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Observational Study of Summertime Ice at the Nakayama Wind-Hole in Shimogo, Fukushima

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Abstract

Nakayama Wind-Hole is an important Natural Monument to be preserved for a rare alpine plant in low altitude which survive under the cold air blowing from the wind hole. It shows a great similarity with the Ice Valley in Korea as a wind hole along the rocky talus. Both of Ice Valley and Nakayama Wind-Hole tend to suffer from less ice in recent years, probably due to the dense growing vegetation. The first step to protect wind hole ice is to understand the mechanism.

We conducted *in situ* special observation at Nakayama during 16 to 17 May, 1998. As a result, following facts are found: (1) The soil temperature distribution (about 16°C in average) shows several low temperature spots (about 2°C) corresponding to wind hole areas where unusual ice remains in the hole. (2) The vertical cross section of air temperature shows that the outer air temperature of 24°C at 5 m above the surface decreases to 2°C in the wind hole. The second protection area has amphitheater shape, so a cold air lake is created by accumulated cold Katabatic wind from the wind holes. (3) About 100 m above the cold wind holes, a warm wind hole is found at the 620 m level near the top of the talus, where warm air blows out during winter, whereas it becomes the intake of the outer air during summer to compensate the cold wind hole circulation.

The seasonal observation suggests that the air within the talus must circulate 100 times during the warm season. Namely, the air must circulate once at every 2 days with a mean speed of u=1 mm/s in the talus. The net heat energy of 1.80×10^{11}J is stored in talus during summer which warms the talus temperature from 0°C to 15°C. The same amount of heat is expected to be released during the winter. The evaluation of heat capacity of the talus suggests that only 1% of talus volume is affected by the annual variation of outer air temperature.

In the beginning of October the cold wind hole circulation turns to reverse to warm wind hole circulation as the outer air gets colder than the wind hole temperature. The circulation is strong when the temperature difference between in and outside talus is large. Therefore, the suction of cold air is the strongest when daily low temperature occurs. The warm wind hole circulation seems to occur as a turbulent overturning of cold and warm air because the temperature stratification is extremely unstable. The coldness in winter is effectively stored into the talus by the dynamic instability, whereas the accumulated cold air is protected by the stable stratification during summer. The result of present observation supports the theory of dynamic thermal filter where only coldness tends to accumulate in the talus by the selective convection.

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INTRODUCTION

Nakayama Wind-Hole is one of the famous natural monuments in Japan where various species of alpine plants grow along the mountain foot of Nakayama, despite its low altitude (about 500 m above the sea level). A comprehensive summary is reported in Shimogo Education Committee Report (1998). Nakayama mountain is located in Shimogo, Fukushima, (37°17'N, 139°54'E) with its summit of 855.6 m (Photo 1). Along the eastern side of the mountain foot, there are six sectors designated as special protection areas for alpine plants. They are numbered as first to sixth protection areas. Those specific areas are surrounded by the iron railing fence to keep a person out. The alpine plants are supported by a localized cold air drainage from the narrow spaces between andesite rocks which sustains the localized cool climate during summer. The phenomenon of the cold air drainage is referred to as wind cave or wind hole in Japan since cold wind blows from a cave or hole. There are some research reports of the wind hole in the literature (e.g., Egawa et al., 1980; Fujiwara, 1985; Ohata et al., 1994a,b). We can find natural ice forming in the small caves or holes during spring to summer along a mountain slope. The unusual summertime ice and cold air drainage at Nakayama Wind-Hole is essential for the alpine plants to live for years. However, the cause and origin of the summertime ice along the mountain slope is not understood yet, despite the long history of awareness and utilization of summertime ice as natural refrigerator.

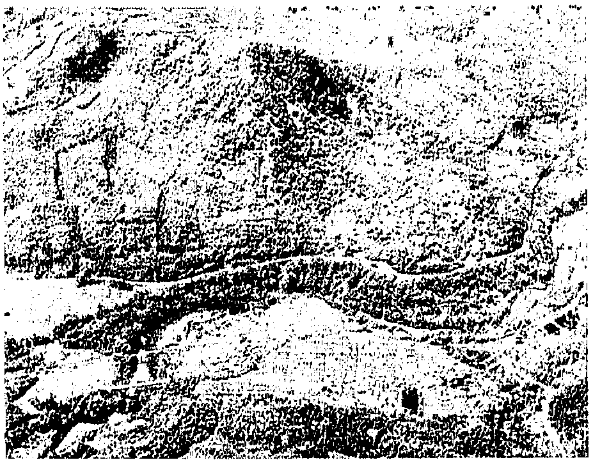


Photo 1. Panorama view of Nakayama in Shimogo, Fukushima. The ridge is approximately 856 m and the bottom at rice field is about 400 m in height. Aga river and Route 121 extend from south to north. Wind hole ice grows around 520 m level which is above the Route 121 in the photo. (Photo by Shimogo Education Committee Report, 1998)

According to a survey by Sasaki (1986), there are about 60 wind caves in Japan, among those 43 are located in the Tohoku district, a northern part of the Honshu Island. Narusawa and Fugaku Wind-Caves located at the northern foot of Mt. Fuji may be the most famous tourist attraction as natural monuments of wind caves. Those wind caves are formed by lava flow and vapor ventilations under the ground during the eruption of active volcanos. The melting lava under the ground flows downward to create a long tunnel. The cave often extends hundreds of meters in depth with few meters in width, so an explorer can walk in the cave. The mechanism of the wind cave that keeps blowing cold air during summer is investigated by many researchers (e.g., Ohata et al., 1994a,b).

According to Ohata et al. (1994a,b), perennial ice at the Fuji Wind Cave is formed by the cold dry air inflow into the wind cave during winter, which accumulate cold air into the cave to freeze the cave ice. During summer, on the other hand, the lava tube cave of 150 m length forbids the warm air to come into the cave by the stable stratification. Therefore, the selective convection in winter and summer acts as a thermal filter which allows only coldness to accumulate in the lava tube cave. The wind cave which maintains perennial ice inside of it is often referred to as ice cave. The perennial ice is located at least few tens of meters inside the cave.

There is a different type of wind caves where the air tube or space is constructed by accumulation of big and hard rocks crumbled from a steep cliff. Such a slope is called talus, where the falling rocks create critical angle of slope (often 35°) by continuous falling and sedimentation of rocks. There are plenty of space between rocks, but the space is too narrow for a person to walk in. Since the geological setting is clearly different from the lava cave, the cold air draining from the talus is referred to as wind hole and is distinguished from the wind cave in this study. The summertime ice is located few tens of centi meters inside the holes, in spite of hot air few meters above the ground.

Probably, the most famous wind hole is the Ice Valley at Milyang in Korea, where unusual ice freezes during hot season along a bottom of the huge talus (Moon and Hwang, 1977; Hwang and Moon, 1981; Bae and Kayane, 1986; Tanaka, 1995, 1997, 1998). Ice Valley's ice appears in early April and melts in fall to winter. It is known that the ice partially melts after the rainfall due to the warmth of rain, but it freezes again a few days after. Surprisingly, the hotter the summer is, the more the summertime ice forms, and there is no ice during winter. An extensive observational study was conducted and reported by Tanaka et al. (1999). The mechanism to freeze during the hottest season is, however, not understood well. At the entrance of the Natural Monument of the Ice Valley, a modern style hotel is built recently to attract more tourists who wish to see the mysterious summertime ice. Unfortunately, the ice tends to disappear gradually in recent years, probably due to the growing vegetation. Yet, cutting vegetation would not necessarily prevent the decreasing trend because we still do not know how the ice forms during summer. On the contrary, cutting vegetation or any kind of protection effort for ice by the local government might cause further destruction of the summertime ice. That would be a serious problem for the Natural Monument of the Ice Valley as a unique summer resort. Hence, the first step to protect the Ice Valley is to understand the mechanism how the unusual summertime ice forms.

Nakayama Wind-Hole in Japan indicates a great similarity with the Ice Valley in Korea as a wind hole along the rocky talus. In this regard, Nakayama Wind-Hole is a good sample of wind hole in Japan for a comprehensive study of understanding the mechanism, although the talus is not as large as the Ice Valley. Nakayama Wind-Hole also tends to indicate less ice year by year as dense vegetation grows. It is therefore important to understand the mechanism of the wind hole to protect the Natural Monument of Nakayama Wind-Hole with interesting alpine plants. For this reason, we have conducted *in situ* observation at Nakayama Wind-Hole for more than a year from February 1998 through July 1999. An extensive observation was carried out during 16 to 17 of May 1998 as a field survey class in Meteorology at the University of Tsukuba. A total of 25 graduate and undergraduate students attend the field survey. A comprehensive report is submitted by Yokoi (1999) to the University of Tsukuba as her graduation thesis work. This paper documents the comprehensive observational result for the summertime ice at the Nakayama Wind-Hole in Shimogo, Fukushima.

