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Numerical simulation of formation and preservation of Ningwu ice cave, Shanxi, China

S. Yang[1,2] **and Y. Shi**[1,2]

[1]Key Laboratory of Computational Geodynamics of Chinese Academy of Sciences,
Beijing, 100049, China
[2]University of Chinese Academy of Sciences, Beijing, 100049, China

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Correspondence to: Y. Shi (shiyl@ucas.ac.cn)

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Abstract

Ice caves exist in locations where annual average temperature in higher than 0 °C. An example is Ningwu ice cave, Shanxi Province, the largest ice cave in China. In order to quantitatively explain the mechanism of formation and preservation of the ice cave, we use Finite Element Method to simulate the heat transfer process at this ice cave. There are two major control factors. First, there is the seasonal asymmetric heat transfer. Heat is transferred into the ice cave from outside, very inefficiently by conduction in spring, summer and fall. In winter, thermal convection occurs that transfers heat very efficiently out of the ice cave, thus cooling it down. Secondly, ice–water phase change provides a heat barrier for heat transfer into the cave in summer. The calculation also helps to evaluate effects of global warming, tourists, etc. for sustainable development of ice cave as tourism resource. In some other ice caves in China, managers installed air-tight doors at these ice caves entrance intending to "protect" these caves, but this prevent cooling down these caves in winters and these cave ices will entirely melt within tens of years.

1 Introduction

An ice cave is a type of natural cave that contains significant amounts of perennial ice. Therefore some parts of an ice cave must have a temperature below 0 °C all year round, and some water must have traveled into the cave's cold zone. An ice cave is a rare phenomenon. Among the best known are Eisriesenwelt ice cave, Austria (May et al., 2011; Obleitner and Spötl, 2011; Schöner et al., 2010), Dobšiná ice cave, Slovakia (Bella, 2006; Lalkovič, 1995), Scărisoara ice cave, Romania (Holmlund et al., 2005; Perşoiu et al., 2011) and Monlesi ice cave, Switzerland (Luetscher et al., 2007, 2008). Eisriesenwelt ice cave is the largest in the world. Dobšiná ice cave is also huge, with an ice volume of over 110 000 m^3 (Bella, 2006). In China, more than ten ice caves

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have been found, including Ningwu, Wudalianchi, Taibaishan, Cuihuashan, Baiyizhai and Shennongjia ice caves.

Studies of ice caves began as early as 1861 (Peters, 1861). In recent decades, in the context of interest in global climate change, six international conferences on ice caves have been held, with the reconstruction of regional ancient climate change as an important topic for discussion (Laursen, 2010). Paleoenvironmental reconstructions from cave deposits are largely based on the assumption of a stable subsurface climate system (Hendy, 1971). However, several articles reported seasonal air temperature oscillations of several degrees from ventilated cave systems (Roberts et al., 1998; Lacelle et al., 2004; Johnson et al., 2006). Therefore, to evaluate the impact of changing climatic conditions on cave environments, a better explanation of subsurface heat and mass transfers is necessary (Luetscher et al., 2008). Meanwhile, ice caves are tourism resources. A better explanation of subsurface heat and mass transfers could help people manage ice caves more scientifically.

In the past, empirical calibrations were enabled to determine the spatial and temporal distribution of cave air temperature as a function of the external atmospheric conditions (de Freitas and Littlejohn, 1987; de Freitas et al., 1982). In temperate karst environments, explanation of the survival of subsurface ice accumulations represents probably the most severe test for models of the magnitude and direction of heat and mass transfers induced by cave air circulation (Luetscher et al., 2008). In mathematics and engineering, Finite Element Method (FEM) and Finite Difference Method (FDM) are popular for finding approximate solutions for partial differential equations. We have not found any study in which these numerical techniques are applied to ice caves.

In China, ice cave studies started only recently, after 1998, when Ningwu ice cave was found. Although Ningwu ice cave has been widely reported during the past decade (Gao et al., 2005; Meng et al., 2006), little was known about the processes controlling the formation and preservation of perennial subsurface ice deposits under changing climate conditions (Chen, 2003). We attempt to apply FEM to simulate the energy fluxes of Ningwu ice cave, and then quantitatively interpret the formation and preservation mechanism of ice deposit in Ningwu ice cave. Some suggestions are given to manage Ningwu ice cave.

2 Study site

Ningwu ice cave (38°57′ N, 112°10′ E; 2121 m a.s.l., Fig. 1a) is the largest ice cave ever found in China. Located on the northern slopes of Guancen Mountain, Ningwu County, Shanxi Province, it is known to local people as "the ten thousand years ice cave". The stratum of the cave consists of Ordovician Majiagou limestone, dolomitic limestone, argillaceous dolomite and thin brecciated limestone which is locally densely fractured (Shao et al., 2007). A geophysical exploration (using magnetotelluric measurement) has been carried out for investigating the spatial form of the ice cave (Shao et al., 2007). They obtained the vertical cross section of the ice cave (Fig. 1b). The cave space is about 85 m depth. The widest part is in the middle, with a width of 20 m.

