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Seasonal reversal at Miryang Eoreumgol (Ice Valley), Korea: observation and monitoring

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ORIGINAL PAPER

Seasonal reversal at Miryang Eoreumgol (Ice Valley), Korea: observation and monitoring

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Abstract We investigate an anomalous phenomenon evident in the Miryang Eoreumgol (Ice Valley), Korea: The wind and water are cold during summer and warm during winter, and ice formation does not occur in winter but in summer. We have initiated observations and investigations into the origin of heat sources particularly with regard to the mechanism of ice formation in summer. Previous theories, e.g., concerning underground gravity currents, water evaporation, diurnal and seasonal respirations of the talus, effects of ground heat, radiation and topography, etc., are considered. After a calculation of heat sources, we propose two new concepts—a repetitious heat separation mechanism and a positive feedback mechanism of cold air generation—to demonstrate that the heat mechanism of the seasonal reversal of the ice valley may be controlled by the use of the phase change between ice and water vapor with only a small amount of additional unknown energy.

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1 Introduction

The ice valleys in Miryang, Korea, have attracted considerable attention worldwide due to unusual phenomena witnessed in these regions. Miryang city, Republic of Korea, is famous for the 'Eoreumgol' (Ice Valley), located approximately 400 m a.s.l. on the slopes of the Jaeyaksan Mountain. This ice valley, one of Miryang's tourist destinations, has gained immense popularity due to the phenomena observed: Naturally, water is frozen even at the peak of summer and the ice melts out in autumn. In winter, hot steam rises from the valley and the water does not freeze. These phenomena are attributed to local airflow patterns. Cold underground air and cold water flowing beneath the talus in the valley are primarily responsible for the subzero temperature environment, leading to the formation of ice in summer. In contrast, both air and water coming out from the talus in the valley are warm, and so the ice is not formed in winter.

Most studies since Kim (1968) have aimed to provide an explanation for two factors: a *cold wind hole*, i.e., a hole in the talus through which cold air is expelled, and the *origin of the cold air*. Kim (1968) suggested that cold air is formed due to the adiabatic expansion of underground air. Other researchers have focused on the effect of water evaporation (Moon and Whang 1977), a huge body of underground ice (Jung 1992), cold air from the polar region (Song 1994; Byun et al. 2003a, b, 2004, 2006), radiative cooling (Whang et al. 2005), and diurnal and seasonal respirations in the talus (Tanaka 1997; Tanaka et al. 2000, 2006). Bae (1990) firstly reported the formation of warm water in winter and cold water in summer in the valley. Later, Byun et al. (2003a, b, 2004) presented several *warm wind holes* in the talus, i.e., those from which warm air is expelled, at higher altitudes in the valley and at distances of 500–1,000 m from the cold wind hole. hey suggest that in the valley, the main ice formation does not occur during summer or winter, but rather in late spring or early summer (when all other ice in the valley melt). Furthermore, it is observed that small-scale ice features are formed in the deeper part of the talus, even in late summer (Byun et al. 2006).

No satisfactory explanation has yet been made regarding the existence of warm wind holes and the timing of the ice formation, partly because the investigations were carried out for very short periods (less than 3 months). In this study, we will explain the wind holes in the ice valley on the basis of 2 years of observations.

There is another ice valley in Yolinam, South Gobi Aimag, Mongolia, (43°31′953″ N, 102°10′715″ E, 1,619 m a.s.l.) where no sunshine reaches the deepest parts of the canyon and a pool of cold air collects, unable to escape due to the local topography. The canyon is shaped so that the wind cannot pass through it; thus, it is completely shielded from the heat of the surrounding desert. Additionally, the volcanic rock distributed there is so good an insulation as to keep the heat from flowing. These factors contribute to the formation of ice, which in winters can attain a thickness of as much as 6 m. The ice thickening process is well defined: On sunny days, water from melted snow over neighboring rocks flows into the valley; at night, it freezes completely; the next day, additional water is supplied over the ice, again freezing during the night, and so on. The deep valley and high surrounding rocks with a very cold climate lead to the above procedure acting continuously throughout winter. The thick ice plate then persists until late August. With the exception of an underground ice body, however, the ice thaws completely and no ice is found on the surface in September. Because, to our knowledge, no studies on the Yolinam ice valley have yet been published, we observed the annual temperature variability in Yolinam for the year 2005. The highest surface temperature was 20°C in early August, while the lowest was −24.3°C. Other details of the observations on the Yolinam ice valley will be published elsewhere.

To avoid confusion, other similar phenomena which can occur in ice valleys are mentioned briefly in the following. Bluus, an ice lake in Yakutsk City, Russia, is similar to the Miryang and Yolinam ice valleys in the sense that ice is present in this region until August and disappears by September. No ice is found in the wind holes in Nakayama Japan after June; however, a seasonal temperature inversion persists throughout the year as in the case of the Miryang Ice Valley. Tanaka et al. (2006) have suggested that the hot and cold air stored underground by gravity currents is responsible for this inversion. Ice valleys are similar to but different from ice caves (Pflitsch and Piaseki 2003). Although there are more than 2,000 ice caves in the Republic of Slovakia and many others in Europe (Italy, Austria, Romania and Russia), studies on these ice caves are complicated and have yielded very few clues to assist explanation of the phenomena of the Miryang Ice Valley (Luetscher et al. 2008; Vrana et al. 2007; Pflitsch et al. 2007; Piasecki et al. 2007; Persoiu et al. 2007; Luetscher and Jeannin 2004; Ohata et al. 1994).

2 Climatology and geology of Miryang Eoreumgol and snow-thawing zones

Not far from the study area, Miryang meteorological station is located (35°29′ N, 128°45′ E) approximately 10 km away. Around Miryang city, the mean temperature for August, the hottest month, reaches 25.6°C. The mean daily minimum and maximum temperatures are 21.5°C and 30.6°C, respectively. In January, the coldest month, the monthly mean temperature is −0.2°C, and the minimum and maximum temperatures are −6.0°C and 6.6°C, respectively. The annual mean temperature is 13.0°C and the annual mean precipitation is 1,239 mm; about 68% of the total precipitation occurs during summer (JJAS).

The Ice Valley is approximately 70 m wide. The total area and volume of the talus are estimated to be ~4.9×10^4 m^2 and ~8.022×10^6 m^3, respectively. The valley is surrounded by large mountains (the Yeongnam Alps), and its topography indicates a bottleneck opening toward the north. These mountains are over 1,000 m a.s.l. and form a wall whose length is >5 km in the southern side of the valley. As a result, winds from the south do not often enter the valley. However, since the northwestern side of the valley is open, the cold northwesterlies enter the valley (Fig. 1a, b). In the south of Ice Valley, there is the Sajapyeong Plateau with a total area of 3.3×10^7 m^2; the water stream flows from this plateau to the upper part of Ice Valley. This water stream forms several waterfalls (generally four, but can vary from five to six after rainfall) that supply water inside Ice Valley throughout the year. The schematic diagram of Ice Valley is represented in Fig. 2.