DESCRIPTION OF THE NAKAYAMA WIND-HOLE

Nakayama Wind-Hole (37°17'N, 139°54'E) is located along the northeastern to southeastern slope of Nakayama mountain (856 m high) in the upper reach of the Aga River (a branch of the Agano River) in Shimogo-machi, South-Aizu-gun, Fukushima-ken, Japan (Fig. 1). Nakayama mountain summit is located just 600 m northwest of the Aga River. Distinctive river terrace develops along the both sides of the Aga River, and a number of hotels are built on the

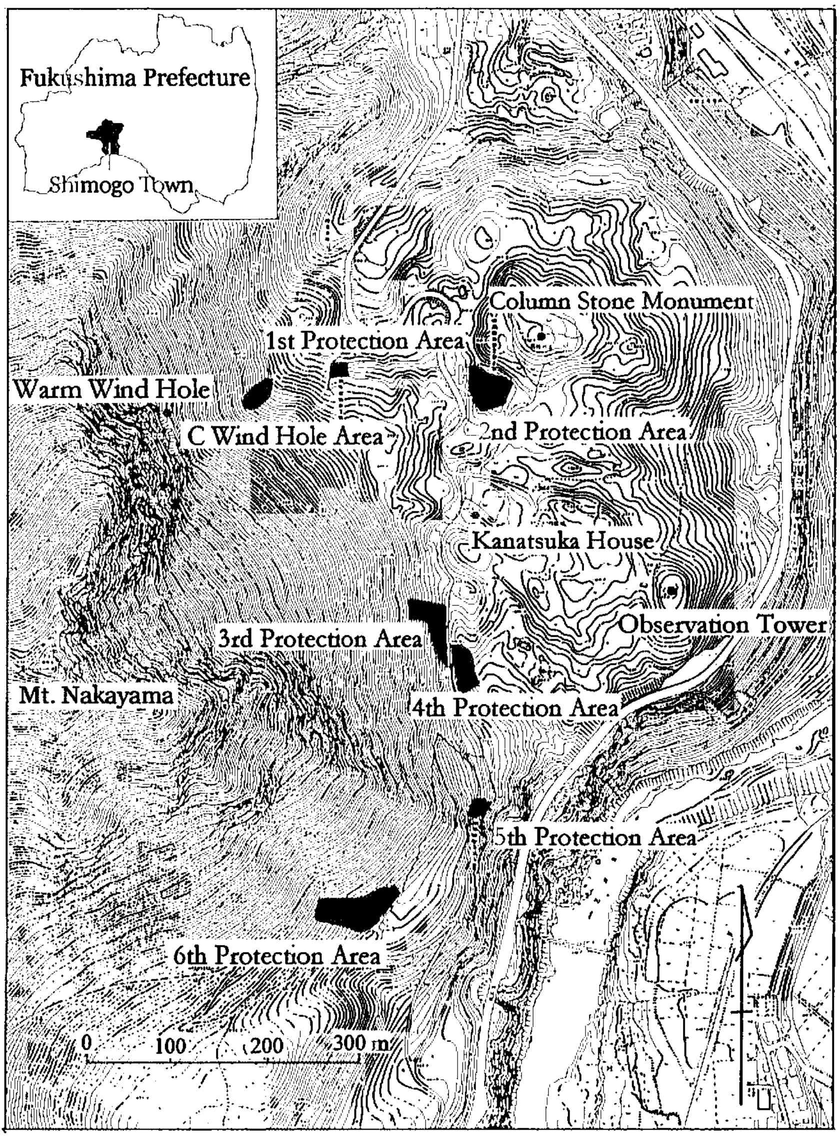


Fig. 1. Locations of the Nakayama Wind Holes in Shimogo, Fukushima. The six protection areas in Nakayama are marked in black. Ice is located at the bottom of the talus. (Base map from Shimogo Education Committee Report, 1998)

river terrace, inviting many tourists to the natural hot spring, known as Yunogami Spa. From this geological setting, the underground temperature of this area is expected to be warm enough for melting ice.

The geological description is reported in detail by Shimogo Education Committee Report (1998). The mountain itself consists of quartz-andesite rocks which intrudes across a green tuff layer known as Tohnohetsuri-layer. There is a famous geomorphological monument called Tohnohetsuri along the Aga River about 2 km upstream the Nakayama Wind-Hole, which is another big tourist attraction in Shimogo. The intrusion of andesite rocks seems to have collapsed eastward to build a mud-flow fill named Column-Stone Monument. The vertical joints developed along the intrusion axis of Nakayama mountain, and andesite rocks keep falling from the cliffs to form present talus along the eastern slope of the mountain (Fig. 2). The talus is about 150 m wide and 300 m long with a gradient of 20-30 degrees. All of the bottom and some parts of the slope are covered with andesite rocks which are about 0.5-1.5 m in diameter (Photo 2). It is estimated that the depth of debris is about 50 m near the cliff which stands in the upper area of the mountain. The volume of talus above the bedrock is of the order of 1.0×10^6 m^3.

The freezing area of the wind hole is located at about 520 m level above the sea level at the very lower end of widely spreading andesite. The entire slope is covered by broad-leaf trees about 10 m tall. The six protection areas with unusual ice are surrounded by Iron fence to keep a person out. Here is a brief description of each six protection area and other notable cites (Fig. 1):

The first protection area is located at the northeastern edge of the talus; it is about 20 m long and 20 m wide under the cover of 10 m trees. Cold air drainage is weak, and the alpine plants are disappearing.

The second protection area is unique in its amphitheater of 60 m diameter and 15 m deep. Cold air drainage is active along the northern slope. The cold air accumulates in the bottom of the amphitheater to create typical cold air lake.

The third protection area is located at the eastern edge of the talus; it is about 60 m long with 15 m wide above the mountain trail. Cold air drainage is active over the steep slope.

The fourth protection area is located at the eastern edge of the talus; it is about 60 m long and 30 m wide below the mountain trail. Cold air drainage is most active here preserving lots of ice.

The fifth protection area is located southeastern edge of the talus; it is about 20 m long and 20 m wide in a dense bush. Cold air

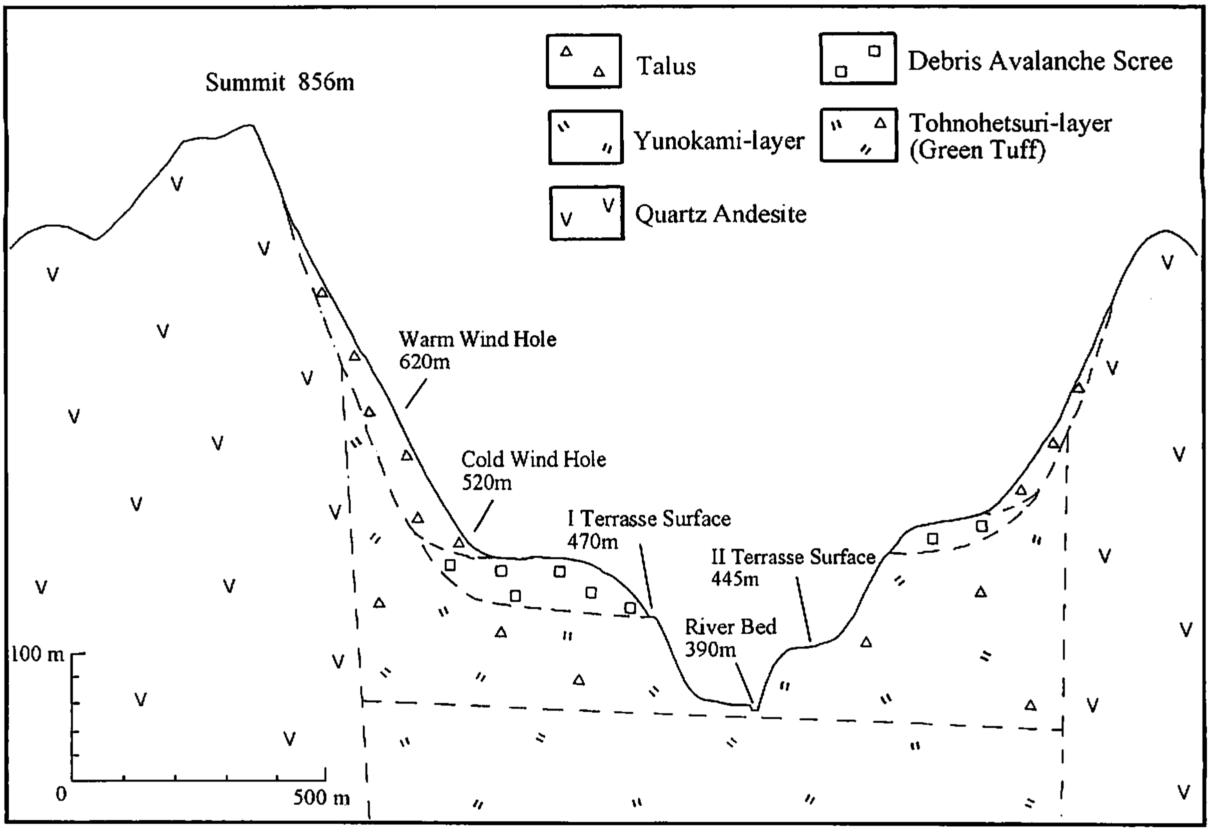


Fig. 2. Vertical cross section from the summit of Nakayama to Aga river (After Shimogo Education Committee Report, 1998). The talus consists of large boulders of andesite debris with the estimated thickness of 50 m. Mud-flow hill extends east of talus over the green tuff layer. The river base is at 390 m, cold wind hole at 520 m, warm wind hole at 620 m, and the summit at 856 m.

