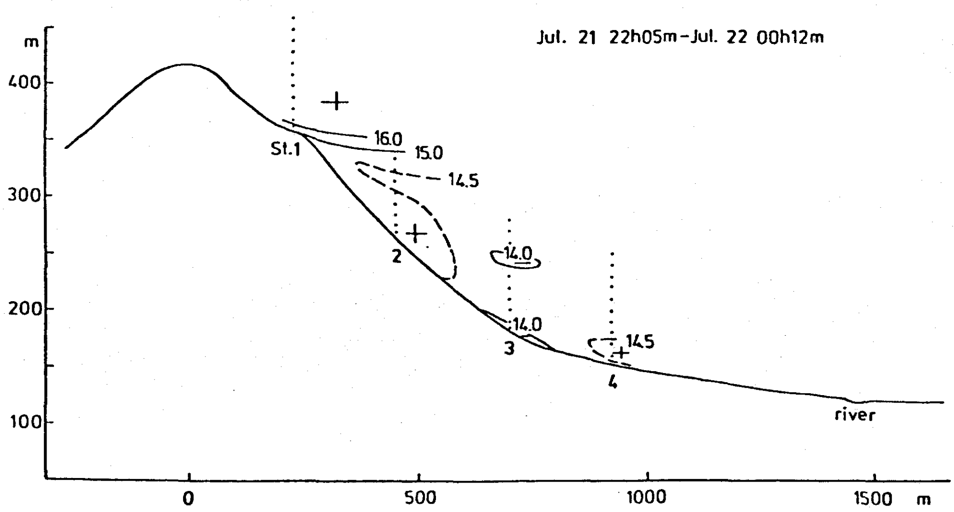

Fig. 5.2 Air temperature profile on the mountain slope in Engaru at night on July 21 - 22, 1979.

upper air layer above that, the anti-downslope wind is found in the layer of 10 - 20 m above the ground at Station No. 2, 25 - 45 m at Station No. 3 and 50 - 100 m at Station No. 4, respectively. It is considered that these stream may make the circulation system which is shown by broken line in Fig. 5.1.

The vertical distribution of air temperature on the slope during this observation time is given in Fig. 5.2. The air temperatures distribute in the range of 14.0 - 14.5 °C in the air layer with about 180 m depth ranging from 150 m to 330 m on the lower part of the slope, that is, the variation of temperature is found hardly in this layer. However, the inversion of about 1.5 °C/ 30 m appears near 350 m height. The warm air layer is observed slightly near the ground at Station No. 2. From the facts that the thickness of downslope wind is very thin near Station No. 2 and that the height of anti-downslope wind above the slope is the lowest among all stations, it is assumed that this warm air layer is formed by the way that anti-downslope wind turns to downslope wind near Station No. 2.

From the results mentioned above, it is possible to draw a model of the circulation system related to cold air drainage on the mountain slope in Engaru, though it is imperfect.

5.2. Vertical Structure of Cold Air Drainage on the Slope of Mt. Ômatsu

5.2.1. The Case of August 25, 1980

Four observation points (Stations C, F, G, and I) were set up on the slope (Fig. 2.3). The mobile observations were carried out with same manner as the observations in Engaru described in Section 5.1. The observations at 2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90 and 100 m heights were conducted in series from Stations C (1,370 m) to I (1,250 m) during the time from 2 h 53 m to 5 h 38 m. The wind velocity was obtained as one minute mean values at each height.

The three dimensional wind velocities in the first 100 m above the ground was calculated by composing the horizontal and the vertical wind velocities and the wind directions at each observation height measured by use of the same method as Section 5.1. The vertical wind velocities were observed by vertically set anemometer. The distribution of the components of the wind along the slope is shown in Fig. 5.3. In this Section, the air stream which has the wind direction within the range of SSE to WNW centering SW will be called downslope wind because the slope faces NE. Similarly, oposed air stream will be called anti-downslope wind.

At Station I, upward motion develops in the first 100 m above the ground (80, 100 m : wind directions are indistinct). At Station G (1,275 m) located on the upper side of Station I, upward motion is found in the first

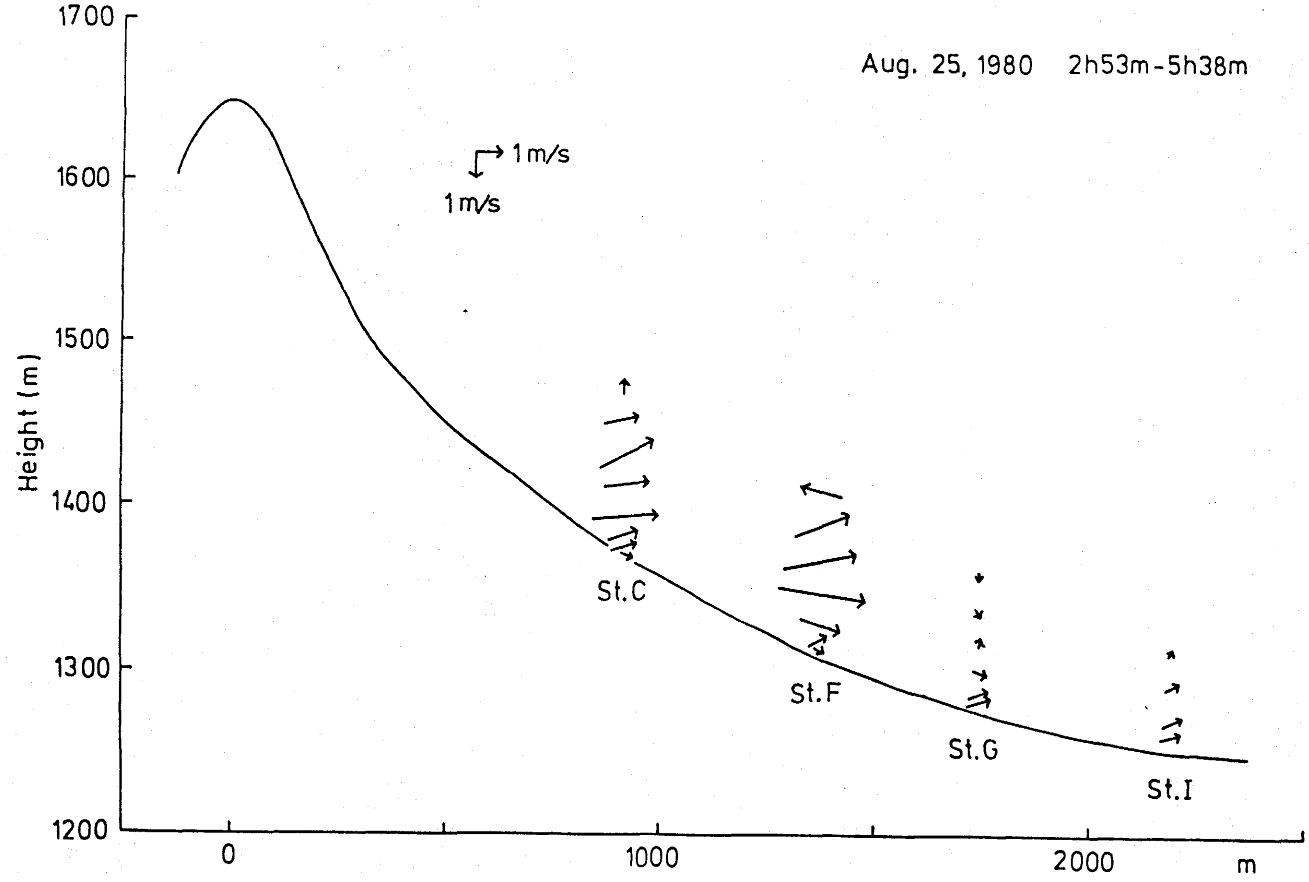

Fig. 5.3 Cross-section analysis of wind along the slope of Mt. Ômatsu at night on August 25, 1980. The horizontal and vertical wind components of the velocity are represented by arrows.

10 m and at 40 m above the ground, and downward motion at 20 m height and above 60 m height. The air in the layer above 40 m height flows across the slope with right angle. At Station F (1,300 m) downward motion is found in the layer below 50 m height except 10 m height, and upward motion in the layer above 50 m height. At Station C, downward motion is found only in the first 5 m above the ground, and upward motion in the whole layer above 10 m height. The velocities of vertical air stream are in the range of 0.21 - 1.10 m/s with the average of 0.33 m/s.

These flows might be expressed by streamline as shown in Fig. 5.4. In this figure, the shaded part shows the area of downslope wind. This area is expanded from the vicinity of Station C to it of Station G along the slope. Moreover, downward motion from the upper air layer appears at Station G and its vicinity. The downslope wind changes to upward motion on the area ranging from Stations G to I. It is considered from these facts that this upward motion forms the circulation system which is shown by broken line in Fig. 5.4. It can be said from the wind directions at 100 m height above Stations C and F that there is the flow toward the direction from Stations F to C as a part of this circulation system.