The ice cave is a major tourist attraction. From May to October, about 1000 visitors enter the cave per day. The ice cave has only one entrance (Fig. 1c), and has wooden spiral stairs leading to a bowling-ball-like room. Ice almost covers the host rock every inch. Ice stalactites, ice stalagmites (Fig. 1d) can be seen in all part of the cave. According to the classification of ice caves (Luetscher and Jeannin, 2004), we consider that Ningwu ice cave is a static cave with congelation ice. Snow crystals are single crystals of ice that grow from water vapor. If humidity enters a cave and then form ice deposit, snow crystals could be discovered more or less (Kenneth, 2005). Actually, it is hard to find snow crystals in Ningwu ice cave. Any clear traces of water or snow entering the cave through its entrance could not be found. Meanwhile, karstified carbonate rock is heterogeneous, highly fractured, and with a permeability developed such that water movement occurs below the surface (Fairchild and Baker, 2012). In summary, we infer that most of the ice in the cave is formed by freezing of infiltration water.

The outside of the ice cave has a temperate climate. The external mean air temperature from June to September is about 14.6 °C, and the mean annual air temperature is 2.3 °C (Meng et al., 2006).The daily temperature from 1957 to 2008 is obtained from Wuzhai meteorological station (about 320 m lower than Ningwu ice cave), which is the nearest station to the ice cave. We use the 51 years of daily temperature to obtain the average daily temperature and the annual temperature at Wuzhai meteorological station, and calculate the difference between the average annual air temperature at Ningwu ice cave and at Wuzhai meteorological station. After reducing the average daily temperature at Wuzhai meteorological station by the difference, we then obtain the annual temperature variation outside the ice cave (Fig. 2).

3 Qualitative analysis

There are different hypotheses about the preservation mechanism of ice deposit in the ice cave. Chen (2003) proposed that the existence of a “cold source” led to the negative geothermal anomaly which preserves the ice deposit. Meng et al. (2006) ascribed the ice deposit to multiple factors including geographical location, “icehouse effect”, “chimney effect” and “thermal effect” produced by the ice deposit and the “millennial volcano”. But they did not give us more details about these factors. Gao et al. (2005) analyzed two aspects: terrain and climate. Because this region has a long cold winter and a short cool summer, they considered that far more cold air than warm air entered the region and then the ice cave stayed cold over year.

The temperature usually increases with depth at a geothermal gradient of about 1–3 °C $(100\,\mathrm{m})^{-1}$ (Hu et al., 2001), and there have been persistent heat flows from the deep crust to the surface. The notion that there is a permanent “cold source” underground is unfounded. Even if a cold region had somehow formed, it would be heated up by the geothermal flux from underneath in geological time. Reversal of geotherms can occur only if when the advective heat transfer exists due to crustal movement or groundwater flow (Shi and Wang, 1987). For example, in subduction zones, when a cold slab dives to the hot mantle, the geotherms can be overturned. The temperature can also be overturned when continental collision with large overthrust faulting at a speed of several centimeters per year sustains for millions of years. However, as long as the motion stops, it will return to normal geothermal gradient under the heating of mantle heat flow. The movement of groundwater can sometimes produces an abnormal geothermal gradient, as long as the movement continues. A reversal of geotherms can also occur from transient changes in surface temperature and be induced by steep topography (Gruber et al., 2004). But the outside of Ningwu ice cave has a temperate climate. It is hard to preserve an ice cave in a temperate climate without a sustainable cooling mechanism. Since the existence of a geothermal gradient, the host rock continuously transfers heat to the ice cave, so there must be a sustainable mechanism to remove the heat from underneath and ensure the maintenance of the ice cave.

The temperature outside the ice cave undergoes annual cyclic variations: in spring, summer and fall, it is higher than the internal temperature, but in winter it is lower. As Ningwu ice cave is bowling-ball-shaped with only an opening in the upper part, cold air in spring, summer and fall is heavy and sinks into the cave and thus will not produce natural thermal convection. Conduction is the main form of heat transfer from the outside down to the ice cave, and at the same time heat transfers into the cave from underground and the host rock due to the terrestrial heat flows. Thermal conductivities of neither rock nor air are high and the conductive heat transfer efficiency is very low, so the temperature rise in the ice cave in the three seasons is quite limited. In winter, the temperature is low inside the ice cave and even lower outside. The air in the ice cave is lighter and air outside the cave entrance is heavier. It could thus become gravitational unstable, and thermal convection could occur. The external cold air flows into the cave to cool it down, and removes the heat transferred into the cave from underground and the host rock, as well as that transferred into the cave through the entrance in spring, summer and fall. Since convective heat transfer is much more efficient than conduction heat transfer, the heat transferred out of the cave in the winter months is enough to balance the heat that transferred into the cave year-round.

Ice melting into water absorbs a lot of latent heat. The melting heat of ice is $334\,\mathrm{kJ\,kg^{-1}}$ and the specific heat of limestone is $0.84\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$. That is, when the summer heat conduction makes the temperature inside the cave rise, if there is no ice, the 334 kJ heat could cause the temperature of 1 kg limestone to rise by 397.6 °C, or make 397.6 kg of limestone rise by 1 °C, but the heat can only make 1 kg of 0 °C ice melt to 0 °C water. When the ambient temperature rises, much of the heat is consumed to melt the ice to 0 °C water. Therefore, ice–water phase change action can reduce the rate of temperature rise. Similarly, when the ambient temperature decreases, ice–water phase change action can reduce the rate of temperature decrease. Therefore, ice–water phase change action in the ice cave can "buffer" the temperature change and make the temperature change in a small range. A small amount of ice melting near the cave entrance effectively prevents the heat from being transferred into the deep cave. When the surface water flows into the ice cave from the entrance, the ice cave temperature will not significantly increase.