Photo 2. General view of the talus at C wind hole near the first protection area, and falling andesite debris with its diameter about 0.5 to 1.5 m. Ice is seen within a reach between rocks where cold air keeps flowing from the inside.

drainage is weak, and the alpine plants are disappearing.

The sixth protection area is located at the southern edge of Nakayama; it is about 100 m long with 50 m wide. Cold air drainage is strong in wind speed.

Apart from these protection areas, there are some other wind hole areas numbered as A, B, C, and so on. Those are not the protection areas, but wind hole certainly exists.

Kanatsuka House is located between the second and third protection areas. It opens only for summer to serve lunch for tourists. There are some plates describing geology, history, and governance of Nakayama Wind-Hole in front of the house.

Column-Stone Monument is located at the northeast of the talus. A general view of Nakayama is seen from this hill. This hill is 540 m in altitude at the top and was formed by landslide in the early stage of Nakayama mountain development.

Observation tower is located at the eastern end of the talus. This hill is 523 m in altitude, and a parking lot and toilet are constructed for tourists.

There are plenty of free spaces between the rocks (Photo 2), so the outside air can penetrate freely into the porous media of talus. Although heat can not be conducted deeper into the talus due to the insulation effect of surface debris, convective motions of air may be possible deep inside the talus. Under ground water is hardly observed near the talus. It is interesting to note that a small concrete box is constructed along the talus slope near Kanatsuka House as a natural refrigerator using the freezing air from the wind hole.

According to the nearby meteorological observatory at Shimogo Town Hall, located 5 km south of Mt. Nakayama, the region has the annual mean temperature 10.4°C, the minimum monthly mean temperature about -2.0°C in January to February, and the maximum mean temperature 23°C in July to August. Precipitation is 1133 mm per year. The duration of sunshine is considerably long throughout the year.

OBSERVATION ITEMS AND METHOD

Grouping for the Special Observation

The special observation was carried out from 16 to 17 May 1998. There are 25 members for the observation divided in six groups. They were allocated for each six protection area. Since the fifth protection area indicates weak cold air drainage, the group was assigned as a moving observation team who walk around the talus looking for the warm wind hole. Likewise, the first protection area indicates weak cold air drainage. We find that the C wind hole area is more active than the first protection area. For this reason, the first team moved to the C wind hole area during the special observation period.

Time Series of Temperature by Micro-Loggers

We prepared temperature Micro-loggers (Celsi Pick) provided by Spirig data logger series. The Spirig data logger is a small data logger made in Switzerland with the size of about 40 mm by 40 mm by 15 mm. The logger can store 2000 data in its memory. Once the logger is set up by PC, it starts to measure 2000 data within the specified time duration. For example, if we set the Celsi Pick for one day, it measures 2000 data within one day. And if we set it for one year, it can measure even annual cycle. The error range for temperature is noted as ±0.2°C.

In present observation, we set the Celsi Pick Micro-loggers in the wind hole at 2nd, 3rd, and 4th protection areas to measure annual variation starting from the end of February 1998 till the beginning of July 1999. In addition, we put a Celsi Pick near the water pump at 530 m level next to Kanatsuka House, representing the outside air temperature. We put a Celsi Pick also in a cave at the top of talus (620 m level) after June 1998, which is hereafter referred to as warm wind hole (Figs. 1 and 2). The warm wind hole is the inlet of outside air into the talus during summer. Conversely, it blows warm moist air during winter from inside the talus to the outside. In oder to distinguish the warm wind hole from the ordinary wind hole, we will refer the ordinary wind hole as cold wind hole if necessary. The warm wind hole is one of the most important findings in this observational study which plays the key role to understand the mechanism of the wind hole.

Vertical Cross Section of Temperature

The wind hole temperature is close to 0°C while the upper air temperature is around 25°C in summer. Vertical cross sections of air temperature and humidity are the important items to understand wind holes. We conducted an extensive observation during 16 to 17 May 1998. Those two days are referred to as a special observation period. Using thermistor thermometers, we measured the vertical cross section of temperature for each protection area along the slope line and strike line which is perpendicular to the slope line. The horizontal distance is measured (every one meter) by tape measure, and a long pole with ruler is used to observe temperature up to 5 m above the ground (Photo 3). Air temperature, dew point, and wind were observed by Assman ventilated psychrometer and rotation anemometer at the center of every protection area.

An extensive observation during the special observation period is referred to as Run. During the observation, 2 sets of Run were carried out

Photo 3. Measuring vertical cross section of temperature using thermistor thermometers at the second protection area. A long pole is used to measure upper level temperature.

and are named as

Run-1: 14:00—16:00, May 17
Run-2: 13:00—16:00, May 18

Spirig data loggers for temperature with external sensor and humidity were useful for vertical sounding lifted by helium balloon. We set the Spirig data logger for two hours duration with four second interval and lifted at the second protection area to measure the temperature distribution within the amphitheater.

Observations by the CCD Camera

A system of CCD video camera set was prepared to monitor the cave ice deep in the wind hole. The camera is about 2 cm diameter, and 10 m wire is connected to the video monitor. Since the inside of the wind hole is dark, two electric lights were attached with the CCD camera. With this method we could see the inside of wind hole to find whether ice exists or not. Moreover, we recorded the wind motion using smoke balls. The CCD camera follows smoke motion to visualize the air flow.

Moving Observations

One of the most important subjects of present observation was to identify the location of air intake to the inside talus to compensate the outflow of cold air from the wind holes. The theory of mass continuity requires that there must be air intake somewhere along the talus as long as cold air keeps blowing from the freezing area. A team of moving observation climbed the talus from the bottom to the top.

There is a mountain trail from Kanatsuka House via third and fourth protection areas to sixth protection area. Except for such a trail, mountain slope is difficult to walk due to the dense bush and trees. Walking the talus with the critically steep slope itself is very danger.

Many tiny holes were measured with digital thermometer-anemometer and burning incenses to check whether the holes indicate outflow or inflow. In addition to the moving team, all teams measured the distribution of soil temperature around the assigned area.

Other Observations

Diurnal cycle of temperature, humidity, and wind speed at the wind hole are observed with thermistor thermometer, moisture gauge, and platinum resistance anemometer at the second protection area. If the wind speed at a wind hole is controlled by the temperature difference in and outside the talus, we can expect diurnal cycle as well as annual cycle.

In order to observe the upper air wind during the special observation period, pilot balloons are launched from the Observation Tower.

Wind hole ice at various protection areas, underground water at various locations in Nakayama, and water of Aga River were collected to measure relative isotopic abundance for evaluation of age of water.

RESULT OF THE SPECIAL OBSERVATION

Ice in the Wind Holes

Although the upper air temperature of this day was 24°C, we can see many wind hole ice at all protection areas. Among those, the fourth protection area indicates the largest amount of ice at many holes.

Photo 4 illustrates an example of ice in the wind hole at the fourth protection area. About 20 cm icicle is seen hanging from upper rock and reaching to the bottom rock. It keeps freezing on the bottom floor rock. The ice location is about 30 cm inside the hole. The temperature is 1°C and humidity 98%. The wind speed is difficult to measure, depending on the location within the hole, but it is approximately 0.5 to 1.0 m/s. The entrance shows green vegetation by abundant solar light.

Photo 5 shows a similar cave ice at the second protection area. A white Micro-Logger box is seen beside icicle. The upper part of the icicle has melted. It seems not growing from the bottom to top, but seems the upper part of icicle has melted due to the slightly warm air in the hole. Although not shown by a photo, the CCD camera observation indicates icicle at least 1 m depth of the wind hole. The surface of side rocks was covered by thin film of ice in the deep wind hole. There are another types of ice, which look like a remaining snow with white bubbles inside ice (Photo 6).

Photo 7 shows the view of the fourth protection area where heavy moss covers the talus slope. A unique ice sheet is seen under moss as shown in Photo 8. There are no big holes, but a wide ice sheet was detected under moss when we lift moss by hand. Moss may be about 10 cm thick. The ice is protected by moss from warm heavy rain and sustained by cold air blowing through the tiny space in the root of moss.

Photo 4. Icicle in the wind hole at the fourth protection area, growing 20 cm long from the top to bottom. The inside is very wet and cold air keeps blowing. Green moss grows under the sun light.