Fig. 5.5 shows the vertical distribution of air temperature. Cold air lake is found in the area of the isothermal line of + 14.0°C or less on the basin bottom,

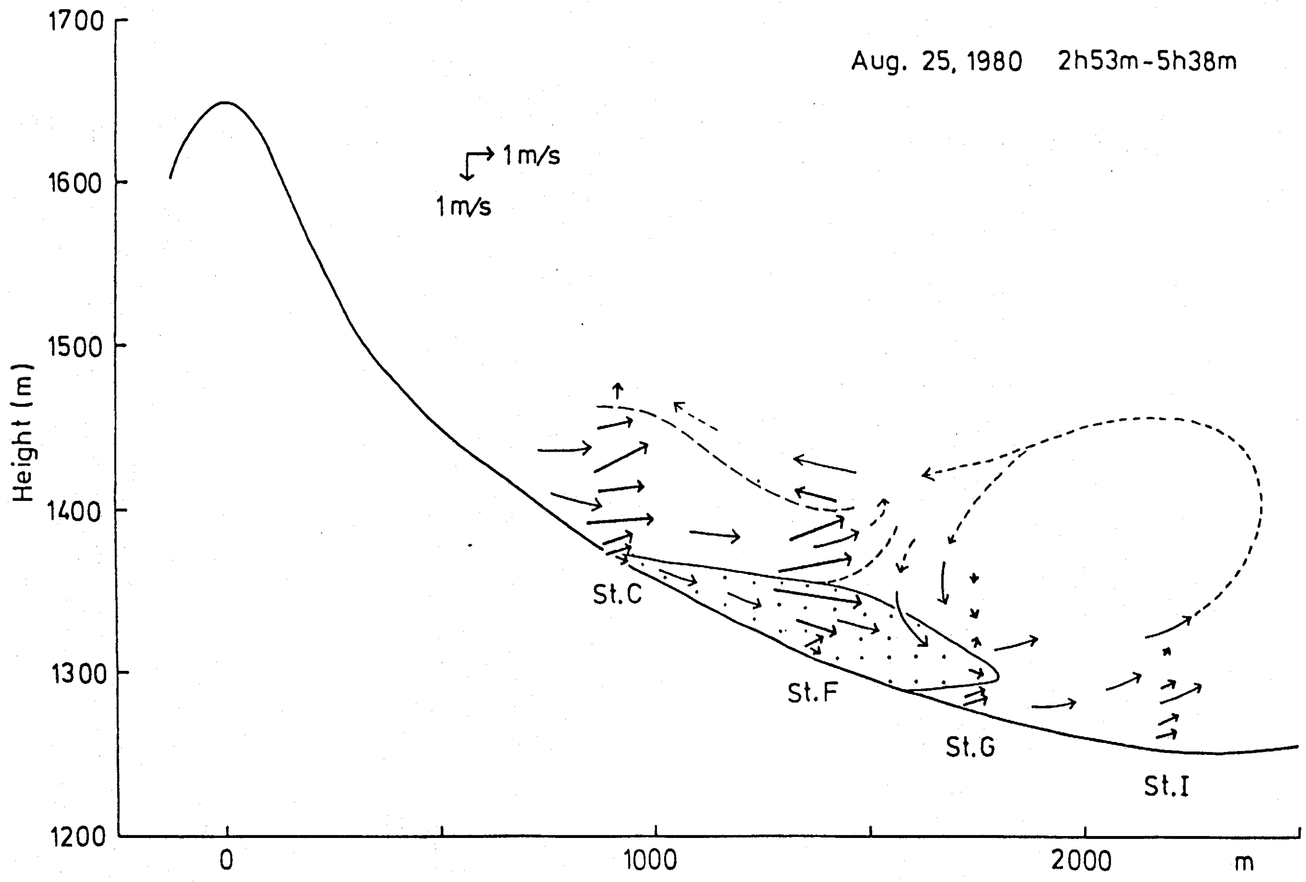

Fig. 5.4 Estimated circulation system on the slope of Mt. Ômatsu at night on August 25, 1980. Thick arrow shows the wind component observed, thin arrow the streamline based on the component, broken arrow the streamline predicted and the shaded part the downslope wind area.

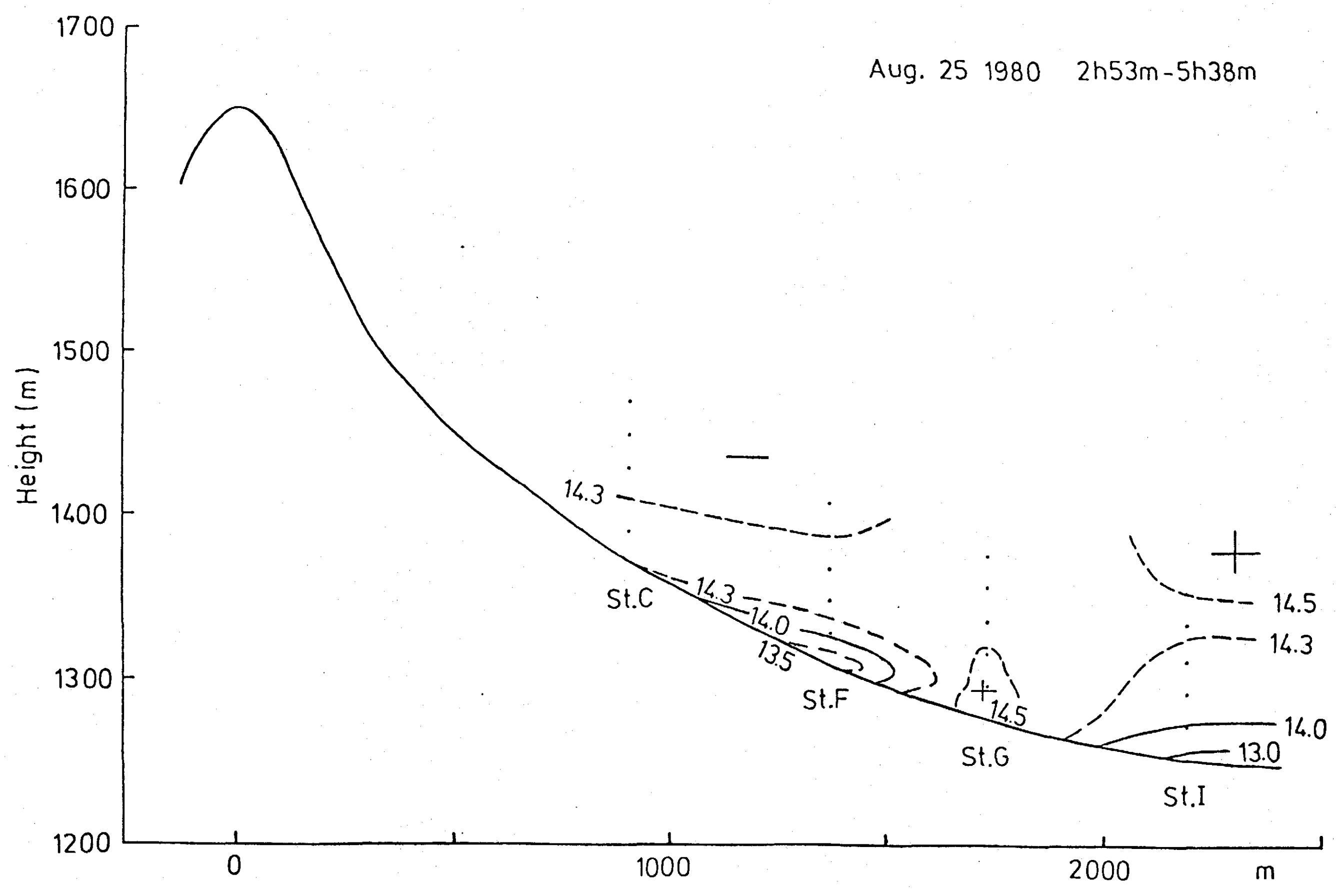

Fig. 5.5 Temperature profile on the slope of Mt. Ômatsu at night on August 25, 1980.