The calculated energy balance of some cave ice (e.g. Eisriesenwelt ice cave) is largely determined by the input of long-wave radiation originating at the host rock surface (Obleitner and Spötl, 2011). Ice almost covers the host rock in Ningwu cave completely. Therefore, we suggest that long-wave radiation originating at the host rock surface is not predominant factor in the processes of the formation and preservation of ice deposit in Ningwu ice cave.

In summary, the air and the host rock transfers heat to the ice cave, making the cave temperature rise in spring, summer and fall. In winter, the heat convection of air makes the heat flow out of the cave, lowering the cave temperature. Meanwhile, four seasons are accompanied by ice–water phase transition effect. The annual heat budget of income and output is balanced, the cave will be in a cyclic state with very small temperature fluctuations and the average temperature is always lower than 0 °C, so ice bodies in the ice cave can persist.

4 Principle of simulation

4.1 Basic ideas of simulation

Two heat transmission mechanisms must be taken into account to explain the preservation of ice mass in ice cave, namely, thermal conduction and convection. The phase change must also be considered. The heat conduction equation can be used to describe the heat-conducting process, while for the convection process, due to the complicated geometrical shape structure inside the ice cave and complex varying boundary conditions, the convection pattern of air and its thermal consequences are hard to determine exactly. In view of this, a widely used simplified method is applied in this study: evaluate the Nusselt number (*Nu*) and solve the conductive equation by introducing an equivalent thermal conductivity of the convecting air. In the case of an upright circular tube, the relation between the temperature difference of the top and the bottom and *Nu* number can be determined by adopting the experimental relation of natural thermal convection. This relation can be applied to the ice cave simulation by introducing an equivalent thermal conductivity into the conduction equation based on the *Nu* number. The enthalpy method can be adopted to calculate the phase change.

In every time step of our modeling process, it is judged if air convection occurs based on the temperature difference between the top and the bottom of the cave. If no convection, the simple conduction problem will be solved, while if the convection occurs, an effective conductivity is used in the thermal equation.

4.2 Equation and physical parameters

The heat conduction equation is

$$c\rho\frac{\partial T}{\partial t} = k\nabla^2 T \qquad (1)$$

where c is the specific heat, ρ is density, T is temperature, t is time and k is thermal conductivity. For the convective heat transfer process, an equivalent thermal conductivity is used in Eq. (1) based on the *Nu*. Details of the *Nu* will be discussed in the next section.

The enthalpy method is used to calculate the phase change process. A physical quantity enthalpy H is introduced in Eq. (2), where T_r is an arbitrary lower temperature limit. For phase change, enthalpy H can be determined by Eqs. (3)–(5) (Lewis, 1996), in particular, the $(T_\mathrm{s}, T_\mathrm{l})$ are phase change ranges.

$$H(T) = \int_{T_r}^{T} \rho c(T)\mathrm{d}T \tag{2}$$

$$H(T) = \int_{T_r}^{T} \rho c_\mathrm{s}(T)\mathrm{d}T \quad T \le T_\mathrm{s} \tag{3}$$

$$H(T) = \int_{T_r}^{T_\mathrm{s}} \rho c_\mathrm{s}(T)\mathrm{d}T + \int_{T_\mathrm{s}}^{T} \left[\rho\left(\frac{\mathrm{d}L}{\mathrm{d}T}\right) + \rho c_f(T)\right]\mathrm{d}T \quad T_\mathrm{s} < T < T_\mathrm{l} \tag{4}$$

$$H(T) = \int_{T_r}^{T_\mathrm{s}} \rho c_\mathrm{s}(T)\mathrm{d}T + \rho L + \int_{T_\mathrm{s}}^{T_\mathrm{l}} \rho c_f(T)\mathrm{d}T + \int_{T_\mathrm{l}}^{T} \rho c_\mathrm{l}(T)\mathrm{d}T \quad T \ge T_\mathrm{l} \tag{5}$$

c_s is the specific heat in solid phase, c_l is the specific heat in liquid phase, c_f is the specific heat in solid–liquid mixing state and L is the latent heat. There are many ways to calculate heat capacity (Lewis and Roberts, 1987). The simple and accurate backward differentiation formula (Lewis and Roberts, 1987; Morgan et al., 1978) is adopted here, as expressed in Eq. (6), where (n) and $(n-1)$ stand for time step. Equation (6) can be substituted into the heat equation along with the relevant material parameters for calculation.

$$(c\rho)^{(n)} = \left(\frac{\mathrm{d}H}{\mathrm{d}T}\right)^{(n)} = \frac{H^{(n)} - H^{(n-1)}}{T^{(n)} - T^{(n-1)}} \tag{6}$$

Relevant materials include limestone, ice, ice–limestone mixture, air and water. Parameters of these materials are listed in Table 1. The physical parameter of ice–limestone mixture is taken as the arithmetic mean of those of ice and limestone. We assume that the ice body exists when temperature is below −0.1 °C, and ice–water mixture exists between −0.1 and 0.1 °C, and this becomes water when temperature exceeds 0.1 °C. The ratio of ice and water in the mixture is linear to the temperature within the phase change range, and so are the physical parameters. The latent heat L of ice–water phase change is 334 $\mathrm{kJ\,kg^{-1}}$.

