

Climate in a Single-Entrance Cave Controlled by Buoyancy-Driven Counterflow and Thermal Inertia

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1 **Climate in a Single-Entrance Cave Controlled by Buoyancy-** 2 **Driven Counterflow and Thermal Inertia**

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5 **Abstract**

6 Karst caves are unique subsurface environments in which climate is governed by the
7 interplay between advective heat transport by airflow, convective heat exchange at the
8 rock–air interface, and conductive heat transport within the surrounding rock. Airflow is
9 therefore a major driver of heat and CO₂ exchange between the underground and the
10 atmosphere, yet the physical mechanisms controlling cave ventilation across different
11 morphologies and time scales remain poorly understood. We investigate temperature and
12 airflow in a single-entrance cave consisting of a dominant down-sloping passage connected
13 to a set of chambers. Such caves exhibit buoyancy-driven ventilation during cold periods,
14 when dense external air descends along the floor of the entrance passage while warmer
15 cave air ascends along the ceiling as a bidirectional counterflow. During warm periods,
16 ventilation is largely suppressed and cave temperatures gradually equilibrate. Airflow
17 measurements and distributed temperature observations reveal complex dynamics
18 governed by heat exchange between the air, surrounding rock, and cave sediments, together
19 with mixing between the opposing airflow layers. Airflow velocity exhibits a non-
20 monotonic dependence on buoyancy forcing, while vertical temperature profiles
21 demonstrate mixing across both flow layers. Cooling of the surrounding rock and
22 sediments during cold-air intrusions sustains the buoyancy driving the counterflow,
23 prolongs ventilation, and alters the airflow response to subsequent cooling events. These
24 observations demonstrate that ventilation in single-entrance caves is controlled not only by

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the instantaneous temperature difference between the cave and the atmosphere, but also by the thermal inertia of the surrounding rock and sediment mass.

Keywords Cave microclimate • Counterflow • Density-driven flow • Natural ventilation

1 Introduction

Karst areas, which cover approximately 15% of the Earth's ice-free land surface, represent a unique interface through which surface hydrological and meteorological signals penetrate deep into the subsurface (D. C. Ford and Williams 2007; Covington et al. 2012). The karst subsurface is usually not isolated from the external atmosphere but is connected to it through conduits and fracture networks of various sizes that permit substantial water and air flow. The transport of heat and mass through karstified structures plays a crucial role in the physical, chemical, and biological processes that drive karst evolution and sustain the ecological functioning of karst landscapes (Luhmann et al. 2015). Understanding these transport processes is important not only for karst research but also for evaluating the contribution of karst areas to the global carbon budget.

Airflow through conduits and dissolutionally enlarged fracture networks plays an important role in the thermal regime of karst massifs and in the transport of gases, particularly CO₂, thereby influencing carbonate dissolution and precipitation (Kowalczyk and Froelich 2010; Kukuljan et al. 2021; Spotl et al. 2005). Airflow through karst massifs is primarily driven by buoyancy forces, external pressure changes, and groundwater movement (Badino 1995; Palmer 2007; J. D. Ford and Cullingford 1976). The dominant driver of buoyancy-driven airflow is the temperature difference between the external atmosphere and the cave air, which is largely controlled by heat exchange between the air and the surrounding rock massif (Lismonde 2002). Consequently, the chimney effect is the dominant ventilation mechanism in caves with multiple connections to the surface at different elevations. In general, the chimney effect drives airflow from lower to higher entrances during cold periods and in the opposite direction during warm periods. However, the geometrical complexity of cave and fracture systems gives rise to intricate ventilation patterns that are still not fully understood (Gabrovšek 2023). In relatively uniform passages, chimney-driven ventilation is approximately symmetric: for the same temperature difference between the external atmosphere and the cave, the magnitude of the upward

55 airflow during winter is similar to that of the downward airflow during summer. However,
56 even a single passage connecting two entrances may exhibit asymmetric ventilation if its
57 longitudinal profile or cross-section is non-uniform. In such cases, upward or downward
58 airflow may dominate under the same external forcing. Extreme examples are V-shaped
59 and Λ -shaped passages (i. e. systems with two entrances at the same or similar elevation
60 and a connecting passage lying below or above them, respectively), where ventilation may
61 be restricted almost exclusively to cold or warm periods, respectively (Gabrovšek 2023;
62 Lismonde 2002).

63 Caves with a single entrance represent another end-member case of asymmetric ventilation.
64 If such systems are ventilated, air must both enter and leave the cave through the same
65 passage, leading to the formation of a bidirectional counterflow. In a down-sloping passage
66 during cold periods, dense external air flows inward along the lower part of the passage,
67 while warmer less-dense cave air flows outward along the upper part. During warm periods,
68 ventilation is largely suppressed. By contrast, in an up-sloping passage the situation is
69 reversed.

70 The seasonal filtering of ventilation, whereby exchange with the external atmosphere is
71 restricted predominantly to either cold or warm periods, gives rise to so-called cold and
72 warm traps (Luetscher et al. 2008; Šebela and Turk 2018). These natural thermal traps have
73 long been exploited by humans for winter shelter (Mihevc 2018), ice harvesting (Mihevc
74 2021), and food storage. Cold traps are also the most favorable environments for the
75 development of perennial cave ice because their mean internal temperature remains
76 significantly below the mean annual temperature of the external atmosphere (Perşoiu and
77 Onac 2012; *Ice Caves* 2018).