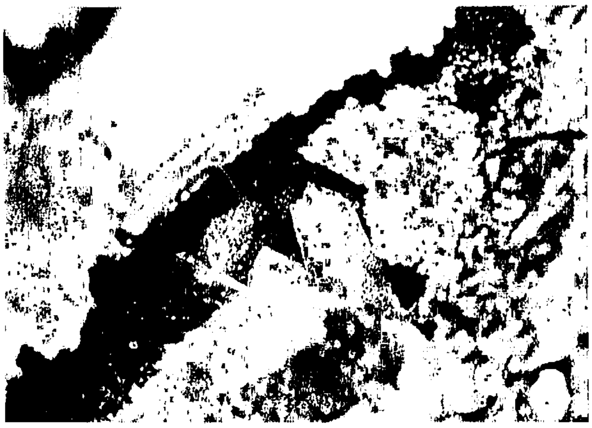


Photo 5. Ice in the wind hole at the second protection area, growing 10 cm long from bottom to top. White Micro Logger is put beside the ice. Care must be taken during winter since Micro Loggers are trapped in the deep ice until spring comes in the next year.

Photo 6. White Ice in the wind hole which looks like the remaining snow. Fiber Scope CCD camera is used to see deep inside the wind cave. Snow surface is relatively clean without accumulation of soil and dust.

Photo 7. General view of the talus at the fourth protection area along the southern slope. Debris are covered by 10 cm thick moss. Large amount of ice is preserved under those moss. Katabatic wind is as strong as 1 m/s.

Vertical Cross Section

Vertical cross sections of temperature were

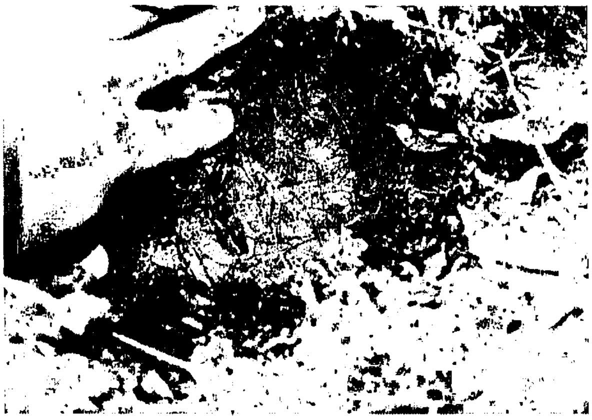


Photo 8. Every root of moss is occupied by a slab of ice. The ice around the root is protected by moss from heavy rain during spring as long as cold air blows from the inside.

measured at each protection area along slope lines A—A' and strike lines B—B' as seen in Fig. 3. Figures 4 to 7 illustrate vertical cross sections of temperatures measured at the C wind hole area, third, fourth, and sixth protection areas, respectively. The upper and lower figures plot the cross sections along the slope and strike lines, respectively.

The C wind hole area is located at the 555 to 565 m level. Cross-section was measured along 25 m in slope A—A' and 10 m in strike B—B'. Within 1.5 m layer from the surface, the upper air temperature decreases from 24°C to a minimum of 2°C on the surface. There is a strong temperature inversion, with stable stratification. The distribution indicates cooler temperature in lower area as the cold air from the hole flows down the slope. The distributions are quite similar for the third, fourth and sixth protection areas. For the third protection area, the cold air near the 526 m level flows down

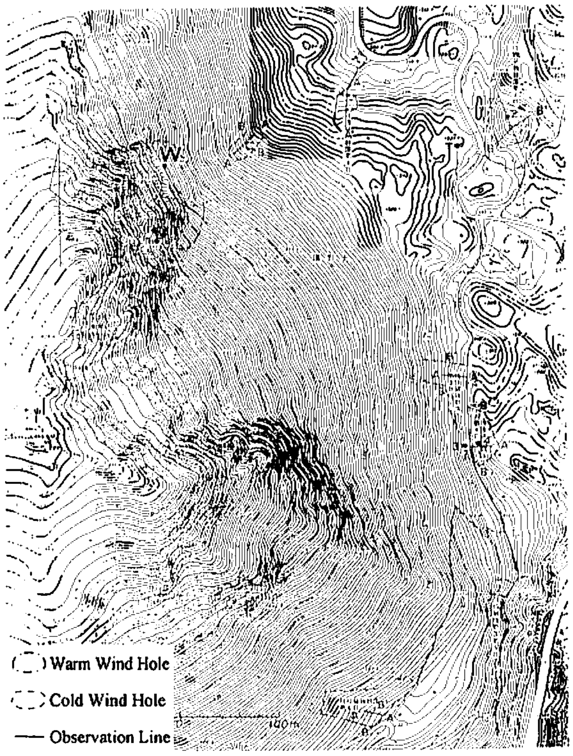


Fig. 3. The six protection areas in Nakayama marked with slope lines A—A' and strike lines B—B' for the special observation. The location of warm wind hole is marked by W surrounded by warm soil area for winter.

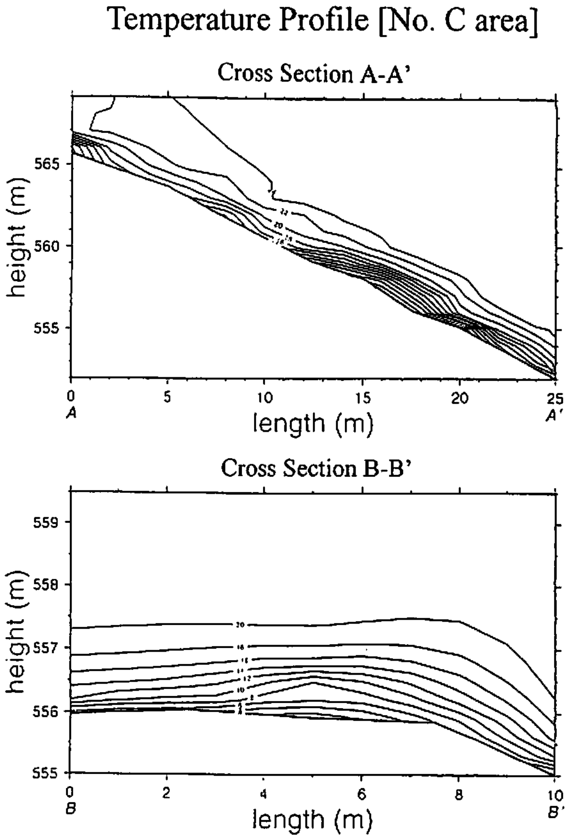
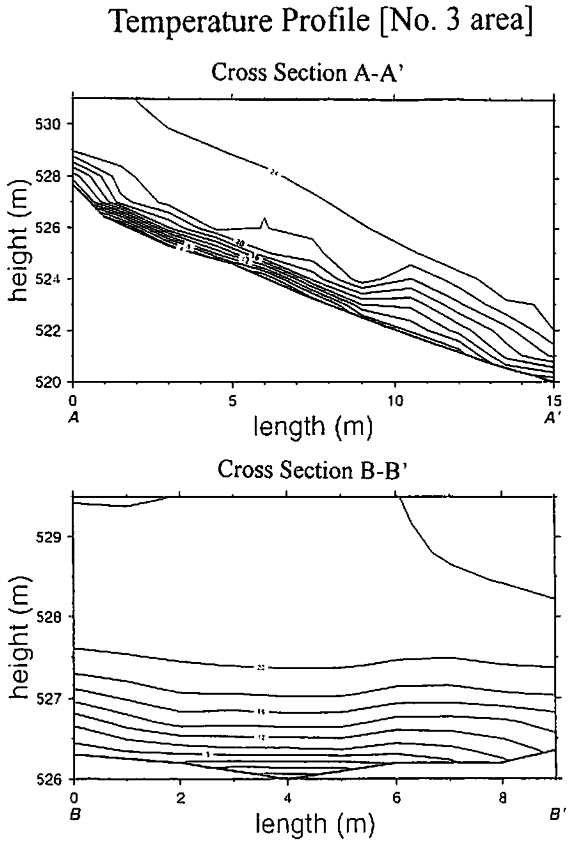


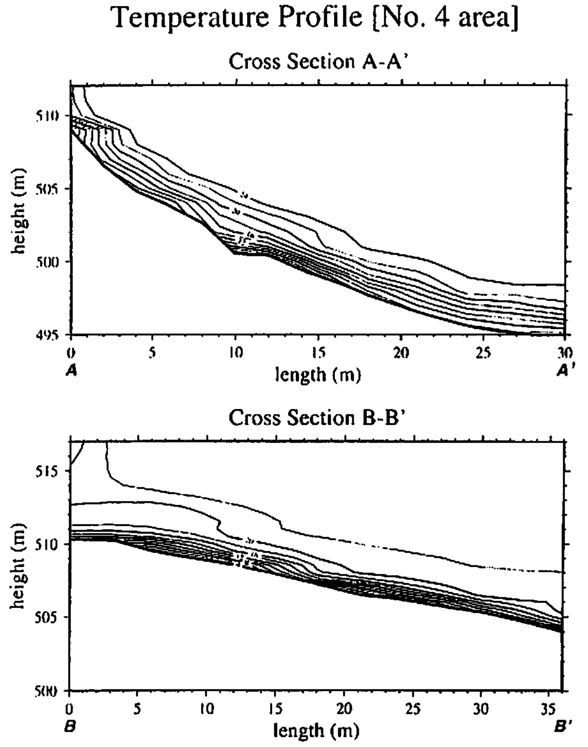
Fig. 4. Vertical cross sections of temperature along the slope lines A—A' and strike lines B—B' at the C wind hole area for the Run 2 during 14:00 - 16:00, May 17. Contour interval is 2°C.