4.3 *Nu* and equivalent thermal conductivity

When the convection occurs, heat transfer is *Nu* times greater than the conductive heat transfer at the same conditions. *Nu*, the Nusselt number, is a dimensionless number, which is defined as the ratio of convection heat transfer to pure conduction heat transfer under the same conditions. In other words, an equivalent thermal conductivity can be introduced, which is *Nu* times greater than the air thermal conductivity (Schmeling and Marquart, 2014). *Nu* is related to the temperature difference of air at the top and the bottom of the cave, physical properties (e.g. viscosity and conductivity of air) and also the geometry of the cave. Ningwu ice cave can be approximated by an upright circular tube. For such a tube, *Nu* can be calculated based on fluid thermodynamics studies. When Eq. (7) is satisfied (Sparrow and Gregg, 1956; Yang and Tao, 2006), which is the case for Ningwu ice cave, the natural convection heat transfer experimental relation (Sparrow and Gregg, 1956; Incropera et al., 2011) is expressed as Eq. (8).

$$d/H \geq 35/Gr^{1/4} \tag{7}$$

$$Nu_{\mathrm{m}} = C(Gr \cdot Pr)_{\mathrm{m}}^{n} \tag{8}$$

In Eqs. (7) and (8), d is the diameter of circular tube and H is the height of circular tube; Nu_m is the Nusselt number, subscript m represents for the arithmetic mean temperature of the boundary layer, Gr is the Grashof number, which approximates the ratio of the buoyancy to viscous force acting on a fluid, Pr is the Prandtl number; C and n are constants, the values of which are shown in Table 2.

The Prandtl number, a dimensionless number, is defined as the ratio of momentum diffusively to thermal diffusively. Pr is dependent only on the fluid material. For air, Pr is 0.7. The Gr number is

$$Gr = g\beta\Delta T l^3/\upsilon^2 \tag{9}$$

where g is the acceleration of gravity, β is the coefficient of cubical expansion, ΔT is a temperature difference, l is a characteristics length and υ is the coefficient of kinematic viscosity. The values are $g = 9.8\,\mathrm{m\,s^{-2}}$, $\beta = 3.67\times10^{-3}\mathrm{k}^{-1}$, $l = 80\,\mathrm{m}$, $\upsilon = 13.30\times10^{-6}\,\mathrm{m^2\,s^{-1}}$ and are substituted into Eq. (9) to obtain

$$Gr = 1.041\times10^{14}\Delta T. \tag{10}$$

According to Eq. (10), when the temperature difference is only 10^{-3} °C, the Gr number can reach 1.041×10^{11}. According to Table 2, we infer that natural convection will occur and the flow state of air is a turbulent flow when the temperature is higher inside than outside the ice cave. Equation (11), relating Nu to the temperature difference, can be obtained when relevant parameters are substituted into Eq. (8).

$$Nu = 11\,000(0.0740\Delta T)^{1/3} \tag{11}$$

Even if Eq. (7) is not satisfied, corresponding experimental relations can also be found in literatures (Cebeci, 1974; Minkowycz and Sparrow, 1974; Yang and Tao, 2006).

4.4 Models and boundary conditions

The rectangular Eulerian computational domain corresponds to a physical domain of 300 m × 190 m on the basis of the ice cave cross section (Fig. 1b). There are 32 825

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nodes and 64 986 elements involved in drawing the FEM grid. The grids for the ice body and the interior air are denser.

The mean value of the geothermal gradient of the Lvliang highland area where Ningwu ice cave is located, is 2.02 °C (100 m)$^{-1}$ (Li, 1996). The mean value of the geothermal gradient of the low-lying Linxian and Liulin areas in Shanxi Province is 2.20 °C (100 m)$^{-1}$ (Hu et al., 2001). We take the normal geothermal gradient value of 2.0 °C (100 m)$^{-1}$ in the model. The temperature boundary conditions are assigned to both sides of the model, with the annual average temperature at the surface and increase with depth following the geothermal gradient. The heat flow boundary condition is assigned for the bottom boundary. The terrestrial heat flow value is the product of the geothermal gradient times the thermal conductivity of the limestone host rock. According to Fig. 2, we prescribe the variation temperature to the top boundary.

The initial thermal structure is calculated assuming the surface temperature remained constant at the annual average (Fig. 3).

During the simulation, models with phase transition included and phase transition neglected are both calculated for comparison. When phase change is considered, latent heat and the material property variation are considered.

5 Simulated result and analysis

5.1 Evolution of an ice deposit forming model

Because of the periodic change of the ambient air temperature, the temperature in the ice cave will show periodic variation correspondingly to conduction and convective heat transfer. Figure 4a shows the evolution of the temperature at the bottom of the ice cave. It can be interpreted as the process of formation of the cave ice. If a cave was formed but not connected with the outside, it may have a temperature distribution similar to Fig. 3. If the cave became connected to the outside, i.e. collapsed at its top and produced an entrance to the cave, an ice cave would then form within a decade due to the winter convective cooling and stabilize in a century. Figure 4b shows the details of first two decades and shows that the calculated results with phase change considered (black line) do not differ significantly from those without considering phase change (red line) in the cooling process. Starting from normal ground temperature, the internal temperature of the ice cave drops rapidly in the first decade, then drops more gradually and finally tends to become stable.

Figure 4b shows the details of temperature evolving in the ice cave during its initial 16 years of formation. It is seen that the cave ice can be maintained below 0 °C all year round after winter cooling for about 5 years. The cave temperature increases in spring, summer and fall and decreases in winter, presenting annually periodic variation. The increasing rate of cave temperature is smaller than its decreasing rate, because the heat conduction in spring, summer and fall is much less efficient than convective heat transfer in winter. With phase change considered (black line), the increased rate of temperature in summer is smaller than that without phase change (red line), because latent heat is required to melt ices near the cave entrance, thus delaying the conduction of heat to the bottom of the cave. In winter, the convective cooling is so effective that the difference is minimized.