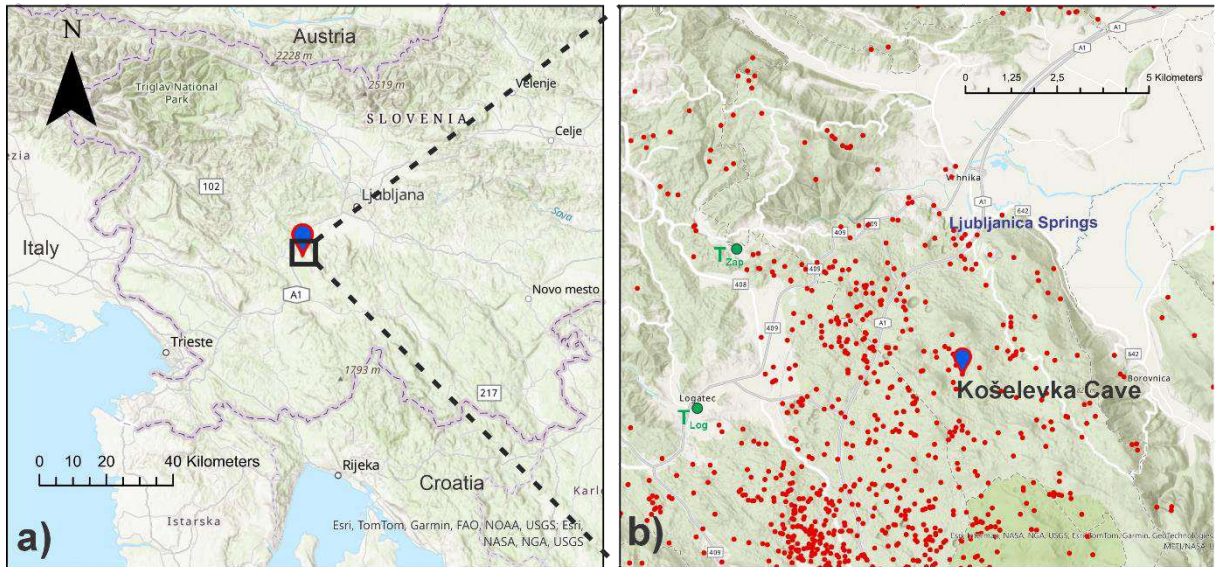
78 The buoyancy-driven counterflow observed in single-entrance caves is closely related to
79 the classical ventilation problem of a room with a single window (Linden 1999). Opening
80 a window to a colder external atmosphere induces the intrusion of dense outside air, mixing
81 within the room, and the simultaneous outflow of warmer indoor air through the same
82 opening. Similar counterflows have also been studied extensively in fluid mechanics
83 because of their importance in geophysical fluid dynamics, oceanic overflows, atmospheric
84 motions, and building ventilation (Meyer and Linden 2014; Lefauve and Linden 2022;
85 Armi 1986).

Despite their abundance, ventilation in single-entrance caves has received far less attention than chimney-effect ventilation, and the physical mechanisms controlling buoyancy-driven counterflow and heat transfer in such systems remain poorly understood (Lismonde 2002). In this work, we present airflow and temperature observations from the single-entrance Koševka Cave in the Dinaric karst of Slovenia. The cave was selected because of its extensive moonmilk deposits, whose formation remains poorly understood (Miller et al. 2018; Ghezzi et al. 2024) and may be linked to cave microclimate (Borsato et al. 2000; Lacanette et al. 2023). Initial observations revealed unexpected ventilation dynamics, motivating progressively more detailed measurements and a dedicated investigation of the cave's meteorology. We interpret the observed airflow and temperature patterns within the framework of buoyancy-driven counterflow maintained by heat transfer between the air, the surrounding rock, and cave sediments.

2 Study site and methods

Koševka Cave is 130 meters-long and 42 meters deep, with its entrance located at an altitude 630 meters above sea level. The cave is a fragment of a partially degraded and collapsed fossil conduit in the hinterland of Ljubljana River karst springs, situated about 330 meters above the present level of regional karst springs (Fig. 1). Since the cave's climate may play a crucial role in moonmilk formation, a series of temperature sensors (HOBO Mx 400) and an anemometer (Gill Ultrasonic) have been installed. Temperature was sampled at 10 min interval, unless specified otherwise. Airflow was sampled at 1 Hz or 0.25 Hz. The measurements were subsequently grouped into 10-minute intervals, from which the mean (v_{av}) and maximum (v_{max}) airflow velocities were calculated. Sporadic CO₂ measurements with a Vaisala MI72 handheld CO₂ instrument have also been conducted. The main observation period extended from autumn 2022 to spring 2023, with some additional observation in 2024. A second, more detailed campaign was conducted during autumn–winter 2025/2026, with additional thermometers distributed along the cave and outside. In 2021–2023, an anemometer was placed about 75 cm above the floor in the downward sloping passage, while external temperatures for the early monitoring periods were taken from the meteo station “Logatec” of Slovenian Environmental Agency, which

is 10 km away to the west and at a similar altitude. Comparison of the official meteo station data with measurements carried out outside the cave in Autumn 2025 revealed only small differences between on site temperatures and temperatures Logatec.



● Košelevka Cave ● Meteo stations ● Registered Caves Area enlarged

Fig. 1 Geographic location of Košelevka Cave. A) regional position. b) enlarged area with position of caves and meteorological station.

The cave (Fig. 2) features an opening of 6 m x 2 m, leading to a 60 meter-long downward inclined passage. This passage opens into a larger chamber, from which a partially collapsed corridor leads to a smaller, dead-end chamber. Two other dead-end passages descend from the main chamber. Additionally, two vertical passages diverge from a side niche of the main chamber, but they become impassable after a few tens of meters. The cave walls are partially covered by speleothems, either in the form of crystalline flowstone and dry or water-saturated moonmilk (i.e., fibrous microcrystalline calcite). The cave floor is covered by a mixture of limestone debris of various sizes, ranging from blocks exceeding one meter in size to cobbles, sand, and fine silt-sized cave sediments.