Temperature Profile [No. 3 area]

Cross Section A-A'

Cross Section B-B'

Fig. 5. Same as Fig. 4, but for the third protection area. Contour interval is 2°C.


Temperature Profile [No. 4 area]

Cross Section A-A'

Cross Section B-B'

Fig. 6. Same as Fig. 4, but for the fourth protection area. Contour interval is 2°C.

the slope, then the mixing with outside air gradually increases the temperature near the 522 m level.

For the second protection area, the cross sections show accumulation of cold air at the bottom of the amphitheater with 15 m deep (Fig. 8). Using a combination of Micro-Logger and a helium balloon, the vertical profiles of temperature and humidity at the center of the amphitheater were observed (Fig. 9). The value at 0 m represent the location of a wind hole. It is 1°C and 96% relative humidity. There is a steep change in the first 1 m layer to 10°C and 65%, respectively, The values then gradually changes to 19°C and 40% at 15 m above the ground. According to the cross section in Fig. 8, top temperature is 20°C and the bottom temperature is 4°C. Distinctive cold air lake is formed by the cold air supply from the wind holes. The entire amphitheater is filled by a strong temperature inversion with stable stratification. Northern slope where many wind holes exist indicates colder temperature. The cold air extends upward at the center of the amphitheater. It is interesting to note that wind holes exist not only at the talus side (western side) of the amphitheater, but also the opposite side (eastern side) facing the Aga River. This implies that the cold air must be lifted from the deep talus up to the Aga River side of the amphitheater.

Moving Observation

The moving observation team and other five teams have both collected the soil temperature measured by thermistor thermometer. Figure 10 maps horizontal distribution of soil temperature around Nakayama. The minimum soil temperature at C wind hole area, first, to sixth protection areas are, 2.0, 4.0, 4.0, 2.0, 2.0, 10.0, and 2.0°C, respectively. The fifth area is apparently too warm for a wind hole. The

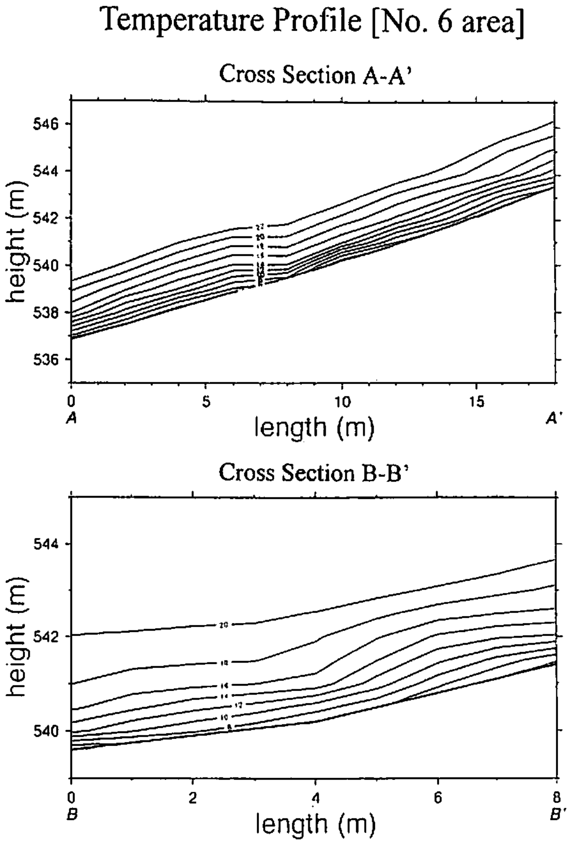


Fig. 7. Same as Fig. 4, but for the sixth protection area. Contour interval is 2°C.

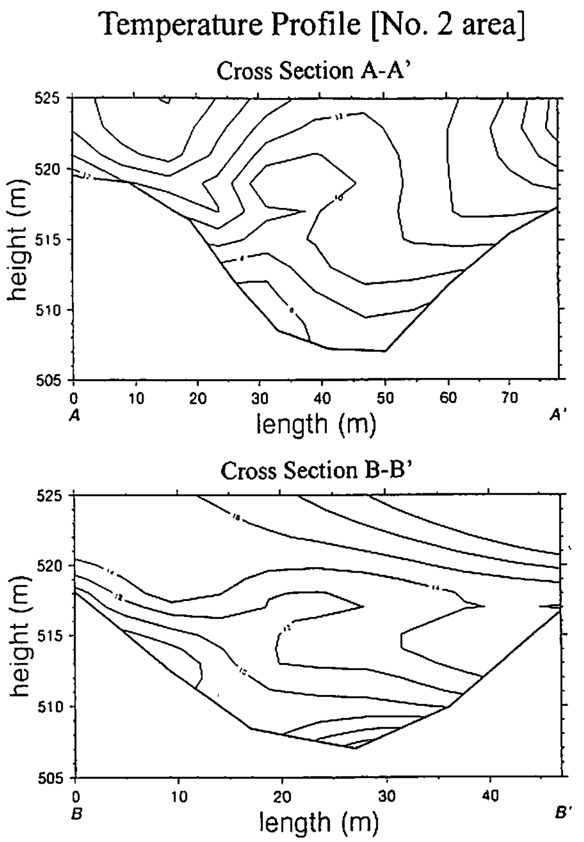


Fig. 8. Same as Fig. 4, but for the second protection area which has an amphitheater shape with 15 m depth. A distinctive cold air pond is formed. The upper air temperature is measured by the Micro Logger lifted by a helium balloon. Contour interval is 2°C.

temperature other than the wind holes is about 16°C. From the result, it is found that the soil temperature is low only at the specific area with wind holes.

One of the most exciting findings in the special observation is the so-called warm wind hole at the top of the talus at 620 m level (Figs. 1 and 2). The team found a distinct cave with its opening about 1 m which is located just at the bottom of the eastern cliff. Photo 9 illustrates a burning smoke ball at the warm wind hole. As seen from the photo, every smoke from the smoke ball is inhaled by the cave. The suction speed is more than 1 m/s. The experiment of smoke suction was recorded by the CCD video camera.

We burned several smoke balls at a time at the warm wind hole, communicating by transceiver with the team at C wind hole area at 100 m apart, whether or not they could recognize the burning smell after some time

Photo 9. The air intake at the warm wind hole (cave) at 620 m level visualized by burning smoke ball during the Run 2. Every smoke from the smoke ball is sucked into the cave.

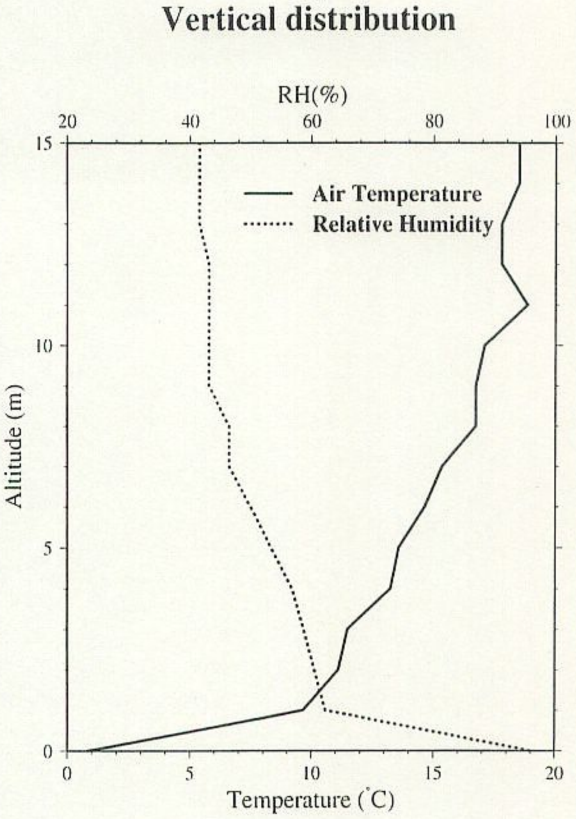


Fig. 9. Vertical profile of temperature and humidity at the second protection area for the Run-2 measured by the Micro Logger lifted by a helium balloon. The bottom temperature and humidity are in the wind hole.