Figure 4c shows the cave temperature annual fluctuations when the process has lasted two centuries, long enough to be evolved to a stable cyclic state. The amplitude of the temperature variation is about 1 °C (from −3.9 to −2.9 °C). Ningwu ice cave has been open to tourists, so the cave temperature has been disturbed. According to our measurement on 5 June 2012, the lowest internal temperature of the ice cave was −1.5 °C. Through the record in literature, the actually measured internal temperature of an ice cave ranges between −1.0 °C (Meng et al., 2006), −4 and −6 °C (Gao et al., 2005). The difference in measured results may be caused by different measuring methods and different measuring time and positions. Similar to Fig. 4b, the cave temperature presents annual periodic variation, and the overall increasing rate of cave temperature is smaller than its decreasing rate, because the heat transfer efficiency of conduction is much lower than that of heat convection. The variation of cave temperature for model with phase change considered (black line) is basically the same with that without phase change considered (red line). The reason is that although we considered phase change during calculation, the temperature of the ice body in the cave is always kept below 0 °C when it reaches a stable cyclic state and no phase change actually occurs.

Figure 5a and b shows the spatial temperature distribution around the ice cave in winter and summer respectively under the stable stage. Both figures show that a small portion of rock at the top of the ice cave presents a negative geothermal gradient and most of the host rock presents a normal positive geothermal gradient. Beneath the bottom of the cave, however, geothermal gradients are much higher than normal. The ice body temperature is always kept below 0 °C, although the external temperature is completely different. In Fig. 5a, the temperature of the shallow ground is lower than 0 °C, corresponding to a frozen zone in winter. In Fig. 5b, the temperature of shallow parts of ground is higher than 0 °C, indicating that the frozen part is melted and there is no permafrost. These features agree with actual conditions.

5.2 Evolution of an ice deposit melting model

The ice body in the ice cave will melt if there is no air convection heat transfer in winter. Taking the temperature shown in Fig. 5a as an initial temperature, the evolution of temperature distribution will be calculated with or without phase change effect considered. The results are shown in Fig. 6 by a black line and a red line respectively. They are the same when temperature does not reach the phase change temperature. The ice body takes much longer to thaw when the latent heat of melting is taken into consideration than when it is not. To thaw the ice body completely takes 23 years when the latent heat of phase change is not considered, compared with 37 years when it is considered.

5.3 Sensitivity to model parameters

The external air temperature, *Nu* and the number of tourists could directly affect the energy transfer in Ningwu ice cave. Therefore, it is need to do sensitivity experiments on these factors. With respect to the external air temperature, we consider two aspects: (1) the mean annual temperature, (2) amplitude. When the mean annual temperature increases (or decreases) 1.0 °C, the computing results are showed as Fig. 7a and b (or Fig. 7c and d). When the amplitude of external temperature increases (or decreases) 5.0 °C, the computing results are showed as Fig. 7e and f (or Fig. 7g and h). For *Nu* increases (or decreases) 10 %, the computing results are showed as Fig. 7i and j (or Fig. 7k and l). About 1000 visitors enter the cave per day from May to October. A person could release 200 cal. We assume that every person spend 1 h in Ningwu ice cave. Meanwhile, there are 200 15 W-light bulbs. When we consider the number of tourists and bulbs, the computing result is showed as Fig. 7m.

Similar to Fig. 4b, Fig. 7a, c, e, g, i and k shows the details of first two decades and represent that ice deposit would be formed in Ningwu ice cave within first two decades in these different experiments. Figure 7b, d, f, h, j and l correspond to Fig. 7a, c, e, g, i and k respectively. As showed in Fig. 4c, Fig. 7b, d, f, h, j and l depict the cave temperature annual fluctuations when the process has lasted two centuries, long enough to be evolved to a stable cyclic state. Compared with Fig. 4c, Fig. 7m represent that the current density of tourists and number of light bulbs in Ningwu ice cave could not melt the ice deposit in it.

6 Discussion

The age of the cave and that of the ice body are different. Formation of the cave cavity could be old and have taken place in a warmer climate. The formation of the ice body in the cave is a much later process that took place when the bowling-ball-like cave was formed and the climate became cold enough. In the present climate, our numerical modeling suggests that the year-round ice body can be formed within a decade.

In spring, summer and fall, air and host rock transmit heat to the ice cave by thermal conduction, increasing the temperature in the ice cave only slightly since the conduction efficiency is low. In winter, heat is transmitted out of the ice cave by natural thermal convection of air, efficiently decreasing the temperature in the ice cave. Phase change accompanies the thermal processes. Considering these mechanisms, the results show that Eq. (1) starting from a normal ground temperature, a year-round ice body will be formed in the cave in less than a decade, about 5 years in our model (Fig. 4b), and the ice cave temperature will decrease continuously for more than a century (Eq. 2) The ice cave will finally reach a stable cyclic state, and its temperature will fluctuate within a certain range, less than 1 °C (from −3.9 to −2.9 °C) for Ningwu ice cave. At this stage, the annual total heat transferred to the cave by thermal conduction and the heat removed from the cave by convection are balanced.

It would be interesting to further investigate the possibility of imitating nature and constructing a new kind of air conditioning system. At locations with similar climate conditions, people may construct a basement more than 10 m deep, using natural air convection to freeze ice in the basement in winter, and circulate air to the basement for air conditioning in summer.