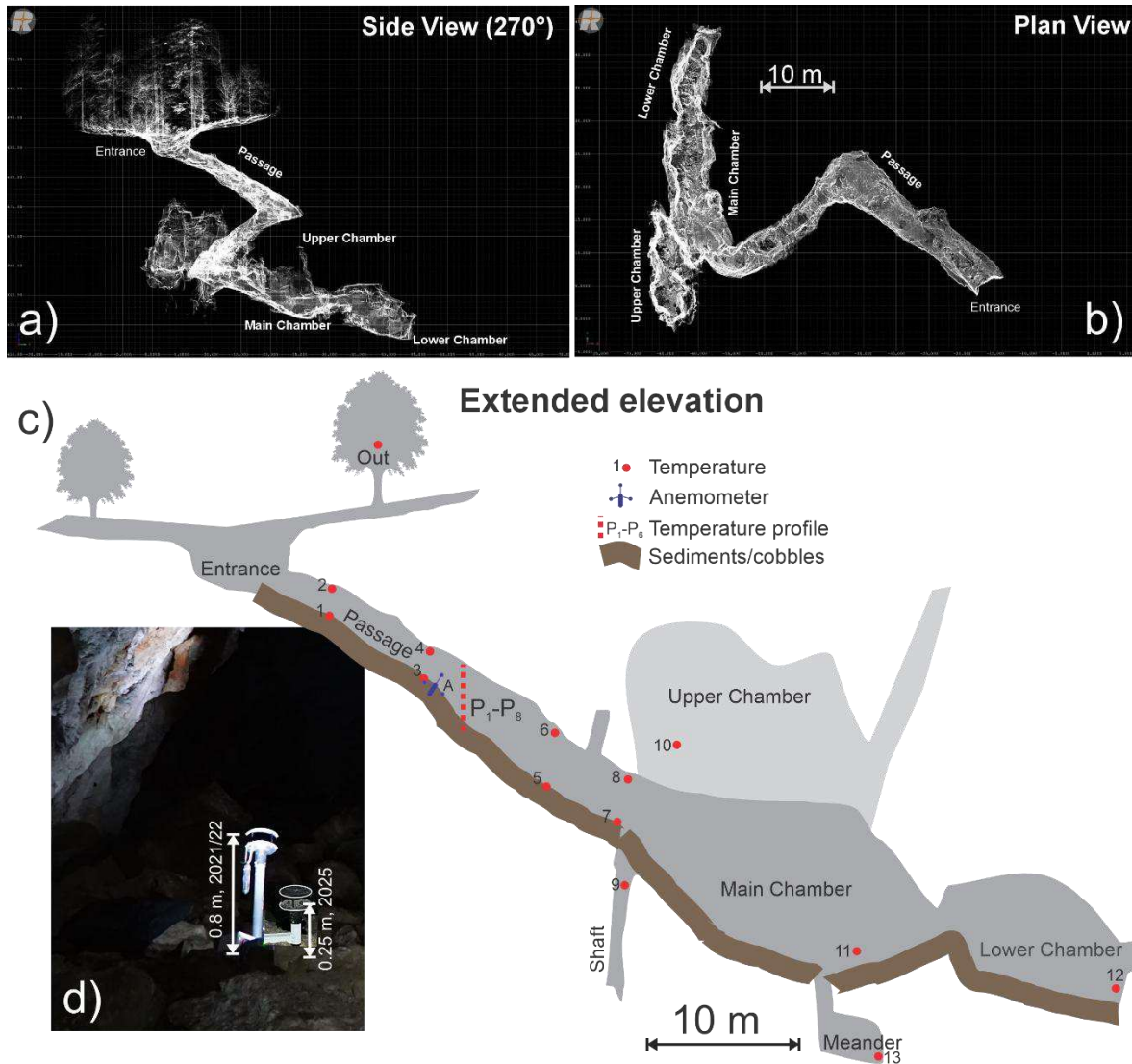


Fig. 2: a) Cross-section of the point cloud taken by a terrestrial lidar. b) Plan view (of the point cloud). c) Simplified cross-section with location of observation points. d) The position of the anemometer in the 2021/22 period and in 2025.

2.1 Local climate

The climate is temperate continental (Köppen Cfb). Winters are cold, with nighttime temperatures frequently dropping below freezing. The number of cold days ($T_{\min} < 0\text{ }^{\circ}\text{C}$) is around 100 per year in the 2020s, with about 10 fully frozen days ($T_{\max} < 0\text{ }^{\circ}\text{C}$). Extreme winter minima can fall below $-20\text{ }^{\circ}\text{C}$. Summers are warm to occasionally hot, with daytime highs reaching up to $30\text{ }^{\circ}\text{C}$, accompanied by cooler nights. The mean annual temperature

in nearby Logatec meteorological station (Fig. 1) for the period 1991–2020 was 8.8 °C, with a clear warming trend of approximately 0.33 °C per decade. In the 2020s, the annual mean has risen to about 10 °C. Precipitation is evenly distributed throughout the year, with a peak in autumn, totaling roughly 1800 mm annually. The number of days with snow cover (>1 cm) shows a decreasing trend (–6 days per decade) and is currently around 30 days per year.

3 Results

Fig. 3a shows the temperature at different locations within the cave and the external temperature at the Zaplana meteorological station (Fig. 1) between October 2021 and July 2024. The record shows episodes of cold air intrusions during the winter period, and asymptotic behavior, with temperatures approaching an equilibrium value (in the case of Košelevka, about 7.5 °C) between spring and autumn. Such temperature patterns are common and typical of caves with a single opening to the surface and a negligible chimney effect, as well as in V-shaped caves (i.e., caves with two entrances at similar elevations) (Gabrovšek 2023; Ravbar et al. 2014; Šebela and Turk 2018; Buzjak et al. 2024; Luetscher et al. 2005). In these caves, a strong ventilation regime occurs during cold periods, while ventilation is minimal or nearly absent in summer. Good qualitative information about the spot ventilation pattern can be obtained using smoke sticks. Fig. 3b shows airflow directions at an external temperature of –1 °C, obtained using a simple method in which smoking sticks were fixed to a rod at different elevations above the ground, about 20 m below the entrance in the downward sloping passage. The results show strong downward airflow into the cave in the lower part of the passage (at 0.3 m above the floor), with a returning upward flow in the upper part of the passage (1.5 and 2 m high), and changing direction in the middle section (1 m-high). From here on, we use *upflow* for air moving upward along the ceiling section of the channel, and *downflow* for airflow descending along the floor section. Videos of the smoke-stick observations are available in the data repository (Gabrovšek 2026).