Many large underground cavities are present in the valley and many cold (Figs. 1c and 3a) and warm wind holes (Figs. 1d, e, and 3b) can also be found. Cold wind holes can be found in the lower parts of the valley, whereas warm wind holes are located at the intermediate and higher parts (Fig. 1d, e). The difference between the altitudes at which the main cold and the main warm wind holes are located is 359 m, and the average slope is 35°. Just below the cold wind hole lie two streams from which non-freezing water flows all year (Fig. 8a, b). The part within the iron

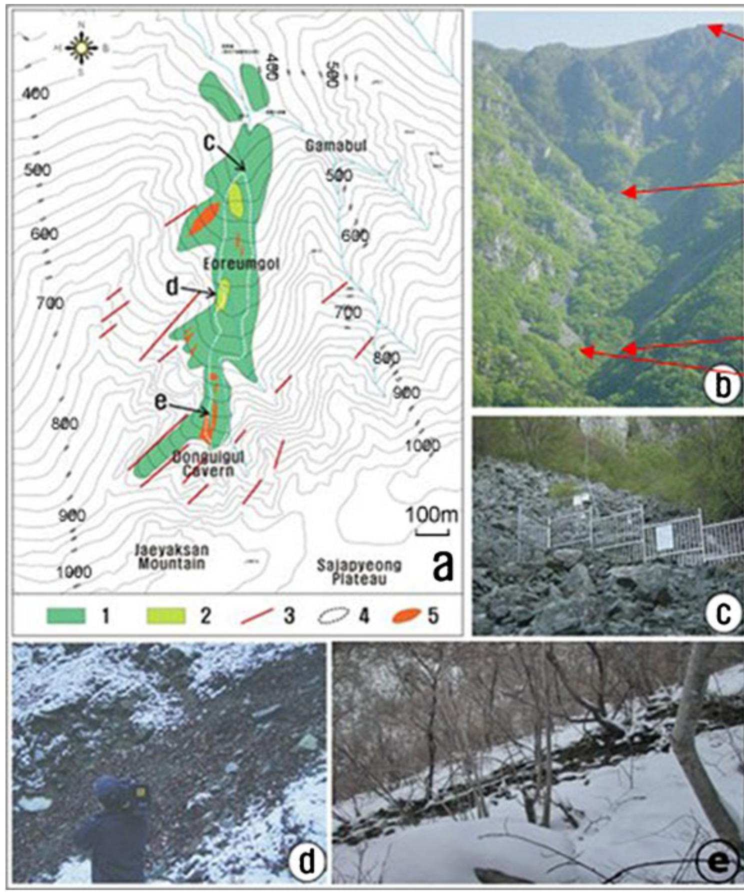


Fig. 1 Geological map and outcrop photographs of the Eoreumgol (Ice Valley) area, Miryang, SE Korea. **a** Geological map. *1* Talus deposited by grain flow. *2* Reworked talus mixed with soil. *3* Lineament or master joint. *4* Vegetation. *5* Snow-thawing area observed on 12 November 2003. **b** Southward view of the study area. The middle zone of the valley is occupied by vegetation. **c** Talus deposited near the cliff. The fenced area is the main cold wind hole that is protected by government. **d** Reworked and crudely stratified deposits containing a little rounded gravels and fine-grained sediment. The moistened horizon (*middle darker part*) is immune from snow fall. **e** Snow-thawing zonal area near the Donguigul Cavern. Photographs (**d**) and (**e**) were taken on 12 November 2003

fence (height 1.7 m) shown in Fig. 1c is the most important cold wind hole—here, the ice remains frozen for the longest time in the Ice Valley. We monitored the temperature in the cold and warm wind holes, and the temperature of the water of the two streams under the cold wind holes as well as ice formation in Ice Valley for about 2 years (2003–2004).

The geology of the study area consists of Late Cretaceous volcanic rock (dacitic welded ash flow tuff and andesite) and biotite granite (Hong and Choi 1988). The part of the valley on the northern slope of Jaeyaksan Mountain is full of rock fragments broken from the rock slopes (Fig. 1a). The rock fragments are deposited near the