Setting an air-tight door at a cave entrance, as one park has done in China to “protect” the ice cave at night during the tourist season and for the entire winter when the cave is closed to tourist, actually blocks air convection in winter. As a result, cold air cannot bring out heat from the cave, and accumulation of heat flow from the surface and the deep crust will finally lead to melting of the ice body in the cave. Our computation shows that it takes less than 40 years to completely melt the whole ice body in the cave. This suggests that scientific management is important for sustainable usage of natural tourism resources. Otherwise, well-meaning acts such as installing a trap door to completely seal the entrance for protection will actually destroy the natural wonder in a few decades.

7 Conclusion

This paper has focused on quantitative analysis of the formation and preservation mechanism of an ice body in Ningwu ice cave, a static ice cave. The finite element modeling leads to the following conclusion: the controlling factor for forming and sustaining the ice body in the cave is effective cooling of the cave in winter by natural air convection. Heat conduction in spring, summer and fall is very ineffective to warm up the cave. Ice-water phase change further prevents melting of ice in summer. The formation of the cave may take a long geological time, but the formation of the perennial ice body in the cave only takes decades of years under the current temperature and geothermal gradient in the Ningwu area by winter air convection. Once formed, the cave temperature will keep a stable cyclic state. Under this stable, the amplitude of annual temperature variation in the Ningwu ice cave is within 1 °C. Environmental warming even up to 1 °C in in Ningwu area will increase the cave temperature, but not melt the perennial ice body. The present heat from electric lighting and visitors will not melt the ice body either. However, if the air convective heat transfer is stopped in the winter as happened in some other Chinese ice caves, the ice body in the cave could be completely melted within about 40 years. This analysis is important for sustainable management of the ice cave as a tourism resource. The mechanism of ice cave formation may be adopted for construction of energy-saving buildings; ice may be produced in winter in basement and used for air conditioning in summer.

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Table 1. Relative material parameters.

Material	Heat conductivity $W\,(m\,k)^{-1}$	Density $kg\,m^{-3}$	Specific heat $kJ\,(kg\,K)^{-1}$
Limestone	2.7	2500	0.84
Ice	2.23	916.5	2.05
Mixture	2.465	1708.25	1.445
Air	0.0243	1.293	1.005
Water	0.58	1000	4.2

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Table 2. *Gr* number and constant for different flow types (Yang and Tao, 2006).

Flow state	Coefficient C	Index n	Gr application range
Laminar Flow	0.59	1/4	1.43×10^4–3×10^9
Transitional Flow	0.0292	0.39	3×10^9–2×10^{10}
Turbulent Flow	0.11	1/3	$> 2 \times 10^{10}$

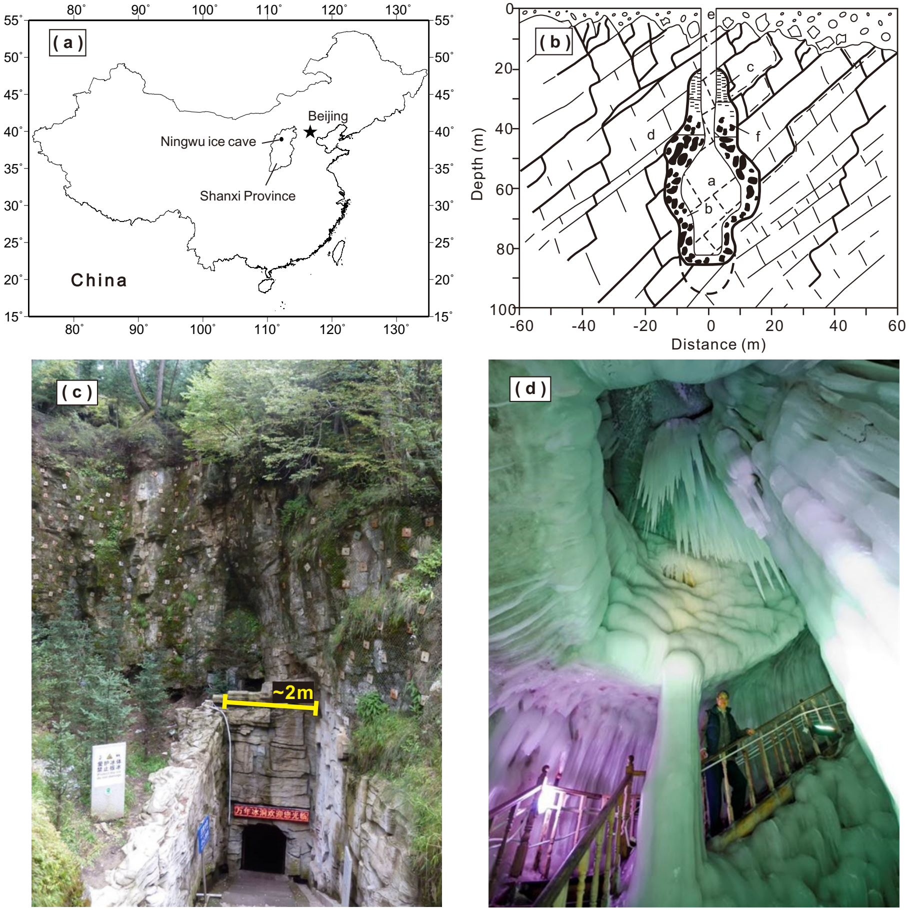

Figure 1. Location **(a)**, cross section **(b)**, entrance **(c)** and inside **(d)** of Ningwu ice cave. In Fig. 1b, **(a)** room; **(b)** block ice; **(c)** layered ice; **(d)** limestone; **(e)** entrance; **(f)** fracture.