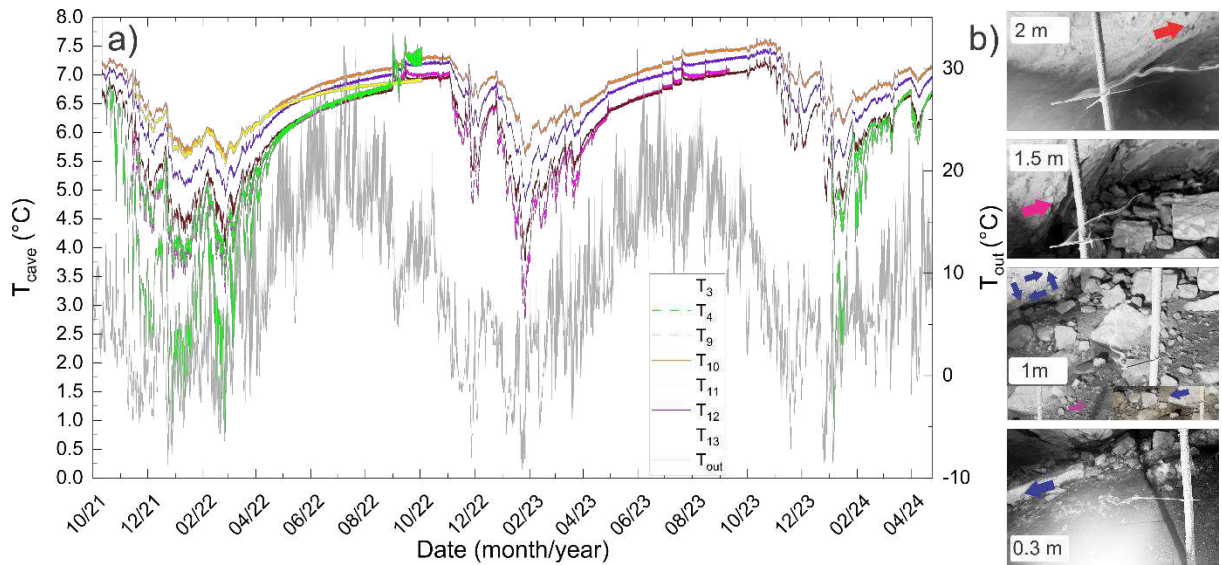


Fig. 3 a) Temperature records at different sites (see Fig. 2) in Košelevka (T_{cave}) and external temperature at Zaplana weather station (T_{out}). b) Smoking sticks indicating airflow at different heights above the floor during cold air intrusion in January 2026. The location of photos is in the inclined passage, about 20 m from the entrance; entrance is to the right.

We now turn to detailed observations in the late autumn, 2025. Fig. 4 presents time series data of airflow, temperatures at points 3 and 4 in the cave, the temperature difference between these two points, and the outside temperature from 9 November to 11 December 2025. The anemometer was positioned in the lower section of the channel, about 25 cm above the floor at point 3 (Fig. 2). At this point, the airflow for the entire period is directed into the cave along the downward-sloping floor (downflow), as observed by smoke sticks (see Fig. 3b).

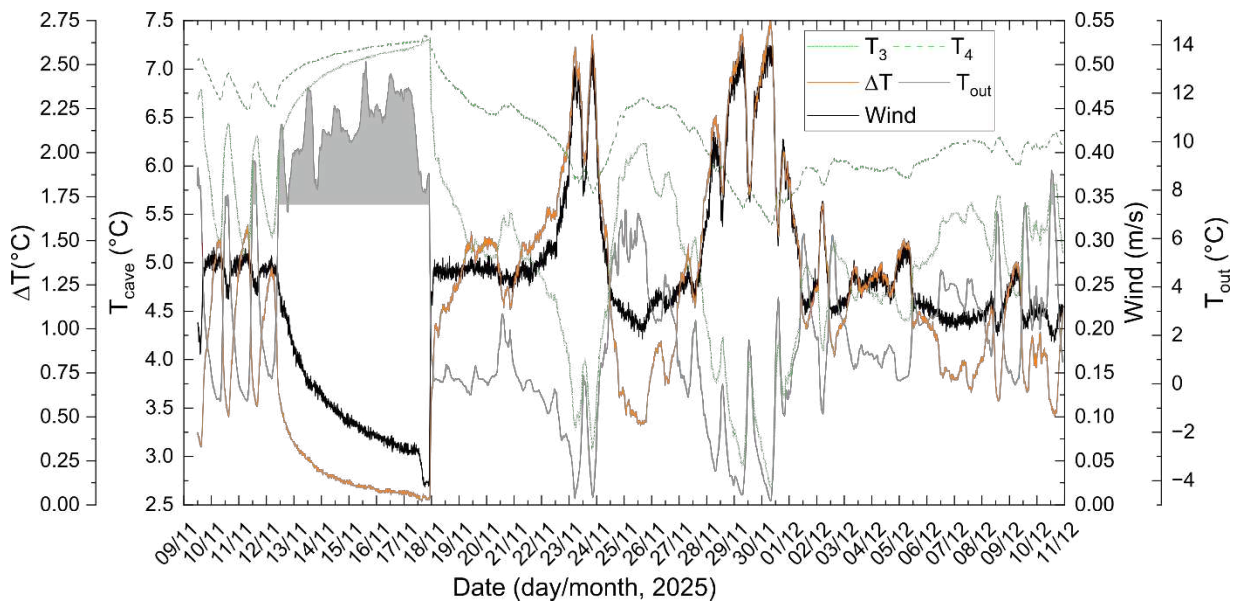


Fig. 4 Cave microclimate in November–December 2025. External temperature, wind speed and temperature 0.25 m above the floor (Point 3 on Fig. 2) and 0.2 m below the ceiling (Point 4) of the inclined passage, and temperature difference between points 4 and 3 ($\Delta T = T_4 - T_3$). Shaded region marks the period when external temperature was above 7.5 °C.