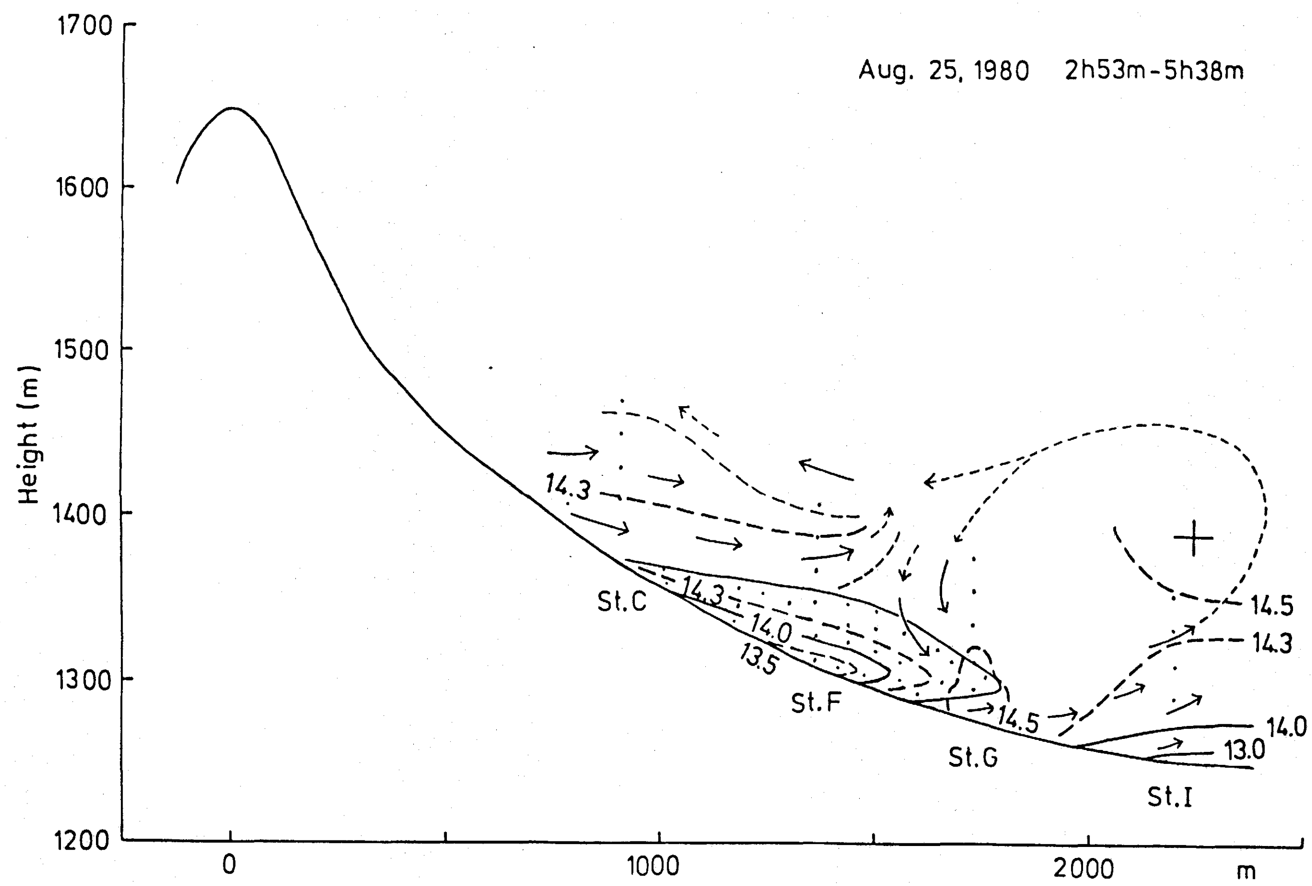

Fig. 5.6 Temperature profile and circulation system on the slope of Mt. Ômatsu at night on August 25, 1980. The temperature profile is superimposed on the estimated circulation system illustrated in Fig. 5.4. The shaded part shows the downslope wind area.

and has the depth of about 20 m. The low temperature area below + 14.0 °C exists also near Station F on the middle part of the slope, and the ground inversion layer is formed strongly in this area. Its thickness amounts to 15 m as a maximum. At Station G located between these two low temperature areas, the weak warm area (warmer than + 14.5 °C) is formed in the first 40 m above the ground.

Then, in order to study the relation between the air temperature distribution and the circulation system, Fig. 5.6 is drawn up. The ground inversion area formed on the slope corresponds nearly with the downslope wind area. Moreover, it is considered that the place, where downward motion from the upper air layer is found strikingly, corresponds to the warm area near Station G.

5.2.2. The Case of August 28, 1980

The mobile observations were carried out by same method as August 25 during the time from 2 h 40 m to 5 h 00 m. The distribution of the components of wind along the slope is shown in Fig. 5.7. At Station I located on the lowest part of the slope, the upward motions are found in the whole air layer except 20 m and 80 m heights. The upward motions at Station G are found also in the all air layer except 30 m and 40 m heights. At Station F, the downward motion is found in the first 50 m above the ground, and the upward motion is found in the air layer

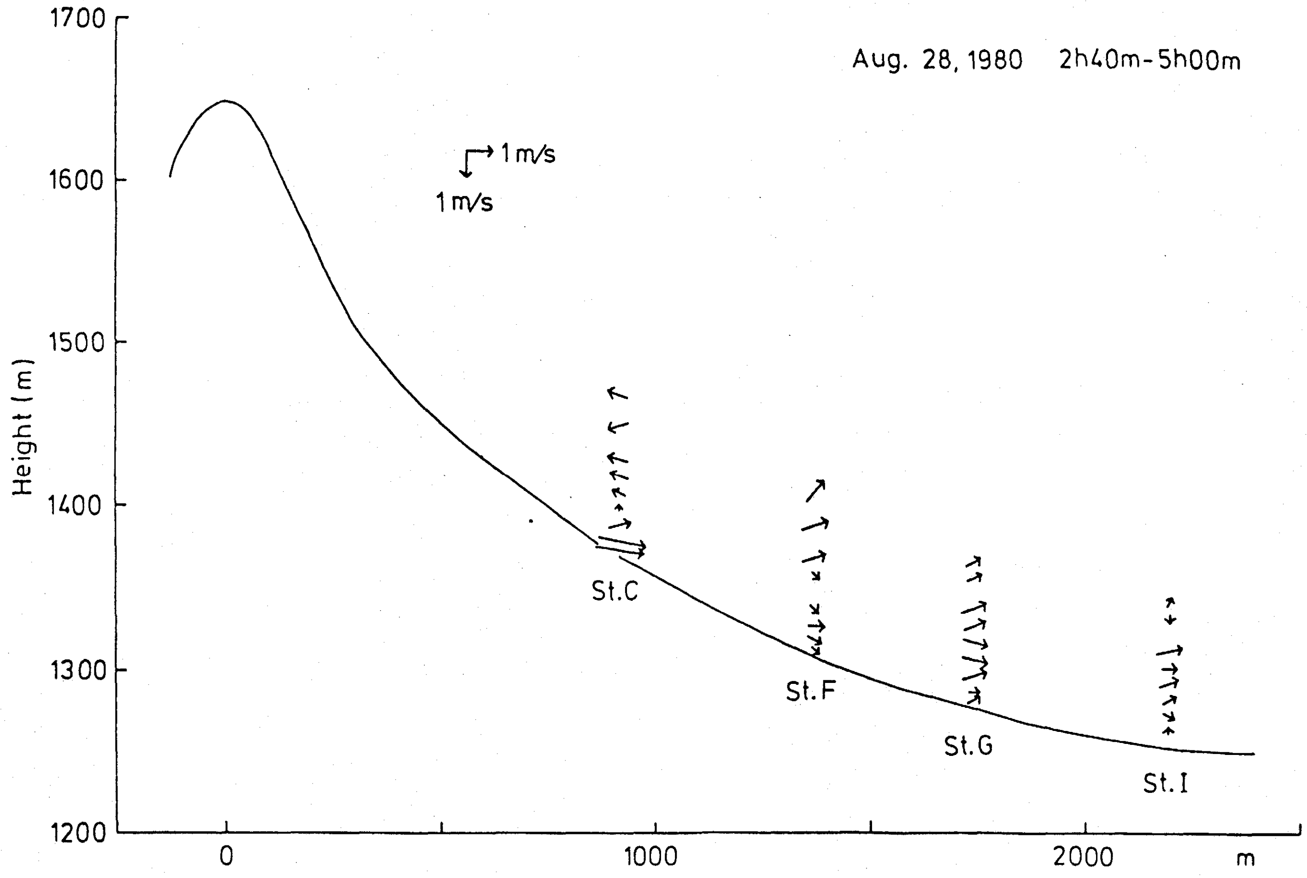

Fig. 5.7 Cross-section analysis of wind along the slope of Mt. Ômatsu at night on August 28, 1980. The horizontal and vertical wind components of the velocity are represented by arrows.

above 60 m height. At Station C, the downward motion is found in the first 10 m and at 80 m height above the ground, and the upward motion is found in the air layer above 20 m height except 80 m height. The velocities of vertical stream are in the range of 0.00 - 0.36 m/s with the average of 0.23 m/s.

These flows might be expressed by the streamlines as shown in Fig. 5.8. The downslope wind along the slope starts to blow from near Station C, and increases gradually its thickness. The thickness of the layer of this wind is about 50 m at Station F. After then, the top of this layer is kept in about 50 m height, and the layer reaches near Station G. The bottom of the air layer was parted from ground surface on the place between Stations F and G, and its height amounts to about 25 m at Station G. The range and shape of this downslope wind area is very similar to those for the case of August 25. At the Stations, G and I, the downslope wind changes to upward motion. Furthermore, the anti-downslope wind blows in the air layer above 40 m height at Station C. From these facts, it is assumed that there is the circulation system which is shown by broken line in Fig. 5.8, and that the place to which the circulation air flows down from the upper air layer is situated at the upper part of the slope than Station F. This is higher than in the case of August 25.