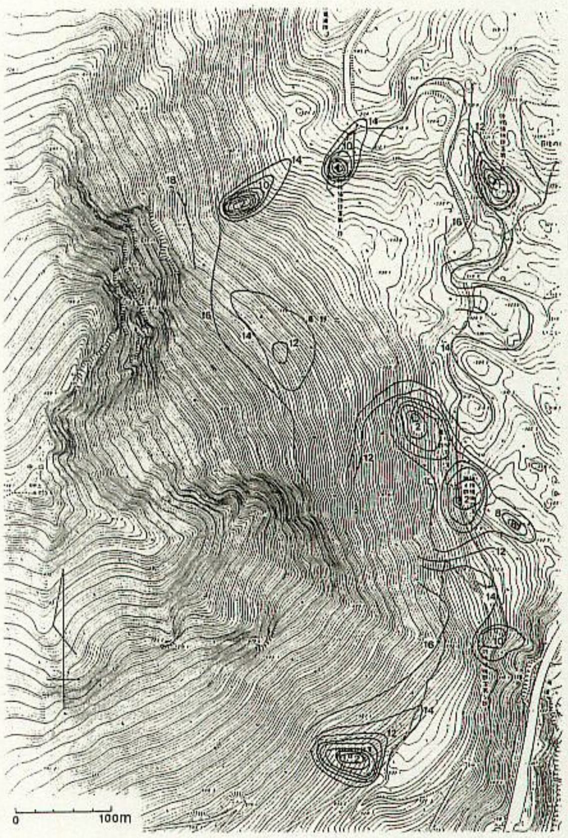


Fig. 10. Horizontal distribution of the surface soil temperature around Nakayama. The minimum soil temperature at C wind hole, first, to sixth protection areas are, 2.0, 4.0, 4.0, 2.0, 2.0, 10.0, and 2.0°C, respectively.

later (Fig. 1). If the air circulates with the speed of 1 m/s for 100 m, it takes only 100 sec to come out from the C wind hole area. It was hard to judge, but the smoke didn't come out within ten minutes or so. The smoke once entered in the talus seems to have spreaded and descend very slowly. To figure out the circulation time scale within the talus may be the key question in the next step.

Diurnal variations

Figure 11 plots the diurnal variation of temperature, relative humidity, and wind speed on June 30 1999. The outside temperature varies from 20°C in mid-night to 38°C at noon. Temperature in the wind hole and ground temperature are approximately constant at about 6°C and 4°C, respectively, and humidity about 99%. Wind speed varies from 0.05 m/s at 5:00 to 0.45 m/s at 16:00. The result implies a rather sensitive response of the wind hole circulation depending on the outside air temperature. While the outside air temperature is high, the temperature difference between outside and inside talus is large, and the pressure gradient force enhances the wind hole circulation. Conversely, while the outside temperature is low, the same mechanism results in ceasing the wind hole circulation. When the cold air flow terminates in the morning, the wind hole feels the outside air by the diffusive turbulent flow, which causes the characteristic decrease in relative humidity at 8:00.

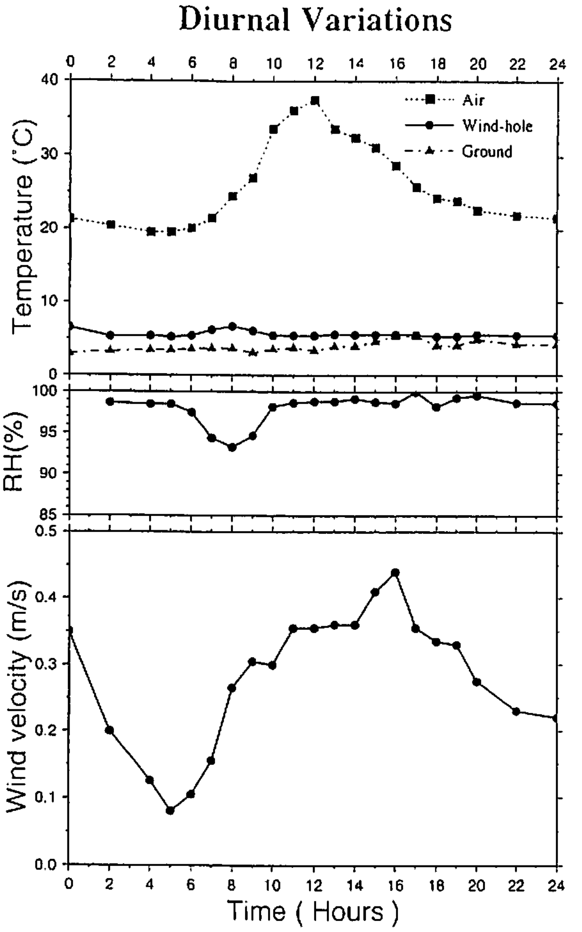


Fig. 11. Diurnal variation of temperature, relative humidity, and wind speed, respectively, inside and outside of the wind hole at the fourth protection area observed on 30 June 1998.

ANNUAL CYCLE OF THE WIND HOLE

Reversing Wind Hole Circulations

The Spirig Micro-loggers were set at wind holes of second, third, and fourth protection areas to measure the annual cycle of wind hole temperature. We put another Spirig Micro-logger at the warm wind hole at 620 m level after the special observation period to measure temperature at the intake of outside air to talus.

Figure 12 plots the result of the annual variations of temperature at outside air (white line), cold wind holes (lower black lines), and warm wind hole (upper black line). The outside air indicates large diurnal variation and passage of synoptic weather system superimposed on the annual cycle. The daily mean during winter is about -2°C with transient variation ranging from -10°C to +7°C. The minimum temperature was recorded in February reaching -15°C. On the other hand, the daily mean during summer is about 25°C with transient variation ranging from 15°C to 35°C.

The temperature of cold wind hole was less than zero till the end of March. It keeps the minimum of zero till the beginning of June, then starts to raise above zero. It is found that the special observation period is just the end of icy period for the cold wind hole. It then gradually warms till the end of September reaching 15°C. The warming speed is calculated as 2.5°C/Month. The warm wind hole follows the temperature of outside air because it is the intake of the air. It is a little cooler than outside air since it is in the cave. This is the period of cold wind hole circulation where warm outside air goes into the talus from the warm wind hole, and cooled air comes out from the cold wind hole. When the circulation is strong, we can find that there is almost no diurnal variation in the cold wind hole.

The beginning of October is a time of special turning point for the wind hole circulation. While the outside air gradually cools as season goes by, cold wind hole gradually warms by the heat of the warm outside air, mostly by advection of air rather than thermal conduction of soil. It is the beginning of October when the temperatures of outside air and cold wind hole air intersect with each other at about 15°C. Beyond that turning point, the temperature time series of the cold wind hole changes drastically. Since the outside air is now colder than the interior talus, cold wind hole circulation is replaced by warm wind hole circulation. For the warm wind hole circulation, outside air goes into the talus from the cold wind holes at the bottom of the talus and comes out from the warm wind hole at the top of the talus.

It is important to note that the colder the outside air is, the stronger the warm wind hole circulation is. The warm wind hole circulation

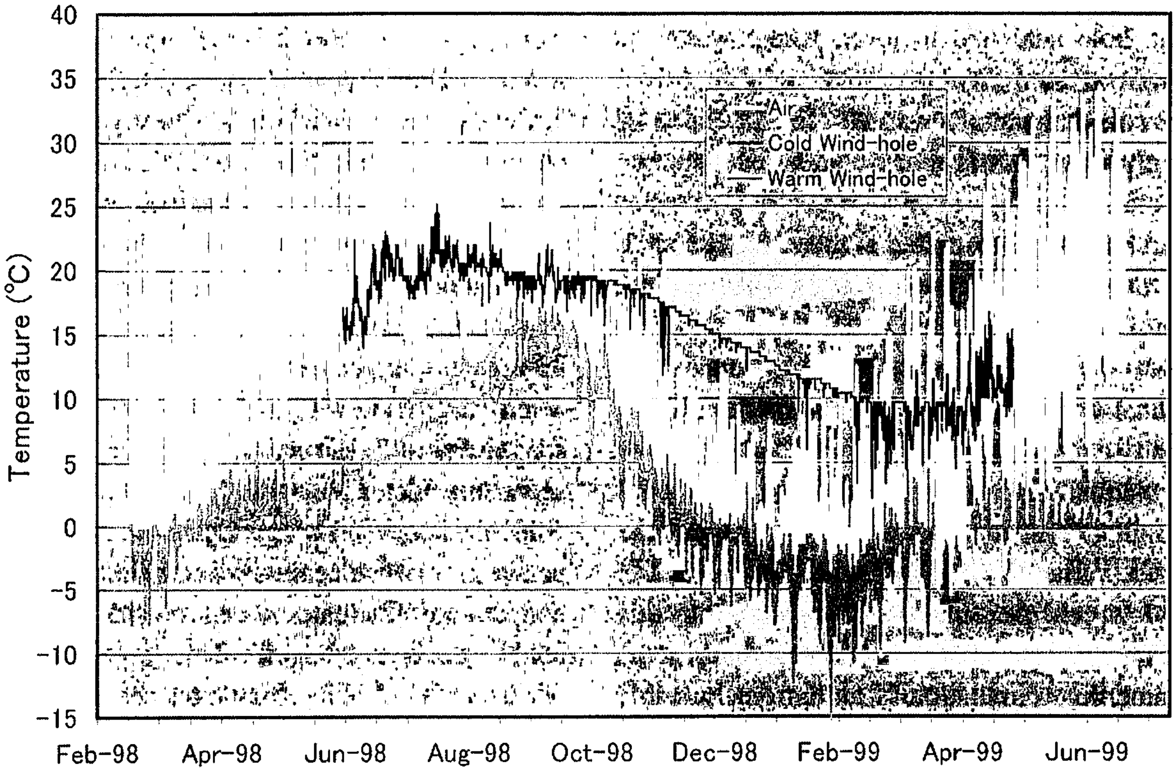


Fig. 12. Annual variations of temperature at outside air (white line), cold wind holes (lower black lines), and warm wind hole (upper black line) measured by Micro Loggers from the end of February 1998 till the beginning of July 1999. The plots for cold wind holes are the combination at second, third, and fourth protection areas.