In Fig. 4, the initial period (9 November to 11 November 2025) was characterized by stable autumn weather with a pronounced diurnal temperature cycle, featuring daytime maxima between 7 °C and 9 °C and night-time minima just below the freezing point. The airflow remained relatively stable during the night and decreased only moderately during the day, when the external temperature rose.

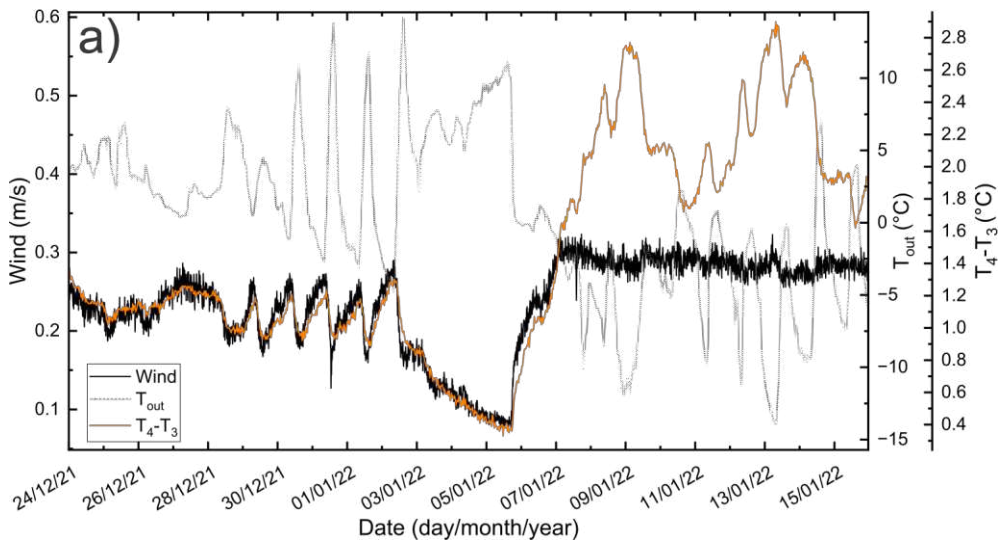
On 12 November 2025, the outside temperature rose above 7.5 °C, when the airflow in the cave began to diminish with a time constant of approximately 1.5 days (approximating the relaxation by assuming exponential decay). Temperatures behaved asymptotically, differences between them diminished, and they both approached 7.5 °C. The temperature inside the cave (see also Fig. 6) was no longer affected by external temperature variations. This indicates that intrusions of external cold air are limited to situations when the outside temperature falls below 7.5 °C, which we refer to as the switch temperature (T_{sw}). The grey area below the T_{out} curve denotes period when $T_{out} > T_{sw}$.

In the night between 17 and 18 November, the outside temperature dropped from 8.5 °C to just above 0 °C within three hours, triggering a rapid intrusion of cold air, as observed by the anemometer as an increase in wind speed and the temperature loggers recorded the

cooling of cave air. Notably, the airflow velocity was similar to that during the initial stable autumn period (around 0.25 m/s) (Fig. 4).

During the remainder of the monitoring period (until 11 December 2025), the external temperature remained below the T_{sw} , reaching a minimum of -4.7°C with the 10 min average airflow speed (v_{av}) reaching maxima around 0.5 m/s. As expected, the airflow velocity is positively correlated with difference between the temperature below the ceiling and above the floor, $\Delta T = T_4 - T_3$. However, as it can be seen, and we demonstrate latter, the relation between the two is far from linear.

During the observations between October 2021 and May 2022, several periods with similar dynamics were observed, some examples of which are shown in Fig. 5. Fig. 5a shows the outside temperature, cave wind velocity and temperature difference ΔT records for a winter period. The external temperature shows diurnal cycles above and below the T_{sw} , followed by warm period and asymptotic behavior of airflow and ΔT , after which a rapid cooling occurs with cold air intrusions into the cave; note that the airflow becomes relatively insensitive to ΔT during cold period, after 7 January. Similar observations are presented on Fig, which shows a longer period with diurnal cycles of external temperature that reached amplitudes above 30°C .



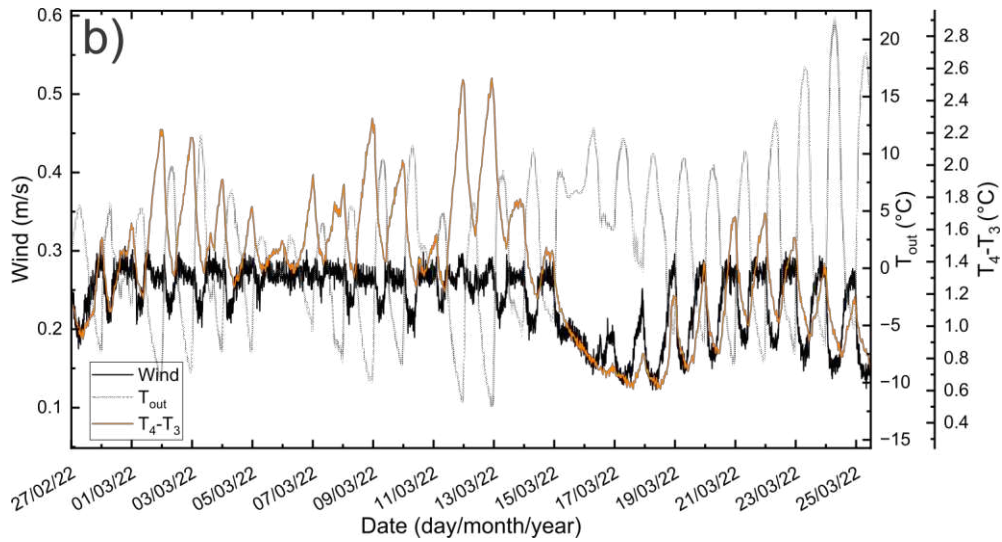


Fig. 5 Records of wind speed, external temperature and difference between ceiling and floor temperature. a) December–January, 21/22, b) February–March, 22.