Fig. 5.9 shows the vertical distribution of air

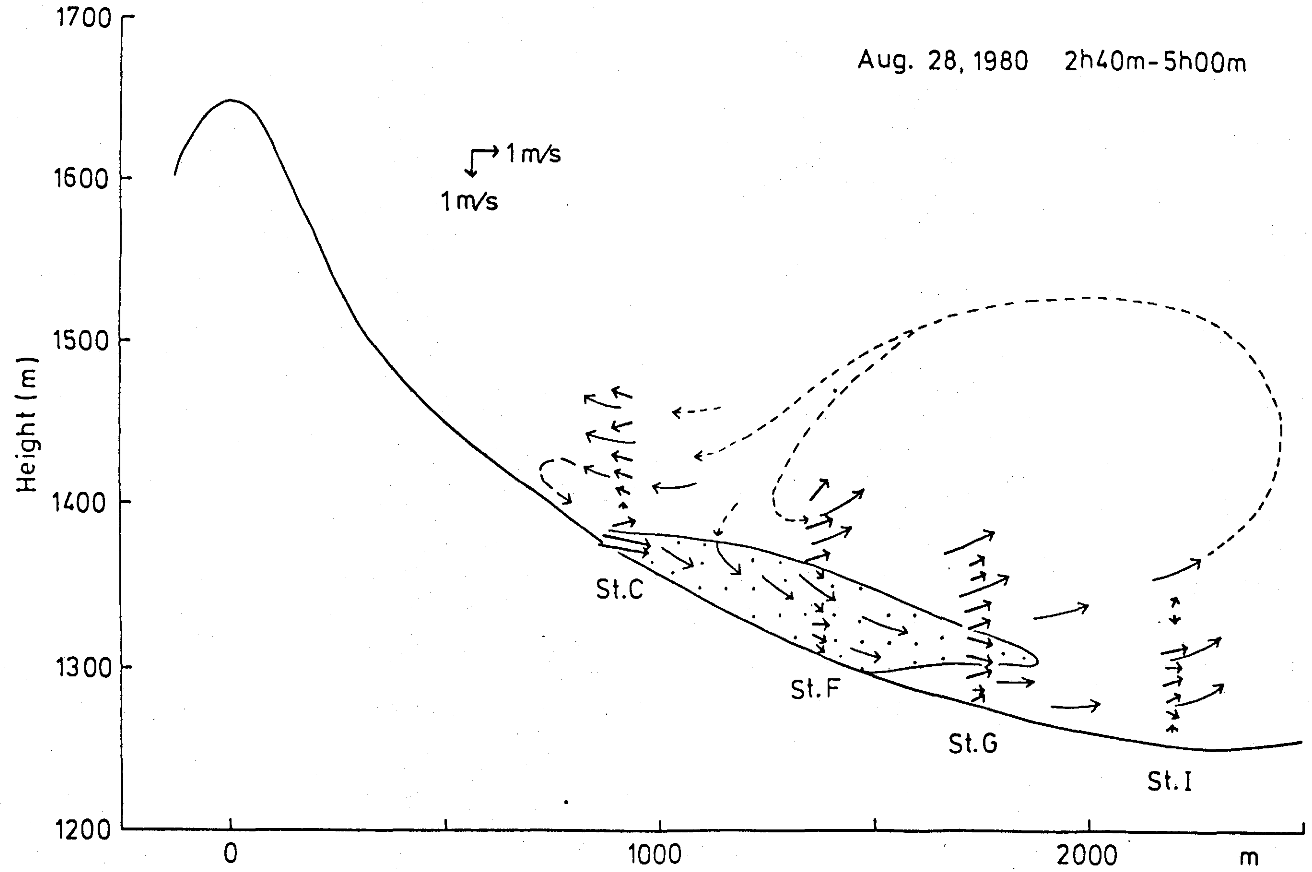

Fig. 5.8 Estimated circulation system on the slope of Mt. Ômatsu at night on August 28, 1980. Thick arrow shows the wind component observed, thin arrow the streamline based on the component, broken arrow the streamline predicted and the shaded part the downslope wind area.

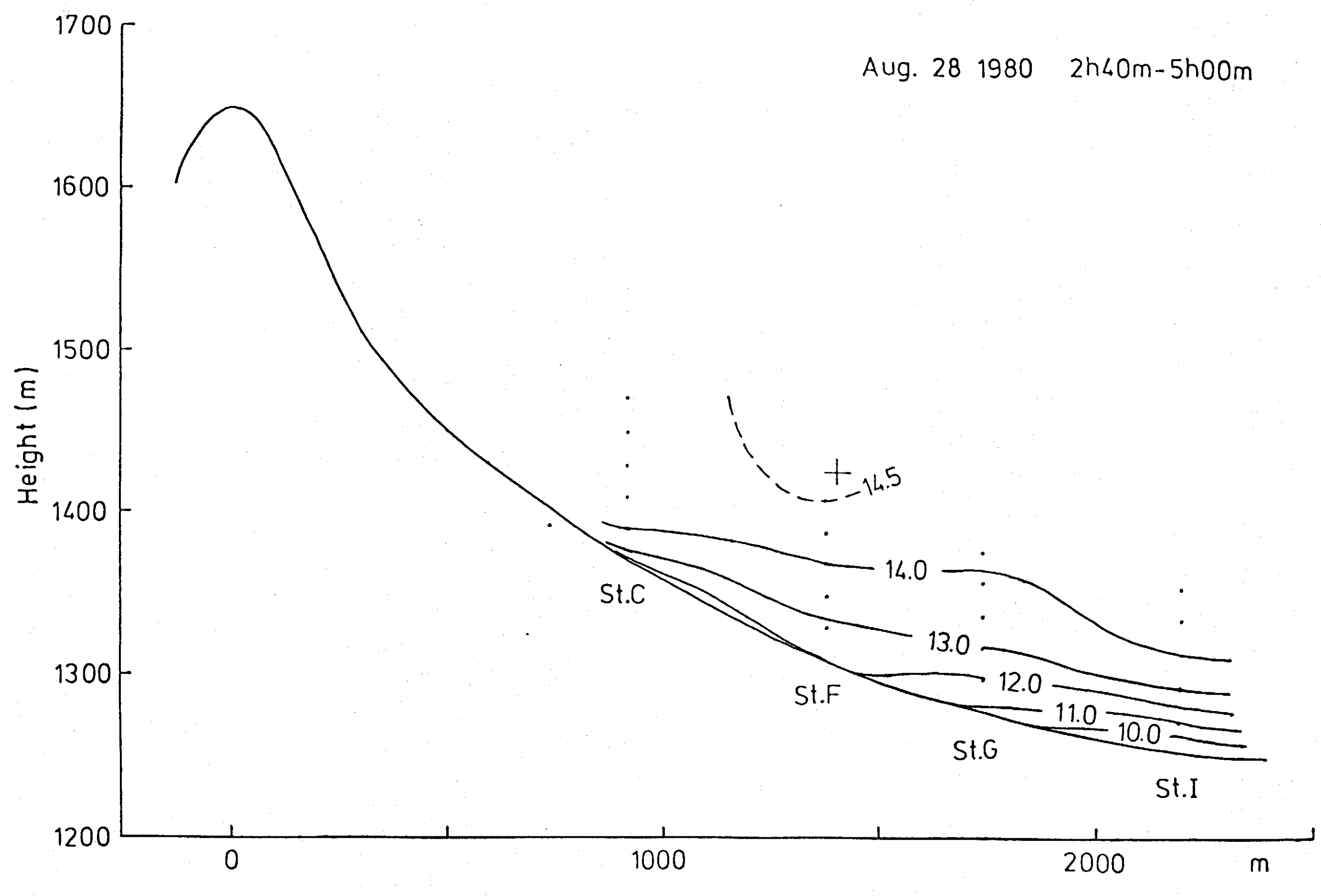

Fig. 5.9 Temperature profile on the slope of Mt. Ômatsu at night on August 28, 1980.

temperature. As the isothermal line below + 13.0 °C is dense near Station I, it can be said that cold air lake has appeared in this place (depth: about 40 m). The ground inversion layer is formed strongly near Station C which goes toward upper part of the slope than in the case of August 25. The maximum temperature + 14.5 °C appears at 100 m height above Station F. The temperature gradient near the ground at Station F is a little more gentle than general aspect on the slope.

Next, Fig. 5.10 was drawn in order to study on the relation between air temperature distribution and circulation system. In this figure, the distribution of the isothermal line of + 14.0 °C is nearly horizontal on the area ranging from Stations C to G. The top of the downslope wind area along the slope nearly agrees with the isothermal line of + 14.0 °C on the area ranging from Stations C to F. As the top of this wind area parallels to the slope on the area ranging from Stations F to G, it doesn't agree with the isothermal line on the area. On the other hand, the bottom of this wind area nearly agrees with the isothermal line of + 1.2 °C on the area ranging from Stations F to G.