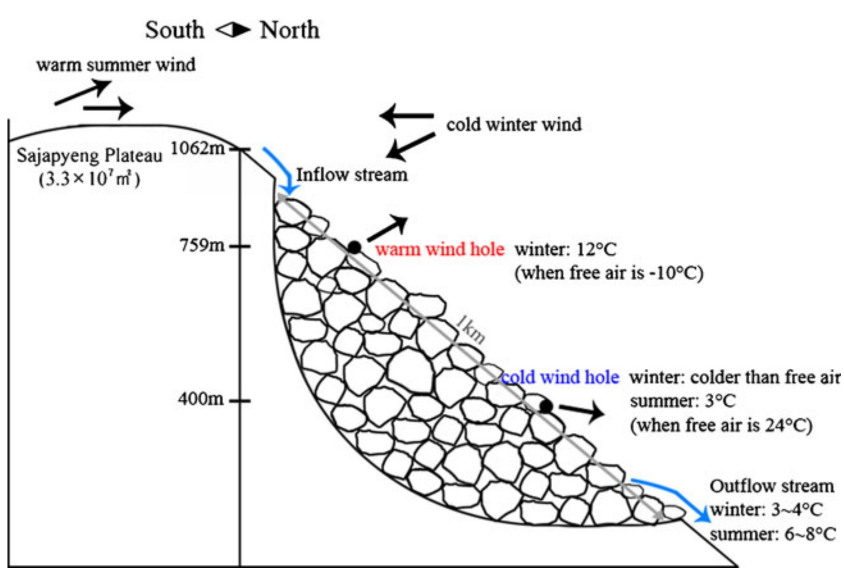


Fig. 2 Schematic cross section of the Eoreumgol

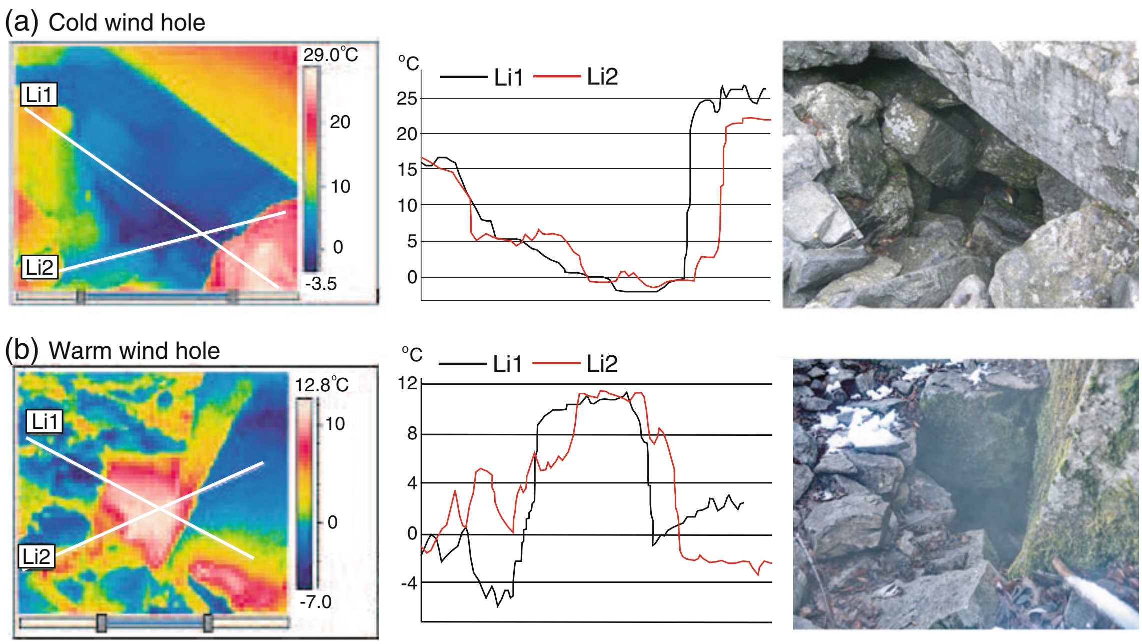


Fig. 3 Thermal image (by Flir-e25) temperature distributions along the lines L1 and L2, shown in the thermal image (*left panel*) and the visual image (*right panel*) of the main cold wind hole, taken on 28 July 2003 (**a**) and the main warm wind hole, taken on 15 January 2004 (**b**). The horizontal lengths of the visual images are approximately 2 m

mountain slope or cliff by grain flow, forming a talus slope (Fig. 1c).

Pebble/boulder-sized angular clasts are transported along the valley by streams formed during rainfall. Consequently, the shape of the clasts becomes more rounded, and the talus deposit contains fine-grained sediments (Fig. 1d). This fine material is sufficiently moist to allow trees to grow even on the rock valley.

Even now, talus continues to be deposited, and newly produced breccias are deposited on the mossy (old) talus depositional units. NE/SW-trending joints are well developed, seen as lineaments, and are responsible for the mechanical weathering of the rocks. In fact, near Donguigul Cavern, steep parallel joints have caused toppling failure.

We have made two attempts at geological mapping, once on 12 November 2003 and then during the following spring. During the first field trip, we observed snow-thawing zones at several places in the valley; it had snowed the previous day (11 November 2003). Near Donguigul Cavern, especially, we found areas where snow had not accumulated or had melted. One area displayed a narrow long zone in the direction of the valley (Fig. 1e). Such phenomena were also found around the warm wind hole near Donguigul Cavern. In an area with gravel–soil mixture, snow had already thawed on the moistened horizon (Fig. 1d). Although snow-thawing zones do not perfectly correspond with warm wind holes, they provide good indications for finding warm wind holes.

The talus originates from an adjacent dacitic welded ash flow tuff with very low heat conductivity (0.588 W m^{-1} K^{-1}). Small-scale waterfalls are common, especially during times of precipitation, along the cliffs as well as in the valley.

Table 1 Geographic locations of observations and equipment

Name	Latitude	Longitude	Altitude (m, a.s.l.)	Equipment
TMT	35°33′42.8″	128°59′00.9″	1,062	Hobo-pro series S1819
WWH	35°33′54.4″	128°59′05.7″	759	Smart button
CWH1	35°34′18.2″	128°59′10.8″	401	Smart button
CWH2	35°34′18.3″	128°59′10.8″	400	Smart button

TMT denotes the air temperature at the summit of Mt. Jaeyak. Detailed information of the equipment can be found at http://www.labsafety.com/search/HOBO/24531815/?type=brand and http://www.smartbutton.com/

WWH warm wind hole, *CWH1* and *CWH2* cold wind holes

3 Summer cold wind and winter warm wind

3.1 Cold wind from cold wind hole

The locations of and the equipment used in our observations are listed in Table 1. Figure 3 shows thermal images (left panel), temperature curves (central panel) along the lines (Li1 and Li2) marked on the thermal images, and photographs (right panel) of (a) a cold wind hole (temperatures measured on 28 July 2003) and (b) a warm wind hole (temperatures measured on 15 January 2004). The temperature of the underground rock in the cold wind hole in July is −3°C, whereas the temperature of the surface rock is 27°C in one case (Fig. 3a) and 47°C in another case (not shown). The corresponding values for the warm wind hole in January are 12°C and −6°C. Steam can be seen rising from the warm wind hole in the visual image.

To determine the temperature changes in the cold wind hole (CWH1, 1.2-m approximate depth), a 1.7-m-long pole was inserted into the hole at a slant angle of 45° with temperature sensors spaced every 10 cm on it. Figure 4 shows the results of these temperature observations. Channel 16 (hereafter CH16) is at the outermost and highest position, while CH1 is at the deepest. Only CH13 exhibits large fluctuations, between 5°C and 12°C; the rest fluctuate much less. The difference between the underground and the aboveground surface temperature is so high that the air is divided into layers of 10 cm or less. This provides evidence of the continuous diffusion of water vapor to the free atmosphere, through the heating by the warm surface air, and the forced turbulent mixing by the surface wind, thus implying that continuous evaporative cooling is possible.

3.2 Intra-annual trend of cold wind

Figure 5 shows a part of the temperature variation at four locations (Table 1). The annual maximum temperature of CWH1 is <10°C, much lower than the free air temperature (TMT in Table 1) in summer. CWH2 is located at a slightly isolated location and indicates higher temperatures than CWH1.

From late September 2003 until Jan 2004, the temperature of CWH1 dropped rapidly only when the temperature at the mountaintop dropped, as observed on 23 October 2003. This indicates that the main source of cold air in the cold wind hole is free air, i.e., cold air that has migrated from the polar region (to not be redundant, further explanations are omitted). When the temperature of the outside air increases rapidly, the temperature of the air in the cold wind hole does not increase, but rather drops marginally. As a result, cold air is trapped in the talus during winter. However, during extreme winter conditions, when the temperature of CWH1 is below 0°C, the temperature decreases or increases gradually, even though the temperature of the outside air experiences large fluctuations. This phenomenon was witnessed from the end of December 2003 until mid-January 2004. The cold air penetrating the talus results in the formation of underground ice, and the cold environment of the talus is not only a result of the air but also the existence of the ice.