3.1 Temperature distribution along the passage and across the airflow layers

Fig. 6a shows temperature records along the floor of the cave (points 1,3,5,7,11) in Autumn 2025 period. Downflow temperature increases rapidly in the initial section (from 1 to 3), after which the rate of increase diminishes along the flow path (from 3 to 11). Along the cave ceiling (Fig. 6b), the upflow temperature decreases from point 8 toward the exit, with the smallest difference observed between points 6 and 4, and highest differences in the entrance part. In the inner part of the cave (Fig. 6c), the highest temperature was observed in the upper chamber (10) but this was similar to the deepest location in the cave (12). The temperature in the shaft (9) was close to temperature at point 7, the nearest temperature logger to point 9 in the downflow part of the inclined passage (Figs. 2 and 6c). Fig. 6d show temperature differences along consecutive points of the flow path. The differences are highest in the entrance part ($T_3 - T_1$ and $T_4 - T_2$) and during cold periods.

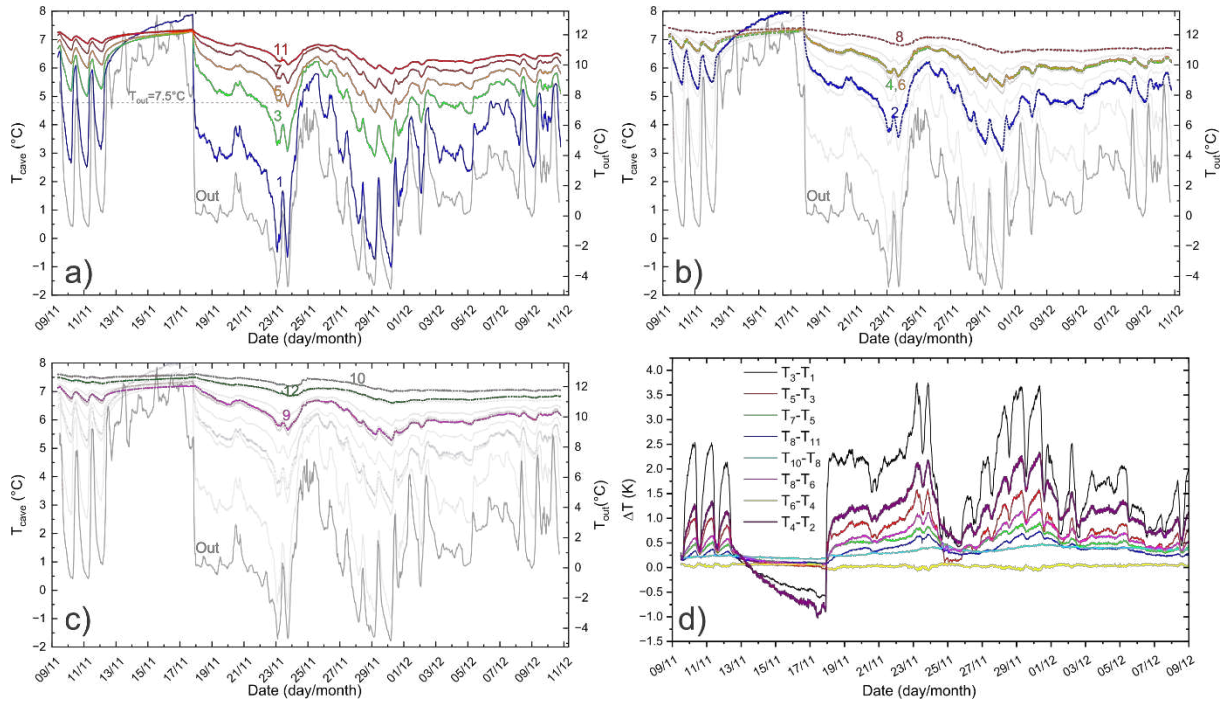


Fig. 6 Temperatures at different locations along the cave passage in autumn 2025. Time series of temperature along the downflow (a), upflow (b) and in the internal part of the cave (c). (d) Temperature differences between successive points along the flowpath (see Fig. 2 for locations). T_{out} and T_{cave} are at the different scales in panels a-c. In (b) and (c), the temperatures at all locations are shown as faint lines for reference.

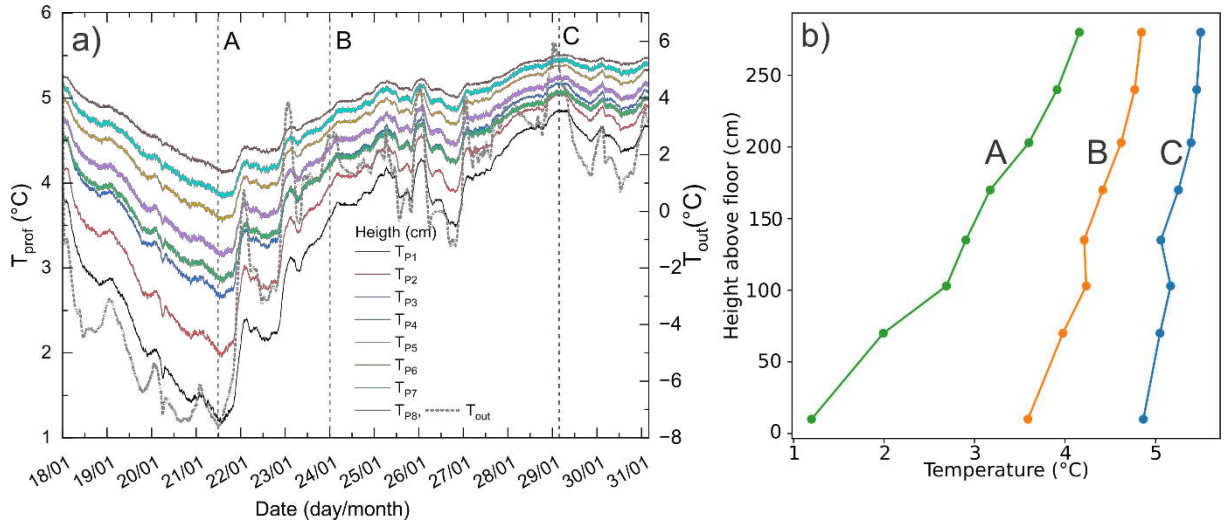


Fig. 7: Vertical temperature profile at point 3: a) Temperature records at different heights along the profile P1–P8 (see Fig. 2) between 18 January and 1 February 2026. b) Characteristic temperature profiles; see dashed lines in (a) for times of when the profiles were extracted.