From these facts, it might be said that the downslope wind may not flow into the cold air lake and it is also found that anti-downslope wind falls from upper air layer and turns down. Then, air temperature increases slightly on the area where the wind falls and turns. Therefore, it

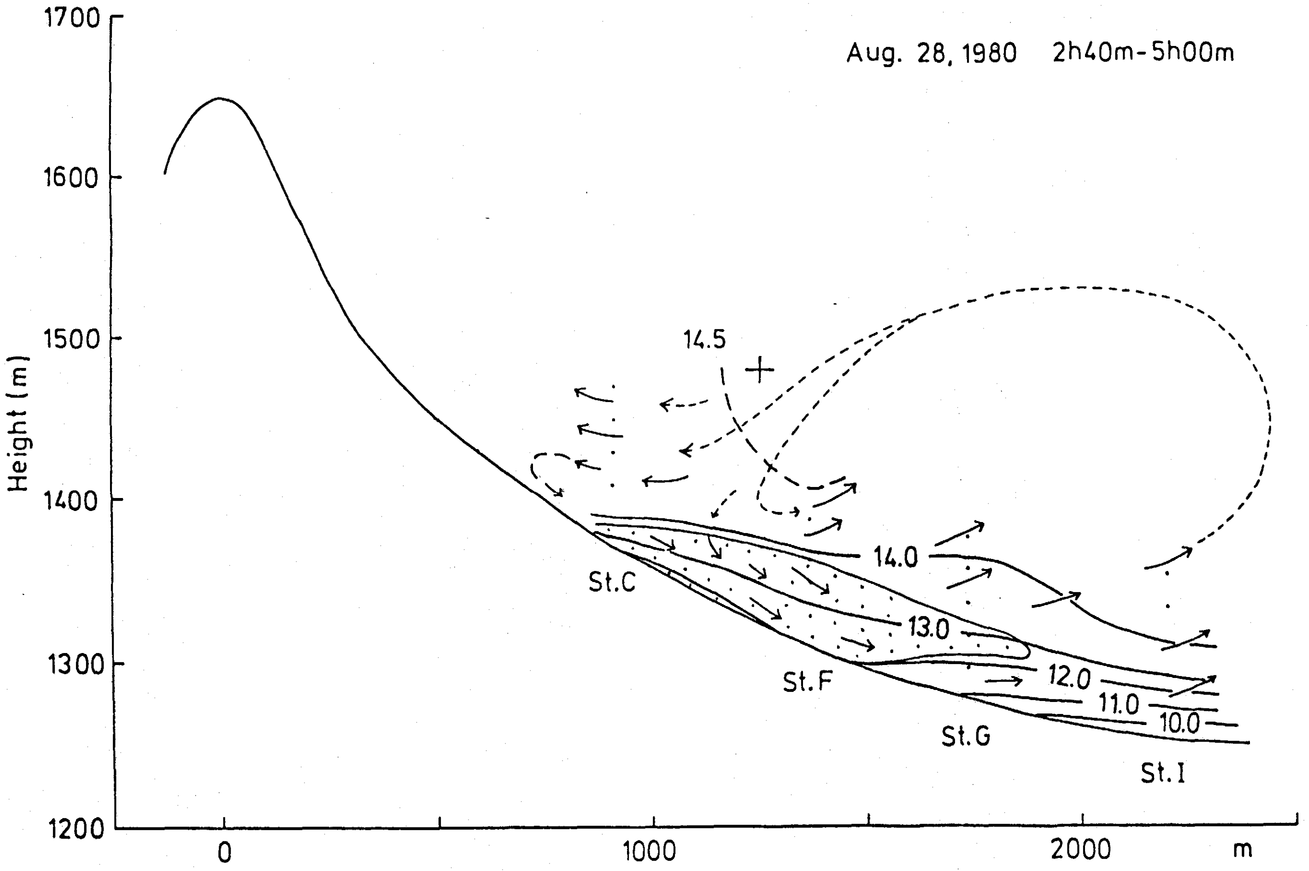

Fig. 5.10 Temperature profile and circulation system on the slope of Mt. Ômatsu at night on August 28, 1980. The temperature profile is superimposed on the estimated circulation system illustrated in Fig. 5.8. The shaded part shows the downslope wind area.

is concluded that the warm area appeared on the slope, which was discussed in Section 3.1.5., is formed in such mechanism. Furthermore, the warm area, that is, the area where the anti-downslope wind undergoes a change of the front, moves with the velocity of 0.3 - 0.8 m/s from the lower part of the slope toward the upper one and the area appears every 30 - 60 minutes. Namely, it can be said that the air circulation system spreads from the lower part of the slope toward the upper one and that after the system attained to certain size, new circulation system appears and begins to spread again from the lower part of the slope and it is repeated. The intermittent drainage of cold air might be caused by this effect.

5.3. Summary for Chapter 5

The whole aspect of cold air drainage was made clear by analyzing the vertical structure of air layer on the mountain slope in detail. The results are summarized as follows:

1. On the mountain slope in Engaru, anti-downslope wind was observed above downslope wind. The air temperature increases slightly in the area, where the anti-downslope wind turns to become the downslope wind.

2. Observation results on the slope of Mt. Ômatsu are summarized as follows:

(1) Cold air lake (depth: 20 - 40 m) is formed on

the basin bottom. Moreover, ground inversion layer (thickness: 10 - 20 m) is formed strongly on the middle part of the slope.

(2) The downslope wind area is formed on the area ranging from Station C (1.370 m) to vicinity of Station G (1,275 m). This wind area begins to be parted from ground surface of the place between Stations F and G.

(3) It is considered that this wind begins to show upward motion on the lower part of the slope, and the circulation system is formed.

(4) The air temperature increases slightly on the area where the circulating air falls from the upper air layer and turns down. This warm area appears periodically and moves from the lower part of the slope toward the upper one. Namely, it is considered that each air circulation system appears periodically at the lower part of the slope and its range is extended more and more toward the upper part of the slope.

CHAPTER 6. CONCLUSION

6.1. Summaries of the observed Reseults

In order to make clear the development of cold air drainage, micrometeorological observations have been carried out on the slope of Mt. Neko and Mt. Ômatsu in Sugadaira, Nagano Prefecture, and on the mountain slope in Engaru, Hokkaido.

In this investigation, new parameters were developed successfully in order to confirm the source and drainage areas of cold air. The one of these is "the degrees of inversion" which is defined as the difference of the temperatures at 1.3 m height and at 0.3 m height above the ground. The other is "the vertical difference of cooling" which is defined as the difference of the air cooling at 0.3 m height and at 1.3 m height above the ground. Using these parameters in addition to net radiation and other data, the author analyzed rationally the formation process of ground inversion layer.

From the primary discussion in this study, the author concluded that the air flow exhibiting the following characters should be defined as cold air drainage: (1) The air temperature correlates negatively with the wind velocity.

(2) The wind direction is within the range of $\pm 45^\circ$ from the center axis of direction of maximum inclination of the slope.

In addition to this conclusion, it was found that the area where "the degrees of inversion" has positive value should be defined as the drainage area of cold air. Also, it was found that the source area of cold air drainage should have the following characters. (1) "The degrees of inversion" has positive value. (2) The variation of air temperature correlates positively with the variation of wind velocity. (3) "The degrees of inversion" correlates negatively with the wind velocity. (4) A drainage area of cold air exists on the lower part of the slope.

From detailed analysis of the observation data, the following knowledges were obtained with respect to the cold air drainage:

1. Generally, cold air drainage occurs intermittently on the mountain slope. Although several peaks for the frequency of its occurrence with time are observed, there is a few major peaks in these and the peak values are considered to increase generally with time elapsed. In the case of the slope of Mt. Neko, three major peaks of the frequency appeared at night of August, from sunset to sunrise, and final peak value was about 70 %.

2. Cold air drainage exhibits the periodicity with its velocity and temperature. Depending upon the condition

of the location, the period so changes that its value is small within the shallow valley on the upper part of the slope and is large within the deep valley on the lower part of the slope.

3. The range of the fluctuation of air drainage with velocity increases linearly with time after sunset.

4. Warm area appears every 30 - 60 minutes on the drainage area of cold air, and moves from lower part of the slope to upper one with the velocity of 0.3 - 0.8 m/s.

5. The velocity for the cold air drainage, U, can be expressed in terms of flowing distance, L. Following expressions are available for the slope of Mt. Neko:

On the snow field, $U = 1.48\ L^{1.57}$.

On the cultivated filed, $U = 1.30\ L^{1.49}$.

6. The drainage time of cold air on the slope of Mt. Neko amounts to value more than 6 hours when the state of atmosphere at the 850 - 900 mb level (same level with observation area) at Wajima and Tateno has stability or conditional instability. Then, the pressure gradient between Wajima and Tateno was less than 6 m/100 km at this level. Wind velocities were lower than 10 m/s below the 850 mb level and lower than 5 m/s at the 1,000 mb level. Further, relative humidity decreases with increasing height, and is lower than 50 % at the 800 mb level.

7. On the slope of Mt. Ômatsu, the cold air drainage after sunset of August 20, 1976 originated near 1,320 m a.s.l. during the time from 19 h 00 m to 19 h 20 m and that

spread downward near 1,280 m a.s.l. during 19 h 14 m to 19 h 27 m.