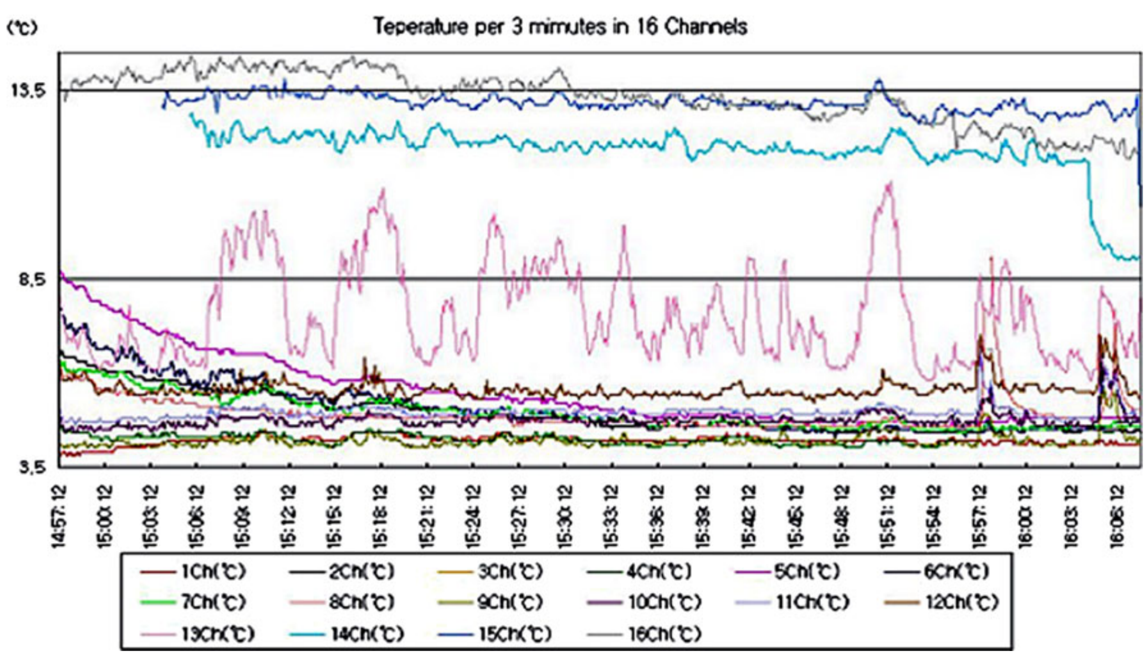
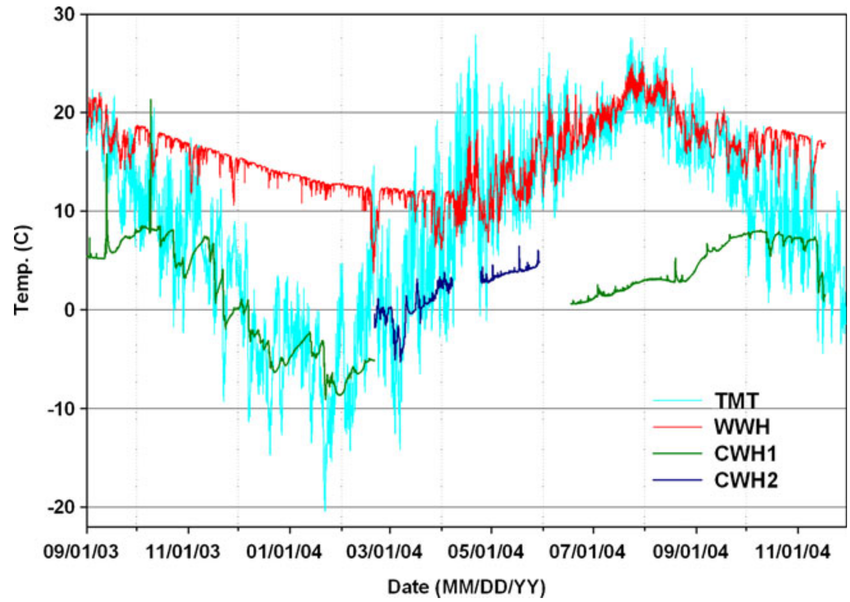


Fig. 4 Temperature variations in CWH1. A 1.7-m-long pole slanting at an angle of 45° equipped with temperature sensors at intervals of 10 cm was inserted into CWH1. CH1 is located at a depth of 1.2 m and CH16 located at the highest part of the outlet

Fig. 5 Temperature variations in the cold wind holes (*CWH1* and *CWH2*), warm wind hole (*WWH*) and at the mountain top (*TMT*). The observation interval is 3 h



Generally, the temperature of cold wind holes increases gradually from the end of January to mid-April. The temperature of CWH1 is assumed to be close to 0°C for the entire duration of the ice melt from mid-April to mid-July. Toward the end of July, the temperature increased gradually and continued increasing. This increase ceased in early October. In this case, cold air flows outwards from the cold wind hole throughout summer, even though the ice in the cold wind hole has disappeared.

A warm wind hole (with air temperature >10°C) is located at 200–700 m from the cold wind hole. In this case, cold air penetrates under the ground along the slanted talus and underground warm air rises. Consequently, it is surmised that underground convection occurs.

3.3 Warm wind in winter

The main warm wind hole is shown in Fig. 3b and its details listed in Table 1. After October, the temperature of the warm wind hole is considerably higher than that of the mountaintop (Fig. 5). It gradually decreases with the soil temperature (at 5-m depth, Fig. 6). Even though the temperature at the mountaintop is −20°C, the temperature at the warm wind hole does not drop but remains consistently above 15°C during January 2004.

4 Formation of ice in late spring and not in winter

4.1 Less ice in winter

In winter, the rainwater or snow that falls on the talus forms ice on its surface, as shown in Fig. 7a. Ice does not form in the cold wind hole. This is because there is little water supply to the cold wind hole. All rainwater falling over higher areas of the valley penetrates deep into the talus before it arrives at the cold wind hole. The penetrating water forms thin ice walls on the rack in the deep talus where a large number of open spaces exist. This can only be observed with a special tool such as an endoscope (Byun et al. 2006).