pattern may be quite different from the cold wind hole circulation, because the circulation is induced by dynamical instability of unstable vertical stratification. A colder air stays aloft over the warmer air in the talus. Since the air can move almost freely in the talus, the over turning of cold and warm air occurs in a minute. The thermal mixing is quite effective in winter to suck the cold air from the cold wind hole into the talus. It is said that a jet of steam-like fog is observed near the warm wind hole sometimes in very cold nights. Therefore, the cold wind hole temperature follows the minimum temperature of the outside air during the night. During the warmer daytime, the warm wind hole circulation may be reduced, so warmer air does not come into the talus. The warm wind hole, in contrast, keeps blowing warm air during winter, and almost no diurnal variation is detectable.

Photo 10 was taken on 28 December 1998 when a slight amount of snow fell on the mountain. We observed a spectacular image of

Photo 10. Distribution of the snow cover and open patches near 620 m level around the warm wind hole. The picture is taken on 28 December 1998. Soil temperature at the patches of open ground are 9°C and warmer, indicating a penetration of warm air from inside the talus.

patched areas of melting snow near the warm wind hole near 620 m level, where warm air flows out from tiny spaces between the rocks. The soil temperature was 9°C for the patch of open ground, but is much colder for the snow covered area. The photo suggests that the warm wind hole is not restricted at the cave we found, but everywhere at the patch of open ground near 620 m level.

As the season goes by, the outside air gradually warms, and in March another turning point comes to reverse the wind hole circulation. The warm wind hole is now changing to suck outside air, thus feeling the diurnal variation. The cold wind hole then starts to blow cold freezing air. Compared with this dynamical instability during winter, the summertime circulation is an extremely stable Katabatic flow where cold air in the talus is protected by the stable stratification, thus tends to be preserved.

Rain and Wind Hole

It is interesting to describe in detail the daily variation of cold wind hole discussed in Fig. 12. Figure 13 plots the daily variations of temperature of outside air, cold wind hole and warm wind hole from 23 to 29 April 1998. The lower figure plots daily precipitation of the AMeDAS station at Tajima. The figure shows 60 mm of precipitation on 25 April when outside air and warm wind hole are about 10°C. It is important to point out that the cold wind hole temperature remains at the freezing point despite the considerable amount of sensible heat supply expected by the heavy rain. The Micro-Logger is set just below 10 cm moss seen in Photo 7. Hence, the heating by rain is a secondary factor for wind hole ice as long as cold air keeps blowing. Contrasted with the persistency of ice against warm rain, wind hole temperature fluctuates when outside air gets cold as seen on 29 April. This is because the persistent wind hole circulation ceased by the vanishing temperature contrast in and outside the talus.

Cooling Wind Hole by Warmer Outside Air

Figure 14 is the continuation of Fig. 13 for 30 April to 5 May 1998. During this period, the outside air temperature temporarily went down to freezing point early in the morning. Very

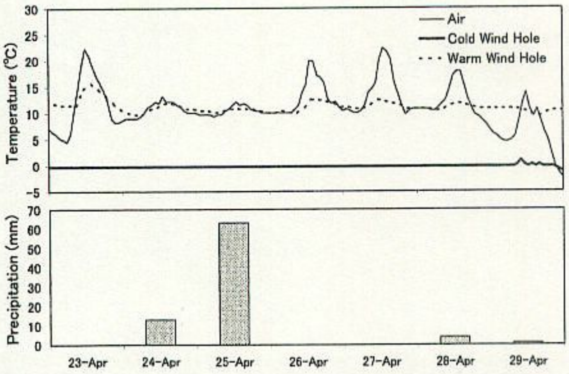


Fig. 13. Same as Fig. 12, but for the period from 23 to 29 April 1999. Precipitation in the lower figure is plotted with the AMeDAS data near Nakayama. Note that no temperature change occurred for the 0°C line of the cold wind hole, despite the large sensible heat supply by the heavy rain for moss at the fourth protection area.

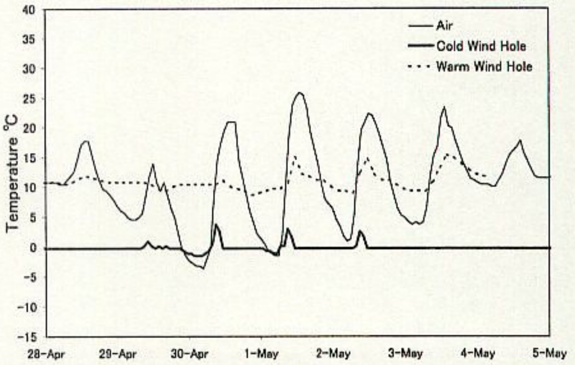


Fig. 14. Same as Fig. 12, but for the period from 30 April to 5 May 1999, just after that in Fig. 13. When the outside air gets colder than that of the cold wind hole, the wind circulation ceases. Then the cold wind hole temperature can feel the outside air temperature. Interestingly, when the outside air gets warmer, the cold wind hole gets colder.

interesting and sensitive response of wind hole was observed. When the outside air is warmer as in Fig. 13, the temperature contrast between in and outside talus excites stronger cold wind hole circulation. As a result, the outlet of cold air drainage cools down to zero degree. On the contrary, when outside air is cooler than the cold wind hole, as in 30 April, the cold wind hole circulation ceases. When the circulation ceases and the cold air drainage stops, the cold wind hole turns to feel the outside air by the diffusive turbulent activities. It results in decreasing temperature early in the morning, but increasing temperature as outside air warms in the late morning. However, the temperature decreases again as soon as the cold wind hole circulation begins due to the heated outside air as seen for 30 April to 2 May. In other words, the hotter the outside air is, the cooler the wind hole is. This mechanism, in part, explains the mysterious summertime ice at the Ice Valley, Korea, where ice grows more when outside is hotter.

Warming Wind Hole by Colder Outside Air

Similar, but opposite, unusual temperature variation occurs for warm wind hole in fall as see in Fig. 15 during 14 to 18 November 1998. During this season, the outside air fluctuate from 0 to 20°C due to the diurnal cycle. The cold wind hole is about 2°C feeling only the daily minimum temperature. When the outside air warms up, cold air drainage cools the cold wind hole as discussed above. In contrast, the warm wind hole is about 17°C, blowing warm air from the talus. Interestingly, the steady warm wind hole turns to fluctuate when the outside air temperature exceeds the warm wind hole temperature. This is because the warm wind hole circulation ceases due to the reversed temperature contrast. As soon as the cold wind hole circulation begins, the warm wind hole feels the outside air and the temperature decreases. But, the warm wind hole gets warmer when th outside air gets colder. This phenomenon is just opposite to the cold wind hole in spring.

The result suggests the importance of the temperature difference between inside and outside of the talus as the key factor to understand the mechanism of the wind hole. The circulation is so sensitive to the temperature contrast that it easily reverses within a minute. The cold wind hole sucks the coldest air during the night into the talus, but it avoids to suck warm air during the day. The mechanism may be regarded as a natural thermal filter which passes only the coldness.

THERMODYNAMIC CONSIDERATION

There was a cold wind hole circulation from April to September. An attempt is made to evaluate the total volume of the air mass circulating the talus during summer season. The total enthalpy flux into the talus is also the subject to be estimated.

The blowing wind speed at the cold wind holes often exceeds 2 m/s in some places although the majority of wind holes shows much weaker wind speed. Roughly speaking,

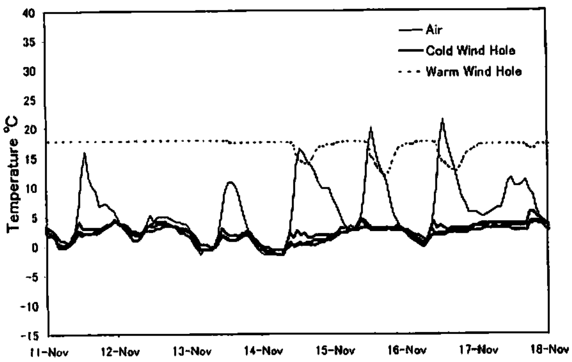


Fig. 15. Same as Fig. 12, but for the period from 14 to 19 November 1998. Note that the warm wind hole circulation ceases when outside air gets warmer than the warm wind hole. Then the warm wind hole temperature can feel the outside air temperature. Interestingly, when the outside air gets colder, the warm wind hole gets warmer.

we estimate the mean wind speed as 0.2 m/s. Since the wind speed indicates diurnal variation with weaker wind during night, we estimated the daily mean as v=0.15 m/s.