8. The formation of ground inversion due to radiative cooling progressed most strongly on the area ranging from 1,320 m to 1,280 m of the slope of Mt. Ômatsu after sunset on July 30, 1978.

Although the knowledge obtained in this investigation is very useful to understand the cold air drainage on the mountain slope, further micrometeorological observations were carried out with captive balloon up to the first 85 m above the mountain slope in Engaru and the first 100 m above the slope of Mt. Ômatsu. Analyzing the results obtained from this observation, the author tried to make clear the whole aspect of cold air drainage on the mountain slope. These results are summarized as follows:

1. On the mountain slope in Engaru, the anti-downslope wind was observed above the downslope wind and it turned toward the ground to become the downslope wind flowing under the anti-downslope wind. The air temperature increased slightly in the area where the anti-downslope wind turns to become the downslope wind.

2. On the other hand, on the slope of Mt. Ômatsu, cold air lake (depth : 20 - 40 m) is formed on the basin bottom. Moreover, ground inversion layer (thickness : 10 - 20 m) is formed strongly on the middle part of the slope.

3. The downslope wind area is formed on the area ranging

from near 1,370 m to 1,280 m on the slope of Mt. Ômatsu. The wind area parts from the ground surface near 1,300 m.

4. From the fact that the downslope wind turns to the upward motion above the cold air lake, it is considered that the air circulation system is formed on the slope.

5. The air temperature on the area where the circulation air falls from the upper air layer and turns down increases slightly, warm area is formed on the slope. This warm area appears periodically and moves from the lower part of the slope to the upper one. Namely, it is considered that each air circulation system appears periodically at the lower part of the slope and its range is extended more and more toward the upper part of the slope.

6.2. Conclusion : A proposed Model

Coordinating the knowledge of the cold air drainage summarized previously, the author completed a model of the cold air drainage at clear and calm night on the mountain slope having 2 km to 6 km lengths of the horizontal distance. In this model, the formation and the drainage process of cold air are divided into 6 major stages as shown in Fig. 6.1.

Stage 1 shows the initial stage of the formation of cold air on the mountain slope after sunset. The thin solid lines in Fig. 6.1 express the isothermal lines. After sunset, the ground inversion layer is more strongly formed

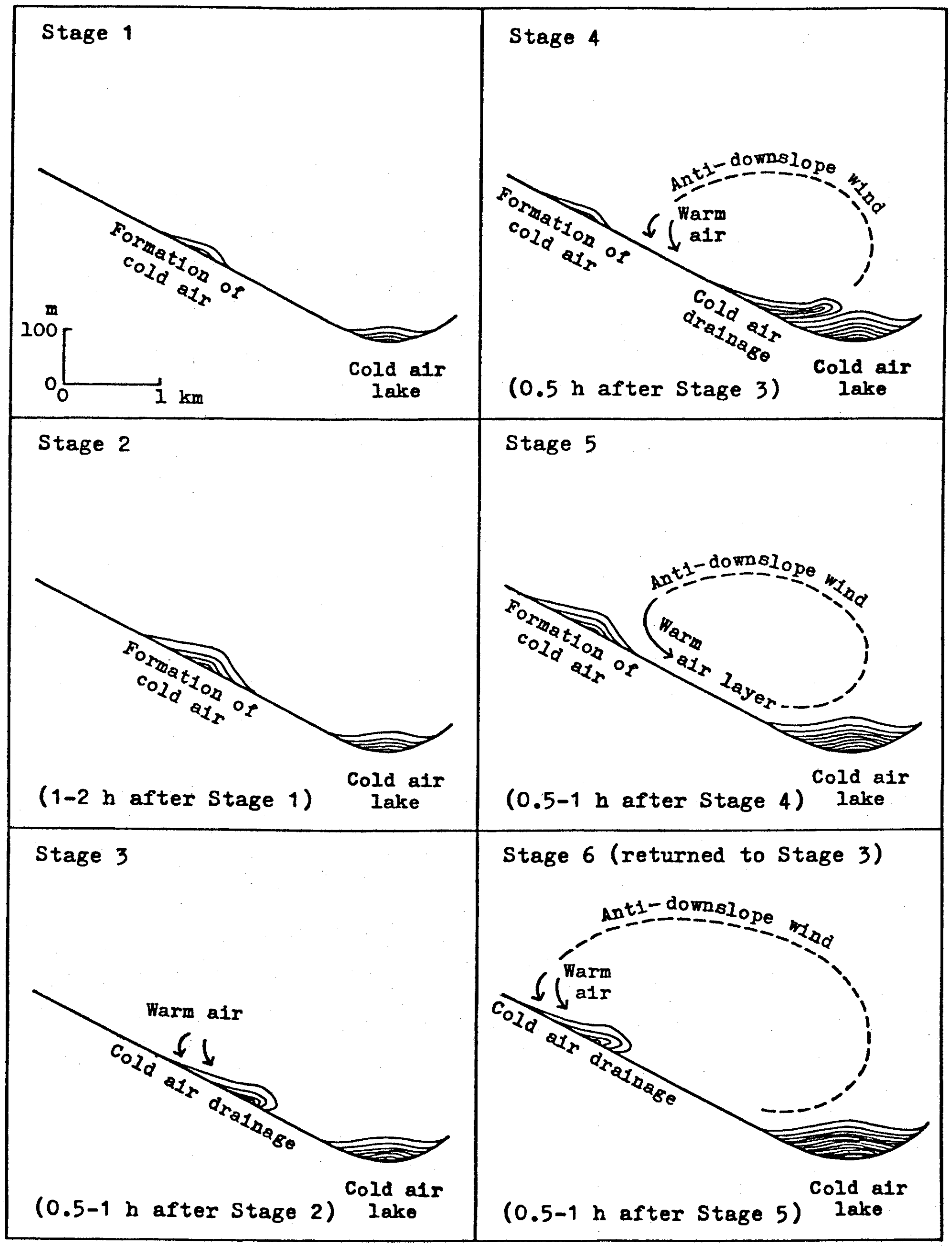

Fig. 6.1 Model of nocturnal cold air drainage on the mountain slope.
Thin solid line shows the isothermal line.

on the middle part of the slope rather than on the upper and lower parts of the slope, because of the general wind on the upper part of the slope and the air stream along the valley on the lower part of the slope. Namely, these wind or stream disturb the formation of the ground inversion layer. Then, cold air mass is formed in this layer. On the bottom of the basin, cold air lake is also formed.

In Stage 2, this inversion layer develops gradually with progressing radiative cooling on the middle part of the slope. Cold air mass of this inversion layer develops up to 0.5 - 1 km length along the inclination of the slope within 1 - 2 hours after sunset. Hence, Stage 2 shows the intensification of formation of cold air on the mountain slope. Durations of Stages 1 and 2 are 1 - 2 hours, which appear at the time after sunset when air temperature decreases rapidly. These two stages are the initial condition for the drainage of cold air so that the initial condition of series drainage is the same as that at these stages as can be seen in latter Stages, 4 and 5. Intensity of the inversion of the cold air lake also increases gradually in the stage.

Stage 3 shows the state of drainage of cold air on the slope. After 0.5 - 1 hour from Stage 2, developed cold air mass overcomes the resistance of friction due to the roughness of ground surface, and begins to flow down toward the downward of the slope. The velocity of cold air drainage is accelerated with flowing down, and it reachs about 1 - 2 m/s on the lower part of the slope. After drainage of cold air, the warm air from upper air layer flows into the air layer near the ground surface layer as compensating stream for the cold air drainage. On the other hand, cold air lake develops more and more in this stage.

Stage 4 shows the stage of the cold air drainage reached on the cold air lake and the formations of anti-downslope wind and new cold air on the upper part of the slope. The cold air drainage reached on cold air lake after 0.5 hour from Stage 3 does not flow into cold air lake since the temperature of the cold air drainage is higher than that in the lake, but it moves onto the lake. The compensating stream for the cold air drainage forms anti-downslope wind above the air layer of the drainage, and air circulation system is completed on the slope. The air temperature increases slightly on the area where the circulation air falls from the upper air later and turns down. The ground inversion layer begins to be formed on the upper part of the slope where the warm air from upper air layer does not flow into the ground surface layer.

Stage 5 is concerned with the disappearance of cold air drainage and the formation process of cold air. The cold air drainage with upward motion above the cold air lake in Stage 4 turns into anti-downslope wind at the Stage 5. After draining cold air, cold air layer on the slope is replaced by warm air due to inflow from anti-downslope wind. The ground inversion layer develops gradually. On the part of the inversion layer situated on the lower slope, the temperature gradient increases between the inversion layer and the warm air layer on the lower part of the slope, and cold air mass in the inversion layer easily flows down.