4.2 Icicles in spring

Most of the ice covering the ground surface melts in the spring; this is also true of the ice present in the upper parts of Ice Valley. The runoff water flowing downwards does not penetrate the talus because of the ice plate that forms during winter; it instead flows over the ice plate, only to refreeze. In this process, ice flows continuously from the upper part of the valley, melting and refreezing, and finally reaches the cold wind hole, supplying it with water. Thus,

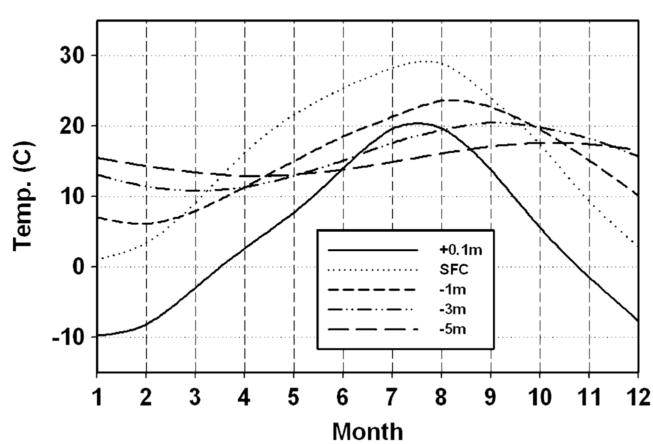


Fig. 6 Underground temperature in Miryang at indicated depths (*sfc* is surface). The −5- and −3-m temperature curves are obtained from Daegu near Miryang

Fig. 7 Icicles in Miryang Ice Valley. **a** Winter icicles after rain and snow on the talus. Spring icicles under the talus growing upwards (**b**) and sublimating icicles in front of the cold wind hole (**c**). **d** In late spring, the outer icicles undergo sublimation while the inner icicles continue to grow

icicles form during late spring in the cold wind hole. In this case, icicles form under the talus and are visible from the outside (Fig. 7b–d). Icicles have diameters up to 10 cm and lengths up to 1 m. Sometimes, five to ten icicles form together.

Within the talus, the temperature decreases with depth. Sometimes, the temperature in the lower part is below 0°C. Then, water dripping from the melting ice on the surface forms icicles that grow upwards from the talus floor (Fig. 7b). The upper parts of the icicles that are closer to the surface melt earlier than the lower parts. At this point, the icicles resemble upward-facing bars (Fig. 7c). During late spring, the icicles near the surface dry due to sublimation, while new icicles form in the deeper talus (Fig. 7d).

4.3 Formation of ice in midsummer

Although extremely rare, ice is also observed in the cold wind hole even in midsummer. A simple explanation for the formation of ice in midsummer is the following. In some open spaces in the talus, cold air is trapped in winter not only by the rock walls but also by the ice walls. In summer, when the ice walls melt, cold air can circulate. Subsequently, cold air flows downwards, reaches the cold wind hole, and forms ice on the talus when it meets water. However, the icicles that form in the summer are not large because the amount of cold air is small. This mechanism will be referred to as “icing by trapped cold air” and will be explained in detail in Section 7.

5 Warm water in winter and cold water in summer

5.1 Warm water in winter

In winter, the streams (below the cold wind hole; Fig. 8) flowing out of the valley are much warmer than the stream flowing into the valley (normal stream at upper part of the valley; Fig. 9). Sometimes, this temperature difference can be as much as 6°C, as shown for January 2004 in Fig. 9. An analysis of the water impurities reveals that the densities of several minerals in the water that flows into the valley are high while those in water that flows out are extremely low during winter (Table 2). This indicates that the water undergoes evaporation in the talus and the water flowing out results from the condensation of the evaporated water. In addition, it is thought that the minerals stored in the talus during winter are washed away by flash floods every summer.

Once water penetrates the deep talus, it evaporates, rises, and condenses while rising as a result of the difference in

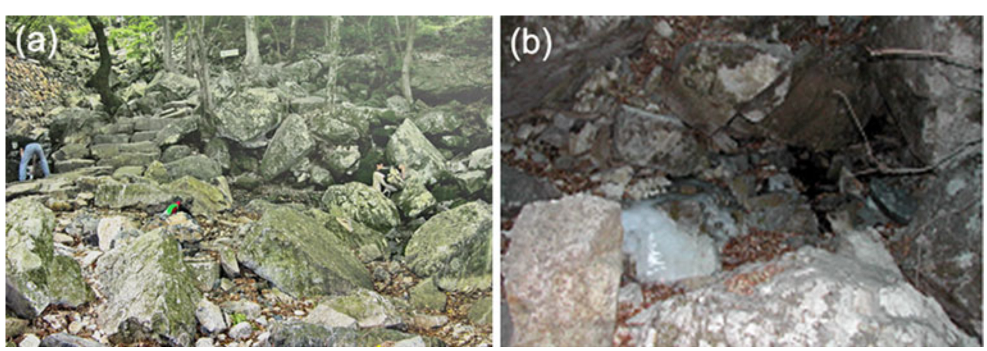


Fig. 8 **a** Two streams located 200 m under the cold wind hole. Two boys are collecting water from streams in the left and right middle part of the photograph. **b** The stream does not freeze even during winter (*black part in right side*)

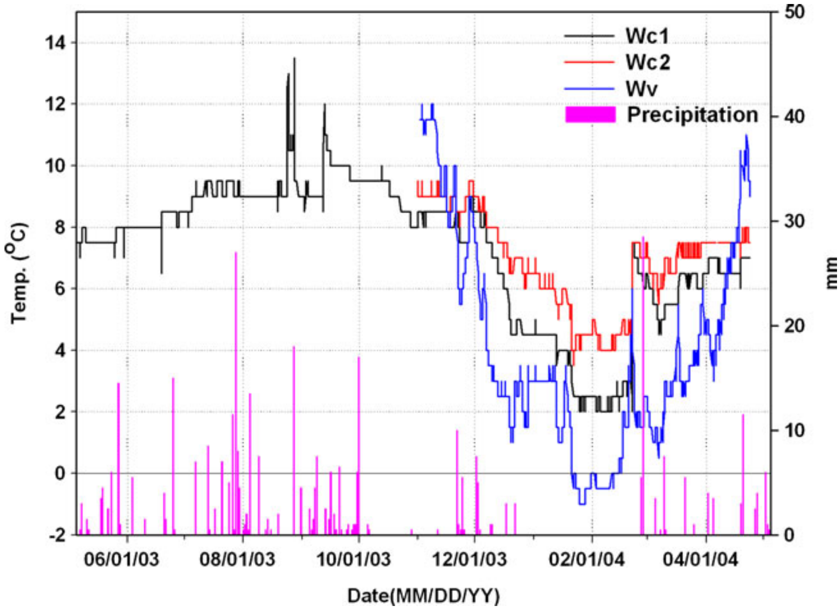


Fig. 9 *Wc1* and *Wc2* represent the water temperature variations in the streams 1 and 2, respectively. Both are located below cold wind hole. *Wv* denotes the one in a nearby normal stream

the ground heat and air temperature between the lower and higher parts of the talus; this condensed water flows down not through the cold wind hole but through other routes in the vicinity. Furthermore, the latent heat of condensation warms the air, which then rises and finally flows out through the warm wind hole. Since this warm air is assumed to be caused not only by the ground heat stored during summer but also by the latent heat of condensation, the warm water flowing out is considered to be heated by both ground heat and latent heat. However, there is insufficient evidence to prove that the ground heat and the vapor in the talus are sufficient to sustain the heat in the warm wind hole and in the warm water. Thus, it is suggested that an underground spa (discussed later) may exist that provides additional vapor, thereby sustaining heat and water vapor. The fact that the amount of water flowing out from the valley is greater than the amount flowing into the valley in winter supports this possibility.