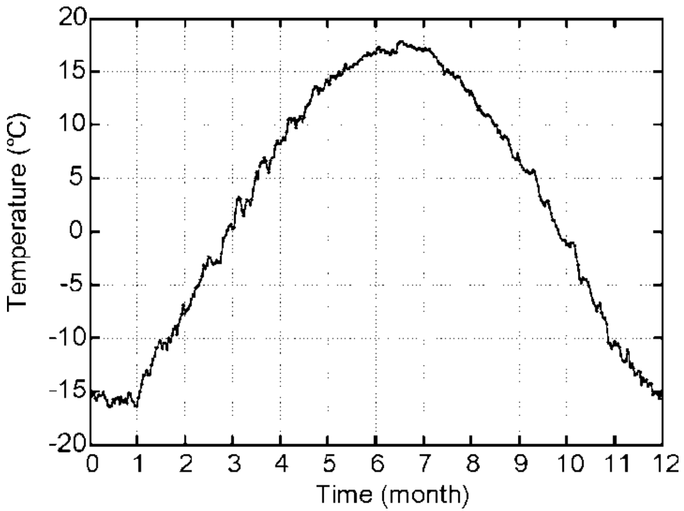

Figure 2. Yearly variation of external air temperature of Ningwu ice cave.

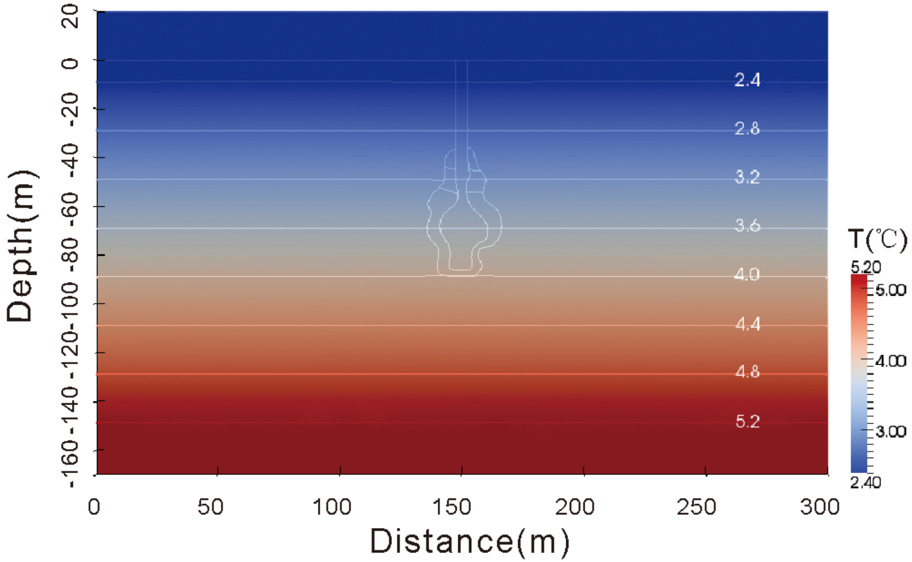

Figure 3. Initial reference temperature distribution around Ningwu ice cave.

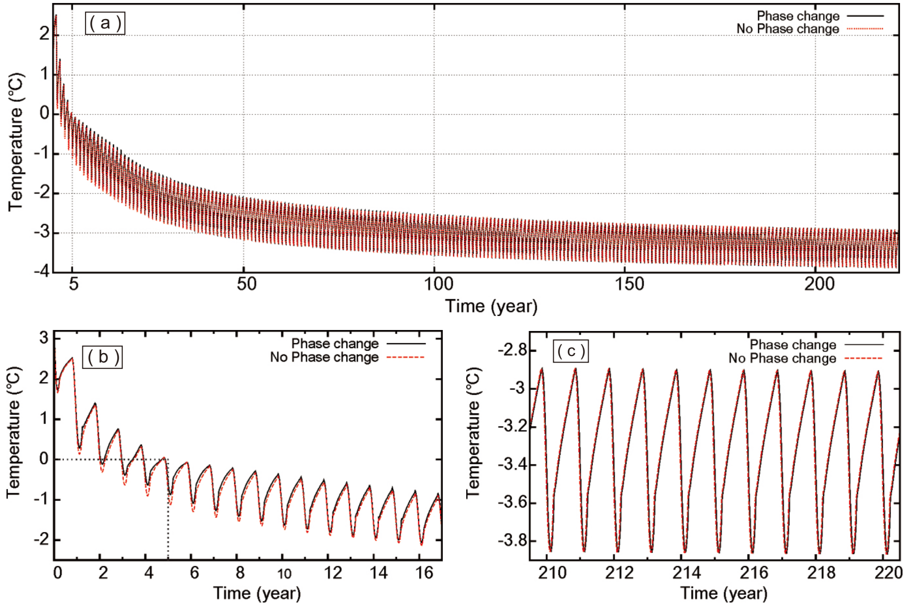

Figure 4. (a) Formation process of Ningwu ice cave; **(b)** initial formation process; **(c)** quasi stable state.