The protection area sizes are 250, 100, 250, 700 m^2 for C wind hole area, first, third and fourth protection areas, respectively. The sum is 1300 m^2. We estimate only 1% of the protection area is actually the area of wind hole, which results in A=13 m^2 as the total. Hence, the estimate of the circulating air volume across the talus is Av= 1.95 m^3/s. When the number is integrated during the summer season, the resulting volume becomes $V=2.14\times10^7$ m^3.

The entire volume of the talus is estimated as $Vr=1.0\times10^6$ m^3 from the area and thickness of andesite rocks over the bedrock. Among those volume we assume that 20% of which is the free space where air can move freely. The final estimate of the vacant air space in the talus is $Va=2.0\times10^5$ m^3. Based on these estimates of volumes, it is suggested that the air within the talus must be replaced, at least, n = V/Va = 100 times during the summer. In other word, the circulation time scale (residence time) is about 2 days from the suction at the warm wind hole to the outlet at the cold wind hole. If we assume the mean path of 200 m for the air route, the mean wind speed becomes $u=1\times10^{-3}$ m/s in the talus.

In Sec. 4.3, we argued the circulation time scale between the warm wind hole and the C wind hole area. If the air moves 100 m by v=0.15 m/s as argued above, it takes only 11 min, but which is unlikely. Since both the cold wind hole in spring and warm wind hole in fall show no diurnal variation, the circulation time scale of 2 day is most likely to be correct.

Now, the total heat energy supplied by outside air to the talus can be estimated by

$$Q = c_p \rho_a n V_a \Delta T$$

Here, cp =1005 J/kg/K is a specific heat of air, ρ_a=1.2 kg/m^3 is density of dry air, nV_a= 2.14×10^7 m^3 is the total volume of air estimated above, and ΔT=7.0 K is the mean temperature difference between the warm wind hole and cold wind hole. The calculation shows Q= 1.80×10^{11}J. The heating rate q, divided by the duration, becomes $q=1.60\times10^4$W.

If this heat energy is used to warm the talus, we obtain:

$$Q = c_r \rho_r \beta V_r \Delta T_r$$

where, c_r=750 J/kg/K is a specific heat of rocks in talus, ρ_r=2500 kg/m^3 is density of rocks, ΔT_r=15 K between spring and summer, V_r=6.0 10^5 m^3 is the volume of the talus, and β is a parameter describing the ratio of the rock volume affected by the transient heating. The calculation shows that the unknown parameter β=0.01, suggesting that only 1% of rock volume in the talus is affected by the annual variation of temperature.

SUMMARY AND DISCUSSION

Nakayama Wind-Hole in Japan shows a great similarity with the Ice Valley in Korea as a wind hole along the rocky talus. It is an important Natural Monument to be preserved in Japan with a rare alpine plants which survive under the cold air blowing from the wind hole. In our former report (Tanaka et al., 1998), an observational study of the Ice Valley in Korea was carried out to understand such a mysterious phenomenon in that natural ice grows in the wind hole during the hottest summer. Interestingly, it has been said that the hotter the summer is, the more the summertime ice grows. Despite this intriguing nature, the mechanism of freezing ice in the hottest season was not understood yet. In this regard, Nakayama Wind-Hole is a good sample for the comprehensive study of wind hole in Japan to understand the mechanism, although the talus is not as large as Ice Valley.

Both of the Ice Valley and Nakayama Wind-Hole tend to suffer from less ice in recent years, probably due to the dense growing vegetation. Yet, cutting vegetation would not necessarily prevent the decreasing trend. On the contrary, any kind of protection effort might end up with destruction of the summertime ice because we still do not know the mechanism of the unusual summertime ice. The first step to protect wind hole ice is therefore to understand the mechanism.

For this reason, we have conducted *in situ* special observation during 16 to 17 May 1998. In addition to this special observation, we kept monitoring the wind hole for more than a year from February 1998 through July 1999.

As a result of the *in situ* special observation during 16 to 17 May 1998, the following facts are found:

1. The soil temperature distribution (about 16°C in average) shows several low temperature spots (about 2°C) corresponding to wind hole areas around the foot of Nakayama mountain. The first and fifth protection areas show less wind holes and less alpine plants compared with other protection areas. C wind hole area is colder than the first protection area. The fourth protection area contains more ice than other areas, where plenty of ice exists under the moss cover of about 10 cm thick.
2. The vertical cross section of air temperature shows that the outside air temperature of 24°C at 5 m above the surface decreases to 2°C in the wind hole. The cold air flows down the slope as Katabatic wind. The second protection area has amphitheater, so cold air lake is created by accumulated cold air from the wind holes.
3. About 100 m above the cold wind holes near 520 m level, a warm wind hole is found at the 620 m level near the top of the talus, where approximately 1 m^2 area of cave indicates air suction of 1.0 m/s. It is estimated that the total area of the cold wind hole is 13 m^2 with a mean blowing wind speed of 0.15 m/s. The air volume of 1.95 m^3/s is comparable to the suction from the warm wind hole.

The seasonal integral of the circulation air from April to September amounts to 2.14×10^7 m^3.

The volume of the eastern andesite talus is approximately 1.0×10^6 m^3 by a field survey. Supposing that the empty space of the talus where air can move is 20%, the capacity of air within the talus is 2.0×10^5 m^3. Hence, the air within the talus must circulate 100 times during the warm season. In other word, the air must circulate once at every 2 days. If we assume the mean path of 200 m for the air route, the mean wind speed becomes $u=1$ mm/s in the talus.

The net heat energy stored in the talus during summer can be calculated from the mass flux discussed above and the temperature difference between the cold and warm wind holes. As a result 1.80×10^{11} J of heat energy is stored during summer which warms the talus temperature from 0°C to 15°C. The same amount of heat is expected to be released during the winter. The heat is expected to be stored in both rock and ice in the talus. The evaluation of heat capacity of the talus suggests that only 1% of the talus mass is affected by the annual variation of outside air temperature.

The annual cycle of the wind hole circulation is summarized in Fig. 16. After ice has melt in July, the cold wind hole warms steadily with 2.5°C/Month till the end of September. It is the beginning of October when the cooling outside air gets colder than the talus temperature. Then the cold wind hole circulation turns to reverse to warm wind hole circulation, where outside cold air comes into the talus from cold wind hole and warm and moist interior air blows out from the warm wind hole. The circulation is strong when the temperature difference between inside and outside of the talus is large. Therefore, the suction of cold air is the strongest when daily low temperature occurs. The warm wind hole circulation may occur as a turbulent overturning of cold and warm air because the temperature stratification is extremely unstable. The cold air in winter is thus effectively stored into the talus as a

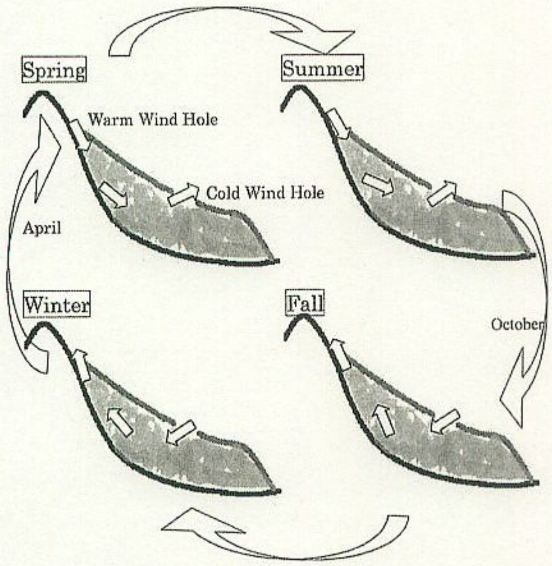


Fig. 16. A schematic illustration of annual cycle of the wind hole circulation. The penetration of cold air from the deep inside talus during summer is the Katabatic flow under the very stable temperature stratification. Conversely, the warm wind hole may occur as a turbulent overturning of cold and warm air because the temperature stratification is extremely unstable. The coldest air during the winter penetrates into the talus in a minute to store the coldness. The talus behaves as a thermal filter which passes only the coldness into the talus, which may be the essential mechanism for the wind hole.

thermal filter which passes only the coldness into the talus.

The result of the present observation supports the selective convection theory of cold air during the winter for the mechanism of ice formation in the wind hole. It is interesting to note that the hotter the outside air is during spring, the stronger the freezing Katabatic wind is. This mechanism, in part, explain the mysterious ice formation at the Ice Valley in Korea during the hottest season.

Acknowledgments

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