Table 2 Concentration of minerals in the water of inflow and outflow

Analyte	Inflow (μg/L)		Outflow (μg/L)	
	Conc. Mean	Conc. SD	Conc. Mean	Conc. SD
Na	6,934.801	51.19	1,916.626	1.2
Mg	1972.397	9.61	22.156	3.3
Al	176.294	0.83	1.761	21.3
K	1,955.836	10.67	242.752	4.9
Ca	6,131.434	25.10	148.979	1.7
Cr	0.296	0.00	−1.125	12.0
Mn	255.798	2.27	2.143	2.7
Fe	22.322	0.39	−28.126	10.3
Zn	22.584	0.07	−0.348	150.2
Cd	0.327	0.01	0.003	55.0

Samples are gathered on 3 March 2004

5.2 Cold water in summer

During summer, i.e., from mid-April until mid-November, stream water is colder than the water in a normal stream. That is, warm water flows into the valley and cold water flows out. Therefore, the theories advocating major ice formation in the talus by Jung (1992) and the evaporation of water by Moon and Whang (1977) are partly convincing. In the summer, however, it is doubtful that the total cold air stored in the talus by seasonal respiration, gravity currents, radiative cooling, and evaporation is sufficient to sustain the cold flow through the cold wind hole and cold streams.

6 Origin of heat

6.1 Origin of cold air

Several scientists (listed in Section 1) have attempted to explain the origin of the cold air. Some have assumed that rocks are cooled during winter by the cold air. Let us assume that (1) 80% of the total volume, V, of the talus is occupied by rock (V_r=0.8 V) and 20% by air (V_a=0.2 V); (2) all the underground rocks and air are cooled to −0.2°C (T_r=−0.2°C), i.e., the mean temperature of the coldest month (January); (3) cold air flows outwards through the wind hole at speed, u_a=0.1 ms^{-1}; (4) the total area of the wind hole, a_a =500 m^2; (5) the free air temperature, T_a=13.0°C, i.e., the annual mean temperature; and (6) the temperature of the water under the talus, T_w=6°C. The specific heat of the rock (C_r), air (C_a), and water (C_w) are 837, 1,005, and 4,186 J kg^{-1} $°C^{-1}$, respectively. The measured density of the rocks, G_r, in the valley is 3.35×10^3 kg m^{-3}, and the density of air, ρ_a is taken as 1.25 kg m^{-3}. As seen above, the total volume, V, of the talus is 8.022×10^6 m^3. The total energy, E_c, accumulated by the cooled rock (E_r) and the trapped-in-the-talus cold air (E_a) at 13°C, is

$$\begin{aligned} E_c &= E_r + E_a \\ &= \{C_r \times |(T_a - T_r)| \times V_r \times G_r\} + \{C_a \times |(T_a - T_r)| \times V_a \times \rho_a\} \\ E_r &= 837 \times (13.0 - (-0.2)) \times 0.8\left(8.022 \times 10^6\right) \times 3.35 \\ &\quad \times 10^3\left(\mathrm{Jkg^{-1}{}^\circ C^{-1}{}^\circ Cm^3kgm^{-3}}\right) \\ &= 2.37529 \times 10^{14}\mathrm{J,\ and} \\ E_a &= 1,005 \times (13.0 - (-0.2)) \times 0.2\left(8.022 \times 10^6\right) \times (1.25)\mathrm{J} \\ &= 2.6605 \times 10^{10}\mathrm{J} \end{aligned} \tag{1}$$

Though E_r is four orders of magnitude greater than E_a, all the rocks in the valley can hardly be cooled down to −0.2°C because the heat conductivity of the rock and the air speed penetrating underground are too small. Further considerations are required. The speed that the cold energy dissipates because of outward flow, SE_a, is

$$\begin{aligned} \mathrm{E_a} &= C_a \times |(T_a - T_r)| \times a_a \times u_a \times \rho_a \\ &= 1,005 \times (13.0 - (-0.2)) \times 500 \times 0.1 \\ &\quad \times 1.25\left(\mathrm{Jkg^{-1}{}^\circ C^{-1}{}^\circ Cm^2ms^{-1}kgm^{-3}}\right) \\ &= 8.291 \times 10^5\mathrm{Js^{-1}} \end{aligned} \tag{2}$$

Additional dissipation of cold energy by continuous stream flow, SE_w, is

$$\begin{aligned} \mathrm{SE_w} &= C_w \times |(T_w - T_r)| \times a_w \times u_w \times \rho_w \\ &= 4,186 \times (6.0 - (-0.2)) \times 0.030 \times 1 \\ &\quad \times 1,000\left(\mathrm{Jkg^{-1}{}^\circ C^{-1}{}^\circ Cm^2ms^{-1}kgm^{-3}}\right) \\ &= 7.786 \times 10^5\mathrm{Js^{-1}}, \end{aligned} \tag{3}$$

where a_w=0.030 m^2, u_w=1 ms^{-1}, and ρ_w=1,000 kg m^{-3} are assumed values for the area, flow speed, and water density, respectively. Note that about the same amount of energy is dissipated by water and air. The time taken for the energy accumulated by the underground air to dissipate,

$$\begin{aligned} t_a &= E_a/(\mathrm{SE_a} + \mathrm{SE_w}) = 2.6604 \times 10^{10}/\left\{10^5(8.291 + 7.786)\right\} \\ &= 1.654 \times 10^4\mathrm{s} = 4.59\mathrm{h} \end{aligned}$$

This result indicates that diurnal respiration of the talus (Tanaka et al. 2006) is also important. However, it is difficult to estimate the extent to which the rocks are cooled in winter because the rock size within the talus is variable and the conductivity (0.588 Js^{-1} $m^{-1°°}C^{-1}$) of the rock (dacitic welded ash flow tuff) is low.