Fig. 7a shows the temperature at different heights above the passage floor in January 2026 (at P1–P8 in Fig. 2). Fig. 7b shows temperature profiles at three selected times with

different T_{out} (-7.7°C (A), 2.6°C (B) and 5.5°C (C)) as marked in Fig. 7a. Overall, the temperature increases from the cave floor toward the ceiling (Fig. 7b). The gradient is highest during the coldest period (green line) and flattens as the system approaches the switch temperature (blue line). The three profiles also indicate the largest temperature change over the first meter from the floor, and thus, the highest degree of mixing at approximately 1 m above the floor, where flow reversals are also observed by smoking sticks.

4 Discussion

The temperature and airflow records indicate that the intrusion of cold air is limited to periods during which the external temperatures (T_{out}) are below the switch temperature (T_{sw}), which in the case of Košelevka Cave was found to be close to 7.5°C , for the shown period (Fig. 4). To elucidate these relations, Fig. 8a shows airflow velocity as a function of the normalized difference between the external and switch temperatures $T_n = (T_{sw} - T_{out}) / T_{sw}$ for the autumn 2025 period (as in Figs. 4 and 6). Colors indicate the position in time as the number of days from 9 November; see Fig. 8b inset graph with color coded line. When $T_n < 0$, the wind and external temperature are uncorrelated (left from the vertical dotted line). The decrease of airflow in the orange-yellow region (recession period; 12–17 November) was independent of the changes of external temperatures while they remained above T_{sw} . Yellow dots show the last part of the warm period where the airflow diminishes (17 November), and the subsequent cooldown on 18 November, when airflow increased vigorously due to the rapid drop in external temperature. Before the cooldown, the cave temperatures were approaching 7.5°C (T_{sw}) and the wind velocity approached zero (Fig. 4). Immediately on the rapid drop of external temperature, the initial increase of airflow was fast and lasted for about an hour (widely spaced yellow dots in Fig. 8a and Fig. 8b). A notable observation is that, apart from the initial rise in airflow velocity during rapid cooling, the airflow changes slowly with temperature for $T_n \leq 1$ but with a further drop of external temperatures ($T_n > 1$), the slope increases. Furthermore, the relation between airflow and T_n also changes in time; in the earlier period (red), the velocity is slightly higher than in the latter period for the same T_n .

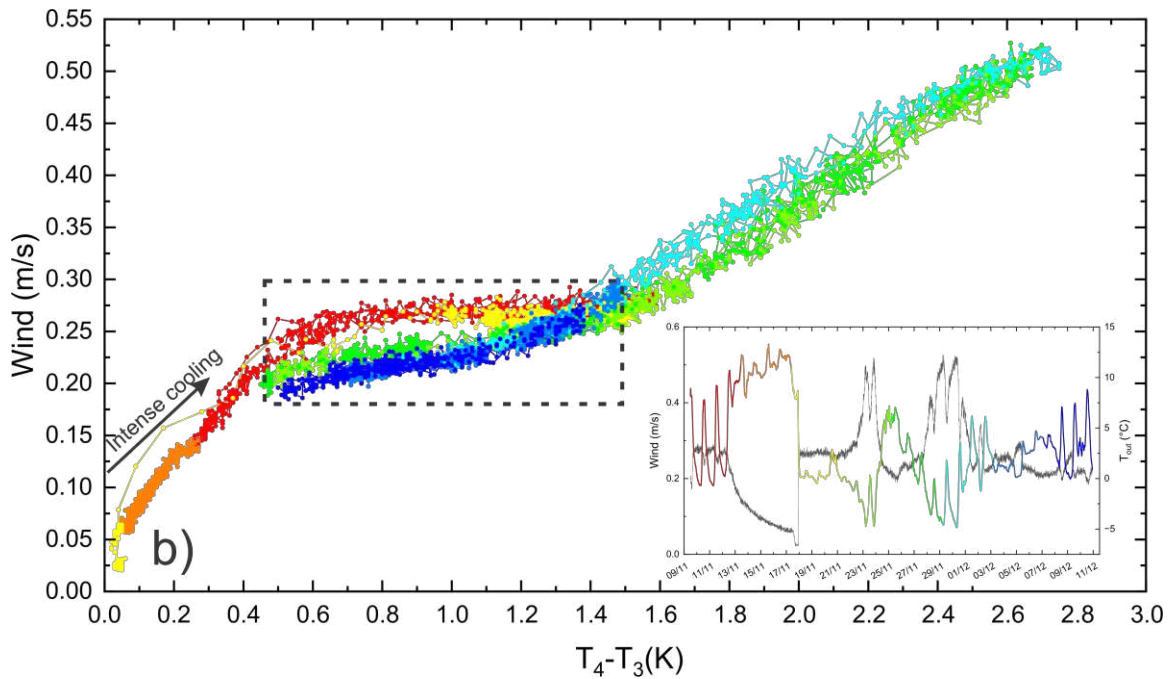
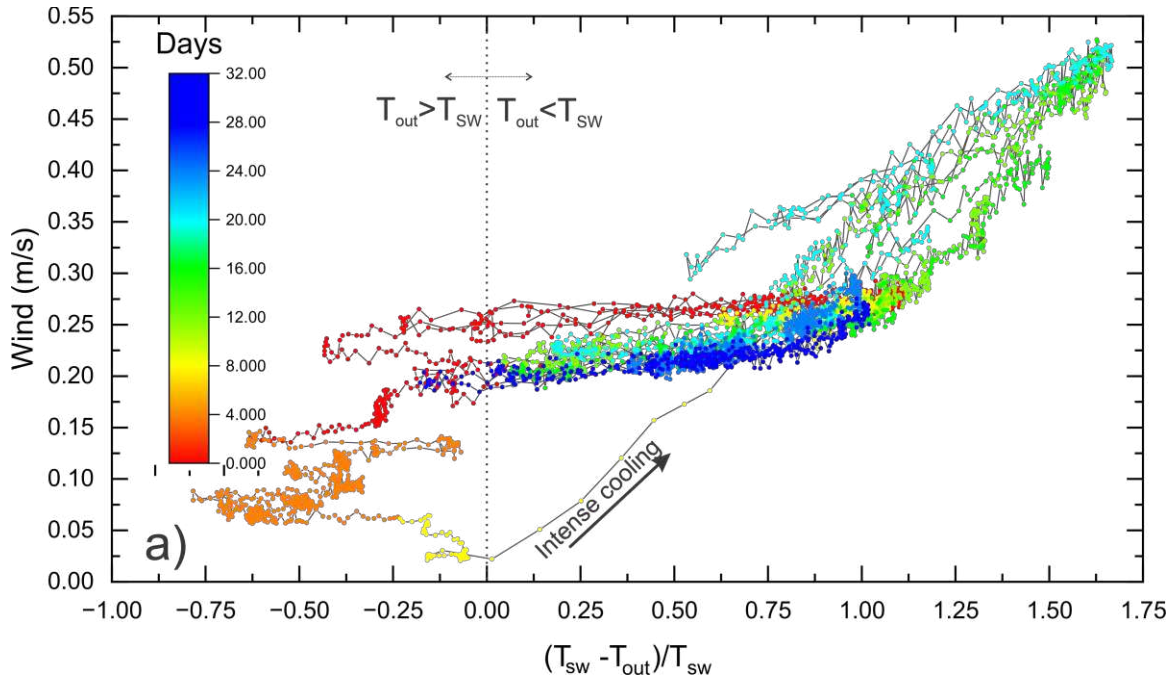