Stage 6 shows the emergence of the second cold air drainage, and it is same as Stage 3 except for the appearance of anti-downslope wind. After 0.5 - 1 hour from Stage 5, cold air flows down toward the downward of the slope. The area where the warm air from upper air layer flows into the ground surface layer as compensating stream for the cold air drainage after draining of cold air transfers to the upper part of the slope. Therefore, enlarging the scale of anti-downslope wind, air circulation system is developed. Consequently, the source area of cold air drainage transfers to the upper part of the slope, and the velocities of the cold air increase every draining because flowing distance of that increases. Namely, the cycle from Stage 3 to Stage 6 is repeated a few times at intervals of 1.5 - 3 hours during the night.

The important factors determining the cold air drainage which were confirmed in this study were taken into accounts in this modeling. The descriptions of the model mentioned above are summarized in Table 6.1. These factors are also given in Table 6.2.

From the comparison with the models previously proposed by many investigators, for example, Mano (1953, 1956),

Table 6.1 Model of nocturnal cold air drainage on the mountain slope.

Stages	Model descriptions
1	(1) Formation of cold air (Sections 4.1 & 4.2) After sunset, the ground inversion layer is more strongly formed on the middle part of the slope rather than on the upper or lower parts of the slope because of the general wind on the upper part of the slope and the air stream along the valley on the lower part of the slope. (2) Cold air lake (Section 5.2) Cold air lake is formed in the basin.
2	(1) Formation of cold air (Sections 4.1, 4.2 & 5.2) The inversion layer develops gradually on the middle part of the slope. The scale of cold air mass formed in this inversion layer develops up to 0.5 - 1 km length along the inclination of the slope. (2) Cold air lake (Section 5.2) Intensity of the inversion of the cold air lake also increases gradually.
3	(1) Cold air drainage (Sections 3.1, 4.1, 4.2 & 5.2)

Table 6.1 (continued)

3	This cold air mass overcomes the resistance of friction due to the roughness of ground surface, and begins to flow down toward the downward of the slope. The velocity of cold air drainage reachs about 1 - 2 m/s.
4	(1) Cold air drainage and cold air lake (Section 5.2) The cold air drainage which reached on cold air lake does not flow into the cold air lake since the temperature of the cold air drainage is higher than that in the lake, but it moves onto the lake. (2) Anti-downslope wind (Section 5.2) The compensating stream for the cold air drainage forms anti-downslope wind above the air layer of the drainage, and air circulation system is completed on the slope. The air temperature increases slightly on the area where the circulation air falls from the upper air layer and turns down. (3) Formation of cold air (Sections 3.1, 4.1, 4.2 & 5.2) Another ground inversion layer begins to be formed on the upper part of the slope where the warm air from the upper air layer does not flow into the ground surface layer.

Table 6.1 (continued)

5	(1) Cold air drainage (Section 5.2) Cold air drainage which had upward motion above the cold air lake at Stage 4 turns into the anti-downslope wind. (2) Anti-downslope wind (Sections 3.1, 4.1 & 5.2) After drainage of cold air, the cold air layer on the slope is replaced by the warm air due to inflow from the anti-downslope wind. (3) Formation of cold air (Sections 3.1, 3.2, 4.1, 4.2 & 5.2) The ground inversion layer develops gradually. On the part of the inversion layer situated on the lower slope, the temperature gradient increases between the inversion layer and the warm air layer on the lower part of the slope, and the cold air mass in the inversion layer easily flows down.
6	returns to the conditions of Stage 3 (1) Cold air drainage (Sections 3.1, 4.1, 4.2 & 5.2) the same with Stage 3. (2) Anti-downslope wind (Sections 3.1 & 5.2)

Table 6.1 (continued)

6	The area where the warm air from the upper air layer flows into the ground surface layer as compensating stream for the cold air drainage, transfers to the upper part of the slope. Therefore, the circulation scale of the anti-downslope wind enlarges.

Table 6.2 Characteristics of the cold air drainage.

No.	Characteristics	Description of factors
1	Occurrence frequency	Cold air drainage occurs intermittently. It occurs generally 3 or 4 times at night, but several times under the very suitable condition.
2	Location of source area	The source area of cold air drainage is situated in the ground inversion layer which is formed strongly on the middle part of the slope. It transfers a location toward the upward of the slope every draining. After the draining of cold air, the inflow of warm air from the upper air layer as compensating stream of cold air drainage is detected. In correspondence with this, the warm area moves from the lower part of the slope toward the upper one.
3	Scale of source area	The lengths of the source area along the slopes of Mt. Ômatsu (the length of the slope : about 2.2 km) and

Table 6.2 (continued)

3		Mt. Neko (the length of the slope : about 6 km) are about 0.5 km and about 1 km, respectively.
4	Drainage area	The thickness of cold air drainage is less than about 50 m on the slope of Mt. Ômatsu. The peak value on the vertical velocity distribution of the cold air drainage appears at a height with 1/4 of the thickness of cold air drainage from the ground surface. During the drainage time of cold air, air temperature decreases on the all drainage area. After drainage of cold air it increases.
5	Velocity	The velocity of cold air drainage increases in proportion to its flowing distance. Furthermore, the velocity of cold air drainage increases with time elapsed after sunset. These are caused by the increase of flowing distance of cold air from the source area. The velocity of

Table 6.2 (continued)

5	Velocity	cold air drainage reachs about 1 - 2 m/s on the slopes of Mt. Ômatsu and Mt. Neko.

Vorontsov (1958), Kimura (1961), Yoshino (1982) and Kudô et al. (1982), it is found that the model obtained from this study has following characteristics:

1. The formation process from the appearance to the disappearance of cold air drainage is shown in detail.

2. Strong ground inversion layer exists on the middle part of the slope, and then cold air drainage is originated in this layer.

3. The source area of cold air drainage transfers a location toward the upward of the slope every draining.

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to Prof. Dr. Masatoshi M. Yoshino of the University of Tsukuba, for his guidance and encouragement in the present study. The author is also grateful to Prof. Dr. Takeshi Kawamura, Prof. Dr. Toshie Nishizawa and Prof. Dr. Isamu Kayane of the University of Tsukuba, for their suggestions and guidance.

The author is indebted to Emer. Prof. Dr. Taiji Yazawa of Tokyo Metropolitan University, Prof. Dr. Tadashi Arai of Rissho University, Assoc. Prof. Dr. Yoshimi Tateishi of Senshu University, Assoc. Prof. Dr. Masataka Yaji of the Yokohoma National University and Prof. Dr. Masashi Mitani of Dohto University for their valuable advice in preparation for this paper, and to Mr. Kinken Makino of Makino Applied Measuring Instruments for suggestion and lending of the instruments.

Finally, the author also sincerely thanks the students of Hosei, Tsukuba, Aichi and Dohto Universities and others for their logistic support.

REFERENCES

Azuma, S. (1957) : Note on the radiative heat transfer in the air layer near the ground. Sci. Rep. Saikyo Univ., 2, 221-228.

Baumgartner, A. (1963) : Einfluss des Geländes auf Lagerung und Bewegung der nächtlichen Kaltluft. In : Frostschutz im Pflanzenbau. Bd. 1, ed. by F. Schnelle, BLV, München, 151-194.

Baynton, H. W., Bidwell, J. M. and Beran, D. W. (1965) : The association of low-level inversions with surface wind and temperature at Point Arguells. Jour. Appl. Met., 4, 509-516.

Berg, H. (1951) : Kleinmeteorologische Messungen im Hohen Venn. Zeitsch. Met., 5, 229-235.

Bergen, J. D. (1969) : Cold air drainage on a forested mountain slope. Jour. Appl. Met., 8, 884-895.

Deacon, E. L. (1950) : Radiative heat transfer in the air near the ground. Aust. Jour. Sci. Res., Ser. A, Phy. Sci., 3, 274-283.

Doran, J. C. and Horst, T. W. (1981) : Velocity and temperature oscillation in drainage winds. Jour. Appl. Met., 20, 361-364.

Elsasser, W. M. (1942) : Heat transfer by infrared radiation in the atmosphere. Harvard Met. Stud., (6), 1-107.

Fleagle, R. G. (1950) : A theory of air-drainage. Jour. Met., 7, 227-232.

Funk, J. P. (1960) : Measured radiative flux divergence near the ground at night. Q.J.R.M.S., 86, 382-389.

Geiger, R. (1961) : Das Klima der bodennahen Luftschicht. Friedr. Vieweg & Shon, Braunschweig, 1-646.

Geiger, R. (1965) : The climate near the ground. Harvard Univ. Press, Cambridge, 1-611.

Heywood, G. S. P. (1933) : Katabatic winds in a valley. Q.J.R.M.S., 59, 47-85.

Hilkenbäumer, F., Schnelle, F. and Breuer, W. (1951) : Bestands und Ertragssicherung in Obstbau druch Frostschadenverhütung. Zweckmässige Arbeitsweise im Obstban, Arbeitsmerkheft, (7), Neumann Verl., Radebeul, 1-88.

Imaoka, E. (1964 a) : Observations and considerations on the structure of the down slope wind. Jour. Agricul. Met., 20, 17-24.

Imaoka, E. (1964 b) : Relation between down slope wind and general wind. Jour. Agricul. Met., 20, 41-45.