The adiabatic expansion theory (Kim 1968) is not applicable because an area with very high pressure is not detected in the talus. Thermal respiration (Tanaka et al. 2000, 2006; Byun et al. 2004) and radiative cooling (Whang et al. 2005) can only provide a partial explanation of the origin of the continuous cold air since the air from the cold wind hole is much colder than expected by these effects. The evaporation effect (Moon and Whang 1977) is only partially satisfactory because the air in the cold wind hole is too cold to be produced by evaporation alone. Such a large temperature difference (i.e., between the cold wind hole air temperature and that of the outside air) is rarely seen in nature.

Jung (1992) proposed that large chunks of ice accumulate during winter in the talus and that these ice chunks act as a source of cold air during summer. This implies that the latent heat consumption during the melting of the ice results in a continuous reduction in the air temperature. However, winter precipitation over the valley is not high enough to support the considerable accumulation required for the formation of underground ice.

The above studies do not explain the formation of ice during late spring when the free air temperature never falls below 0°C. In addition, most of these studies do not consider the existence of a warm wind hole. In this study, however, we do, and we propose two further mechanisms. One is the repetition of heat separation by water and topography and the other is the positive feedback mechanism of cold air generation, explained in Section 7.

6.2 Origin of warm air

The heat sustained in the warm wind hole during winter has been attributed to two underlying causes: the ground heat stored during summer and the latent heat produced by the underground condensation of water vapor that rises along the slope of the talus. The latter is considered to be a more significant contributor because the heat capacity of the rock is not sufficiently high (20% that of water) to retain the ground heat for several months.

Assume that 80% of the total volume of the talus is filled with rock at T_r=25.6°C, i.e., the mean temperature of the hottest month (August) and that warm air at T_a=13.0°C (i.e., the annual mean temperature) flows out from the talus at u_a=0.1 ms^{-1} over an area, a_a, of 500 m^2. Energies, E_r and E_a, are given by Eq. 1 and the dissipation speed of the energy, SE_a, is given by Eq. 2, and they are equal to 2.26732×10^{14} J, 2.5396×10^{10} J, and 7.914×10^5 J s^{-1}, respectively. These are values very similar to those for the cold wind hole. While the temperature is higher and the flow amount lower, the energy dissipation by warm water in winter is also supposed to be similar to that for the cold wind hole case.

Warm air flows outwards from the talus throughout the winter. Furthermore, the warm wind hole is always humid throughout winter. Moss growth is observed in the areas adjacent to the warm wind hole, as shown in Fig. 3b. However, this region is dry during the summer. This condensation process needs to be taken into account. When the outer air is cold, warm underground air, heated by the ground and latent heat, gets buoyant, because of the difference in gravity between the cold free air and the warm underground air, and rises with underground vapor along the slope of the valley, and finally condenses and warms the air near the warm wind hole. However, when the outside air is warm, counter buoyancy forces exist under the talus because of the colder and heavier underground air. Thereby, it becomes similar to free atmosphere and it appears that the temperature decreases in the temperature curve of the warm wind hole, e.g., see the temperature curve of Fig. 5 for 22 February 2004.

The flow direction is governed and maintained by the gravitational difference between the cold and warm air. The underground heat at a depth of 5 m (Fig. 6) in the neighboring area is lowest during mid-April. This is another reason why warm airflow persists until April. However, the above explanations are still unclear. If the ground heat and the condensation effect are sufficient heat sources to generate a warm wind hole, then many warm wind holes must exist worldwide, but they are extremely rare. Even in Korea (where there are more than 26 cold wind holes), only two warm wind holes are known. For this reason, a spa is assumed to be the heat source.

7 Mechanisms for the origin of cold and warm air and ice

7.1 Repetition of heat separation

When evaporation occurs in the talus, the vapor does not stay in it. Because the vapor is light, it rises and joins the free air or moves toward the upper regions of the talus. The air cooled by evaporation penetrates the talus or migrates downwards along the slope of the valley. Cold air flows downwards into the deeper regions of the talus, while warm air flows upwards in the shallow region of the talus or merges with free air. This separation process is caused by the density difference between the humid and dry air. Moist air is lighter than dry air at the same temperature and pressure (e.g., Chepil 1945).

On rising in the talus, the vapor becomes saturated because the underground air is humid and it undergoes condensation. Finally, the latent heat is released. The dehumidified air warmed by the released latent heat moves upwards, while the water droplets fall. When the air rising in the talus encounters the water droplets, repetitious evaporation occurs. The continuous repetition of these condensation and evaporation cycles over a distance of 1 km separates the warm air from the cold. Finally, the warm air moves upwards while the cold air moves downwards.

The sloping of the valley helps the heat separation process. Cold air can accumulate more easily in summer than in winter. The vapor produced by underground evaporation cannot recondense easily because the free air is warmer than the underground air. Subsequently, the evaporation that causes the talus to become colder occurs more frequently than condensation. The many waterfalls present in the valley continuously supply the water required for evaporation. The difference in the temperature between the cold wind hole and the free air is largest during the summer (Fig. 5). Different effects such as radiative cooling, thermal respiration, etc. also contribute to the cooling of underground air. However, it is assumed that the total of the other effects is smaller than the effect of evaporation. The evaporation effect has almost no limit in the slanted rocky valley, but other effects are limited.

On the other hand, condensation can occur more easily than evaporation in winter because the free air is colder than the underground air. The difference in temperature between the warm wind hole and free air is largest during winter (Fig. 5). The warm wind in the warm wind hole during winter is a result of repetitious condensation along the long slope of the valley. In this case, a continuous supply of water vapor is required for condensation. If the main source of water vapor is rain or snow, the temperature of the warm wind hole should rise after rainfall. However, this is not observed (Fig. 5). As a result, spas or underground water bodies that supply vapor continuously are suggested to be the heat source in the warm wind hole. However, this suggestion cannot be verified easily.

7.2 Mechanism of ice formation

With regard to ice formation, the most important question is what causes the water to freeze. More specifically, what is the origin of the cold air that freezes the water? All the theories listed in Section 1 explain the generation of cold air. However, none of them provide a satisfactory explanation for why the air temperature is below 0°C in late spring even though the daily mean temperature is above 10°C. Under normal circumstances, the evaporation of water cannot lower the temperature of cold air below 0°C, so evaporation does not lead to the formation of ice and melting ice cannot produce cold air in which the temperature is below 0°C because the melting process stops. Radiative cooling cannot produce cold air with a temperature <0°C in late spring when the daily mean temperature is above 10°C.