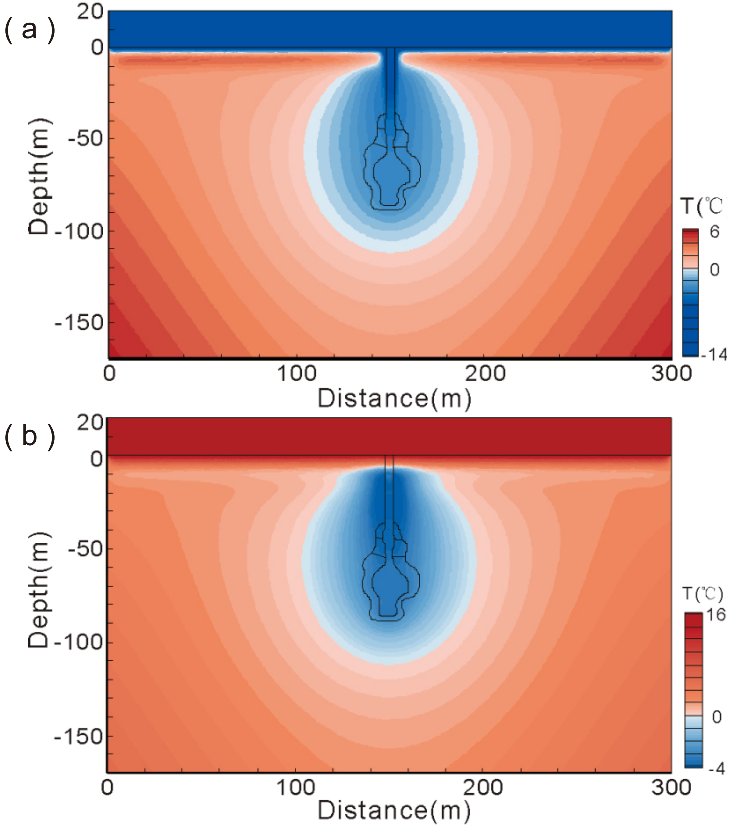

Figure 5. Temperature distribution around Ningwu ice cave in winter **(a)** and summer **(b)**.

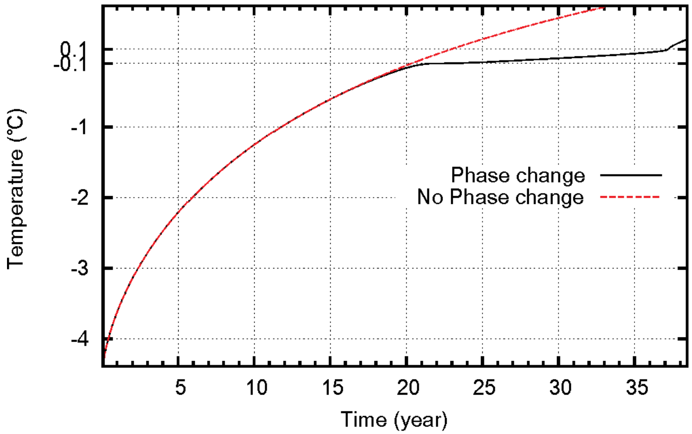

Figure 6. Internal temperature evolution diagram when ice in melting.

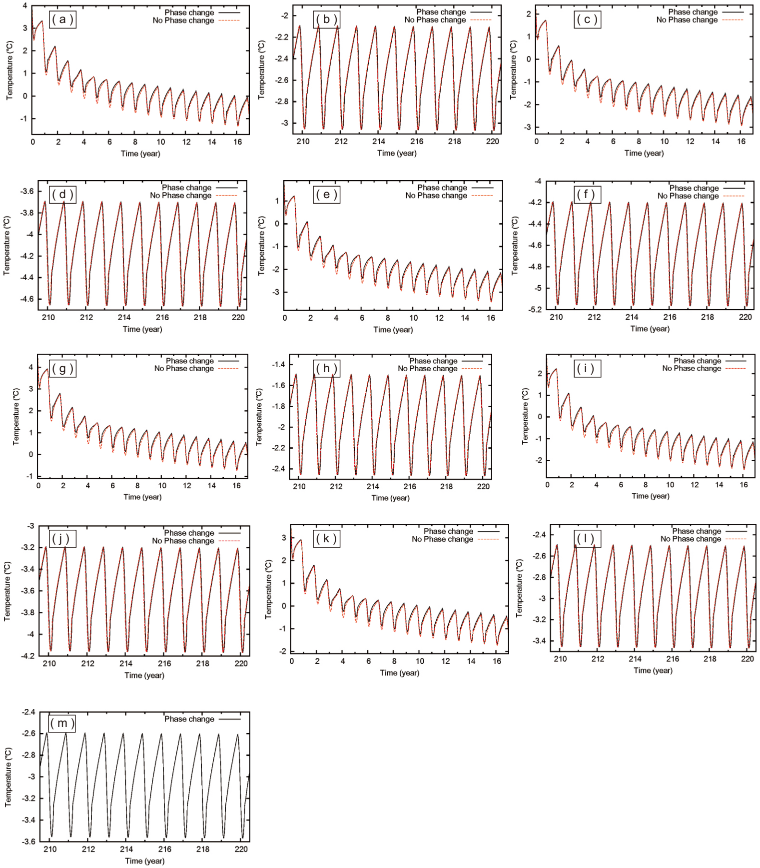

Figure 7. (a, c, e, g, i, k) Initial formation process of Ningwu ice cave in different sensitivity experiments. **(b, d, f, h, j, l)** Corresponding Quasi stable state. **(m)** Tourists and bulbs sensitivity experiment.