Ishikawa, N. and Ishida, T. (1973 a) : Observations of radiative cooling at basins in midwinter and snow-melting season. Jour. Met. Soc. Japan, Ser. II, 51, 197-203.

Ishikawa, N. and Ishida, T. (1973 b) : Numerical prediction of heat balance over dry or wet snow cover under conditions of nocturnal radiative cooling. Low temp. Sci., Ser. A, 31, 107-116.

Ishikawa, N. (1977) : Studies of radiative cooling at land basins in snowly season. Cont. Inst. Low Temp. Sci., Ser. A, (27), 1-46.

Iwasaki, T. (1975) : On the micrometeorology in the hollow and the analysis of nocturnal temperature variation. 50 Shûnen-kinen-ronbunshû, Dept. Geog. Nihon Univ., 103-114.

Kimura, H. (1961) : A micrometeorological study on small islands. Micrometeorological surveys at Hakatajima and Ôshima-small islands in the Inland Sea of Seto. Met. Notes, Met. Res. Inst., Kyoto Univ. Ser. 2, (22), 1-60, 1-140.

Koresawa, S. (1961) : On downslope wind and temperature distribution near the ground in clear and calm night. Mem. Fac. Edu. Niigata Univ. (2), 3, 28-45.

Kudô, T., Tanaka, H., Toritani, H. and Hwang, S. (1982) : Formation of cold air lake in Sugadaira Basin. Geog. Rev. Japan, 55, 849-856.

Küttner, J. (1949) : Periodische Luftlawinen. Met. Rdsch., 2, 183-184.

Lake, J. V. (1956) : The temperature profile above bare soil on clear nights. Q.J.R.M.S., 82, 187-197.

Lawrence, E. N. (1954) : Nocturnal winds. Prof. Notes, (111), 1-13.

MacHattie, L. B. (1970) : Kananaskis valley temperatures in summer. Jour. Appl. Met., 9, 574-582.

Mano, H. (1953) : Sudden increase of nocturnal temperature in valleys or basins. Jour. Met. Res., 5, 525-545.

Mano, H. (1956) : A study on the sudden nocturnal temperature rise in the valley and the basin. Geoph. Mag., 27, 169-204.

Mason, B. (1958) : An example of climatic control of land utilization. In : Climatology and microclimatology, Proc. Camberra Symp. UNESCO Arid Zone Res. 11, 188-194.

Masatsuka, A. (1949) : Investigation of temperature lapse rate and inversion on the Mt. Aso. (2), Jour. Met. Res., 1, 402-405.

Miura, K. (1971) : An example of the formation of cold air lake. Ann. Tôhoku Geog. Ass., 23, 37-40.

Munn, R. E. (1966) : Descriptive micrometeorology. Academic Press, London, 1-245.

Nakamura, K. (1976) : The nocturnal cold air drainage and distribution of air temperature on the gentle slope. Geog. Rev. Japan, 49, 380-387.

Nakamura, K. (1978) : Appearance and drainage areas of the cold air stream on the slope of Mt. Ômatsu, Sugadaira, Central Japan. Geog. Rev. Japan, 51, 793-803.

Nakamura, K. (1980 a) : Radiative cooling and ground inversion on the slope of Mt. Ômatsu, Sugadaira, Central Japan. Geog. Rev. Japan, 53, 758-768.

Nakamura, K. (1980 b) : On the relation between the wind speed and the flowing distance of cold air drainage on the Mt. Neko, Nagano Prefecture. Bull. Dohto Univ., Fine Arts, (3), 69-78.

Nakamura, K. (1982) : Nocturnal circulation system of cold air drainage on the mountain slope. Kikôgaku-kishôgaku Kenkyû-hôkoku, Univ. of Tsukuba, (6), 22-31.

Nappo, C. J. and Snodgrass, H. F. (1981) : Observations of nighttime winds using pilot balloons in Anderson Creek Valley, Geysers, California. Jour. Appl. Met., 20, 721-727.

Nitze, F. W. (1936) : Untersuchung der nächtlichen Zirkulationsströmung am Berghang durch stereophotogrammetrisch vermessene Ballonbahnen. Biokl. B., 3, 125-127.

Oke, T. R. (1970) : The temperature profile near the ground on calm clear nights. Q.J.R.M.S., 96, 14-23.

Petkovšek, Z. and Hočevar, A. (1971) : Night drainage winds. Arch. Met. Geoph. Biokl., (A), 20, 353-360.

Prandtl, L. (1942) : Führer durch die Strömungslehre. Friedr. Vieweg & Sohn, Braunschweig, 1-382.

Reiher, M. (1936) : Nächtlicher Kaltluftfluss an Hindernissen. Biokl. B., 3, 152-163.

Rikitake, T. (1962) : On the heat budget of the cold layer near a bare soil surface at night. Jour. Met. Res., 14, 730-736.

Robinson, G. D. (1947) : Notes on the measurement and estimation of atmospheric radiation. Q.J.R.M.S., 73, 127-150.

Sahashi, K. (1962) : A study of the down-slope wind (I). Met. Notes, Met. Res. Inst., Kyoto Univ. Ser. 2, (26), 1-72.

Sahashi, K. (1974) : A simple theoretical treatment of the down slope wind. Bull. Sch. Edu., Okayama Univ., (40), 17-25.

Saitô, T. (1964) : Meteorological instruments for agriculture. Chap. 2, Radiometer. Kishô Kenkyû Note, 15, 472-493.

Saitô, T. (1966) : Some problems of nocturnal cooling of wheat plant layers. Jour. Agricul. Met., 21, 137-142.

Saitô, T., Tomari, I., Hayashi, T. and Mihara, Y. (1966) : An explanation of severe low temperature in a depressed ground at night. Jour. Agricul. Met., 21, 143-144.

Schnelle, F. (1956) : Ein Hilfsmittel zur Feststellung der Höhe von Forstlagen in Mittelgebirgstälern. Met. Rdsch., 9, 180-182.

Sakamoto, Y. and Ishida, T. (1973) : Nonstationary model of katabatic winds with consideration to heat barance. Low Temp. Sci., Ser. A, 31, 87-105.

Shôno, S. (1958) : "Kishôgaku-sôron (Introduction of meteorology)". Chijin-shokan, Tokyo, 1-356.

Suomi, V. E. and Kuhn, P. M. (1958) : An economical net radiometer. Tellus, 10, 160-163.

Szasz, G. (1964) : Bestimmung der nächtlichen Mikroadvektion durch Ausstrahlungsmessungen in der bodennahen Luftschicht. Ang. Met., 5, 7-12.

Tanner, C. B., Businger, J. A. and Kuhn, P. M. (1960) : The economical net radiometer. Jour. Geoph. Res., 65, 3657-3667.

Tateishi, Y. (1961) : Cold air drainage in Sugadaira, Nagano. Tenki, 8, 366-371.

Thompson, A. H. (1967) : Surface temperature inversions in a canyon. Jour. Appl. Met., 6, 287-296.

Vorontsov, P. A. (1958) : Aerologicheskie issledovaniia pogranichnogo sloia atmosferi nad melkosopochnim repiefom zelinnik. Trudy GGO, (73), 61-86.

Wagner, A. (1938) : Theorie und Beobachtung der periodischen Gebirgswinde. Beitr. Geoph., 52, 408-449.

Wagner, R. (1970) : Kalte Luftseen in den Dolinen. Acta Climat., 9, 23-32.

Yamada, T. (1981) : A numerical simulation of nocturnal drainage flow. Jour. Met. Soc. Japan, 59, 108-122.

Yamamoto, G. (1952) : On a radiation chart. Sci. Rep. Tôhoku Univ., Ser. 5, Geophys., 4, 9-23.

Yamamoto, G. (1954) : "Taiki-fukushagaku (Atmospheric radiation)". Iwanami-shoten, Tokyo, 1-174.

Yamamoto, G. (1976) : "Shinpan kishôgaku-gairon (New edited introduction of meteorology)". Asakura-shoten, Tokyo, 1-244.

Yoshino, M. M. (1960) : Recent researches on cold air drainage and cold air lakes. Jour. Agricul. Met., 15, 161-165.

Yoshino, M. M. (1975) : Climate in a small area. Univ. Tokyo Press, Tokyo, 1-549.

Yoshino, M. M. (1980) : Local climatological study of cold air drainage. Saigai-no-kenkyû, 11, 124-135.

Yoshino, M. M., Tanaka, M. and Nakamura, K. (1981) : Formation of a cold air lake and its effects on agriculture. Jour. Nat. Disas. Sci., 3, (2), 1-14.

Yoshino, M. M., Tanaka, M., Ôwada, M. and Nakamura, K. (1982) : Local climatological study of the cold air drainage and cold air lake, and the relation between these and cold summer damage. Kikôgaku-kishôgaku Kenkyû-hôkoku, Univ. of Tsukuba, (6), 4-14.

Yoshino, M. M. (1982) : On the model of cold air drainage and cold air lake. Kikôgaku-kishôgaku Kenkyû-hôkoku, Univ. of Tsukuba, (6), 37-39.