This question may be somewhat solved by introducing the theory of "icing by trapped cold air" proposed in Section 4.3. Since the heat capacity of water (4,218 J kg^{-1} K^{-1}) is approximately four times that of air (1,004 J kg^{-1} K^{-1}) at constant pressure, ~4 g of air (volume= 0.0032 m^3) at −1°C is required to reduce the temperature of 1 g of water from 1°C to 0°C. In order to freeze 1 g of water into ice, ~334 J, the equivalent of 0.256 m^3 of air at −1°C, is required. If the air temperature is −10°C, then 0.0256 m^3 of air is required. If 20% of the total volume (8.022×10^6 m^3) of the talus is occupied by cold air at −0.2° C, i.e., the mean air temperature of the coldest month in Miryang, then the total amount of ice produced by this cold air is

$$\left\{20\% \times \left(8.022 \times 10^6\right)\mathrm{m}^3 \times |-0.2|^\circ\mathrm{C}\right\}/0.256^\circ\mathrm{Cm}^3\mathrm{g}^{-1} = 1.253 \times 10^6\mathrm{g}$$

That is, only 1,253 kg of water can be converted to ice as a consequence of the cold air trapped in the talus. However, this calculation is not important because there is insufficient cold air to sustain the cold airflow throughout the year, as well as the cold water during summer. To understand the origin of the cold air, it is important to understand how much the rocks cool down in winter, and this both depends on the winter cold and precipitation. It is thus difficult to quantify the amount of cold air required. Therefore, we arrive at the question "can cooled rock during the winter make water freeze in the summer?" We prefer to say "possibly" because the heat conductivity of the rock (dacitic welded ash flow tuff) of the talus is low (0.588 J s^{-1} $m^{-1\circ\circ}C^{-1}$), the vacancy in the talus is large, and winter in Miryang is long and cold enough to cool down the rocks. This concept is not sufficient because in nature, it is very difficult to imagine how cold rock induces summer ice. For this, we propose another mechanism, which we call the feedback of cold air generation.

7.3 Positive feedback of cold air generation

Han and Lee (2005) improved upon Eq. 1, proposed by Cho (1969) after Penman (1948), by comparing the observed data and found

$$E = (0.0146 + 0.0063u)(e_\mathrm{w} - e_\mathrm{a}) \quad (4)$$

where E is the evaporation in millimeters per hour, u is the wind speed in meters per second over an altitude of 1 m, e_w (e_i) is the saturated vapor pressure in hectopascal of air having the same temperature as that of water (ice), and e_a is the vapor pressure in hectopascal of air over a height of 1 m calculated using the dew point temperature.

From Eq. 4, it is clear that if e_i is greater than e_a (when the dew point temperature is lower than the ice temperature), sublimation will occur with the consumption of latent heat (when ice is at 0°C, the latent heat of sublimation is 2.834×10^6 J kg^{-1}) and ice dries because of the production of air that is colder than 0°C. After sublimation, the resultant vapor with the released latent heat rises either to the free air or to higher places in the valley such as the warm wind hole. However, the generated cold air sinks into the talus and accumulates in the lower valley. In this case, the sublimation of 1 g of ice can either reduce the temperature of $\left\{\left(2.834 \times 10^6\mathrm{Jkg}^{-1}/4.186\mathrm{J}\right)/4\mathrm{g}\right\} \times 0.0032\mathrm{m}^3 = 541{,}615\mathrm{m}^3$ of air from 0°C to −1°C or convert $\left(2.834 \times 10^6\mathrm{Jkg}^{-1}/3.34 \times 10^5\mathrm{Jkg}^{-1}\right) = 8.5\mathrm{g}$ of water into ice (where 3.34×10^5 J kg^{-1} is the latent heat of fusion).

In the next stage, several times, 8.5 g of ice can be formed if the cold air comes into contact with a sufficient amount of water. Several stages of feedback can be repeated along the 1.02-km-long slope of Ice Valley. In this manner, the cold environment in the talus is a result of either the ice formed or the cold air deposited. Therefore, if the air is colder than the ice in the first stage, air colder than 0°C can be continuously produced as long as there is enough ice to sublimate in the inclined talus. This cold air, on contact with water, freezes it, thereby leading to further generation of cold air. Thus, a positive feedback mechanism for cold air generation is established. In fact, ice that dries rather than melts can easily be found in Ice Valley in late spring (Fig. 7c, d). An example of this additional cooling by sublimation was observed toward the end of January 2004 (Fig. 5) when the outside air was considerably colder. The fact that large ice plates form underground only once during late spring when the underground air is much colder than 0°C serves as further evidence. Finally, the phenomena in Ice Valley demonstrate that the continuous generation of cold air is a function only of the temperature difference between ice and air in the region, given the topography is favorable. That is, ice under the colder air can generate even colder air that can freeze more water. This repetitious cold air generation in the valley is assisted by the sloped rocky valley.

On the other hand, if e_a in Eq. 4 is greater than e_w (e_i), condensation (deposition) occurs and the ice melts, producing air that is close to or warmer than 0°C, and no ice forms. In this case, it is difficult to understand that the amount of evaporation or sublimation is independent of the relative humidity of air, and it is determined by the difference between the water temperature and the dew point temperature of air (Eq. 4). However, examples are easy to find. When water is boiled, steam rises even if the relative humidity is ≥100%; cold air, though it is already saturated, can absorb additional water vapor from the ocean to form sea fog.

8 Discussion and conclusion

We have investigated the phenomena of the Miryang Ice Valley based on long-time observations and diagnoses. In winter, there is very little ice present in the talus, the wind in the warm wind holes is considerably warmer than free air, and the water in the streams under the cold wind holes does not freeze throughout the year. In summer, a large number of icicles form in the talus in addition to a large amount of ice. Even in midsummer, small ice plates form in the talus. Furthermore, a continuous cold wind flows through the cold wind holes and the water in the streams is cold.

The major ice formations and icicles are not produced in the cold winter but during the late spring or early summer. Several upward-facing icicles can be observed, even though most of the icicles grow downwards. Although the cold wind holes in the summer are not converted to warm wind holes in winter, there exists a period in which the air in the cold wind holes is warmer than the free air. The water under the cold wind hole is colder (warmer) than the water in the other streams during summer (winter), although the summer temperature is higher than the winter temperature. The effects of radiative cooling and thermal respiration in the valley are insufficient and can only partly explain the existence of higher and lower temperatures. As a result, two new concepts have been proposed with regard to the thermal mechanism of the generation of cold air, warm air, and formation of summer ice—one is a repetitious heat separation mechanism and the other is a positive feedback mechanism of cold air generation.

However, because the amount of heat generated from these processes in the warm wind hole is still far from sufficient, an underground spa is assumed to be the additional source of continuous vapor supply during winter. The reason ice forms in late spring and not in winter is explained by the time taken by the water to reach the cold wind hole. During winter, water cannot reach the cold wind hole. The sublimation process and its positive feedback mechanism, however, are of significance in this observation.

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