Fig. 8 Dependence of airflow velocity on temperature difference. a) Airflow velocity as a function of normalized difference between *switch temperature* and external temperature. Colors denote the number of days since the beginning of observations (see also inset in Fig. 8b). b) Relation between wind speed and temperature difference below the ceiling and above the floor ($T_4 - T_3$). the color of each data point indicate the time elapsed since the start of the observations on 9 November (see the color scale and inset in Fig. 8b). The inset shows the time series of wind speed (black line) and external temperature, with the temperature plotted using the same color scale.

The drop in external temperature causes the instability that leads to intrusion of cold air. The airflow driven by the density contrast between the descending cold-air layer (downflow) and the ascending warm-air layer (upflow), and is therefore a function of temperature difference between the two. This is demonstrated in Fig. 8b, which shows the relation temperature difference (ΔT) between the *upflow* at the ceiling (T_4) and *downflow* at the floor (T_3) in the middle part of the inclined passage (see Fig. 2). The red—orange-yellow region before the rapid cooling shows the decay of airflow during the period with $T_{out} > T_{sw}$.

In the region highlighted by the rectangle in Fig. 8b, the airflow responds only weakly to increasing ΔT . Hereafter, we refer to this region as the velocity plateau.

As observed also for correlation with the outside temperatures (see Fig. 8a), the airflow in the early period (red) is slightly but distinctly stronger than in the latter periods (green, blue) for the same ΔT (Fig. 8b rectangle).

We can summarize the above presented observations as follows:

1. Starting from a stable situation, following a long period of external temperatures above the switch temperature (T_{sw}), with no measurable airflow and almost uniform temperature in the cave, the situation becomes unstable, when external air temperature drops below T_{sw} , and the buoyancy driven counterflow initiates.
2. The downward flow along the lower section of the main inclined passage continues along the main chamber and lower chamber and returns along the upper part of the passage cross-section as an upward flow towards the exit.
3. Temperature increases along the path in the downflow layer and decreases along the upflow, with fastest changes close to the entrance.
4. Temperature increases monotonically from the floor to the ceiling with smallest gradients in the middle, indicating most efficient mixing in the mixing layer.
5. When external temperature rises above T_{sw} , after a period of cold air intrusion(s) the airflow diminishes toward standstill and cave temperatures approach T_{sw} .
6. Airflow shows a nonuniform sigmoid relation to buoyancy with a clear plateau, or even a double-sigmoid behavior for the higher positioned anemometer.

We consider the temperature as the dominant factor influencing air density. Generally, there may be a situation in which variations in humidity or CO_2 concentration may play a

role, but in the observations discussed here, we can safely consider the temperature as the dominant factor of air density differences (see Gabrovšek 2023).

4.1 Seasonal evolution

A longer period of observations, from autumn 2021 to summer 2022, revealed a similar pattern between the temperature difference in the inclined passage and the airflow velocity. However, the anemometer was placed at a higher position, about 75 cm above the floor, which resulted in some differences with respect to the 2025 situation. Fig. 9 shows the relationship between the temperature difference ΔT , and the wind speed. Fig. 9a presents time series from winter to summer, whereas Fig. 9b shows the correlation between ΔT and wind speed; triangles denote 10 min mean airflow velocities, while circles denote the corresponding 10 min maximum velocities. The relation is even more intriguing than the 2025 dataset; $v_{\max}$ increases with ΔT , and passes local maximum and minimum, until it rises again, but the increase is limited; v_{av} shows a plateau with less pronounced maximum. Colors denote the number of days since 24 October 2022, when the measurements started; this coincides with the beginning of cold air intrusions. Besides an intriguing general pattern with maximum and minimum, it also shows a clear seasonality pattern, when the airflow is stronger in the earlier part of cold season (red) than in the spring (green) for the same ΔT (Fig. 9).

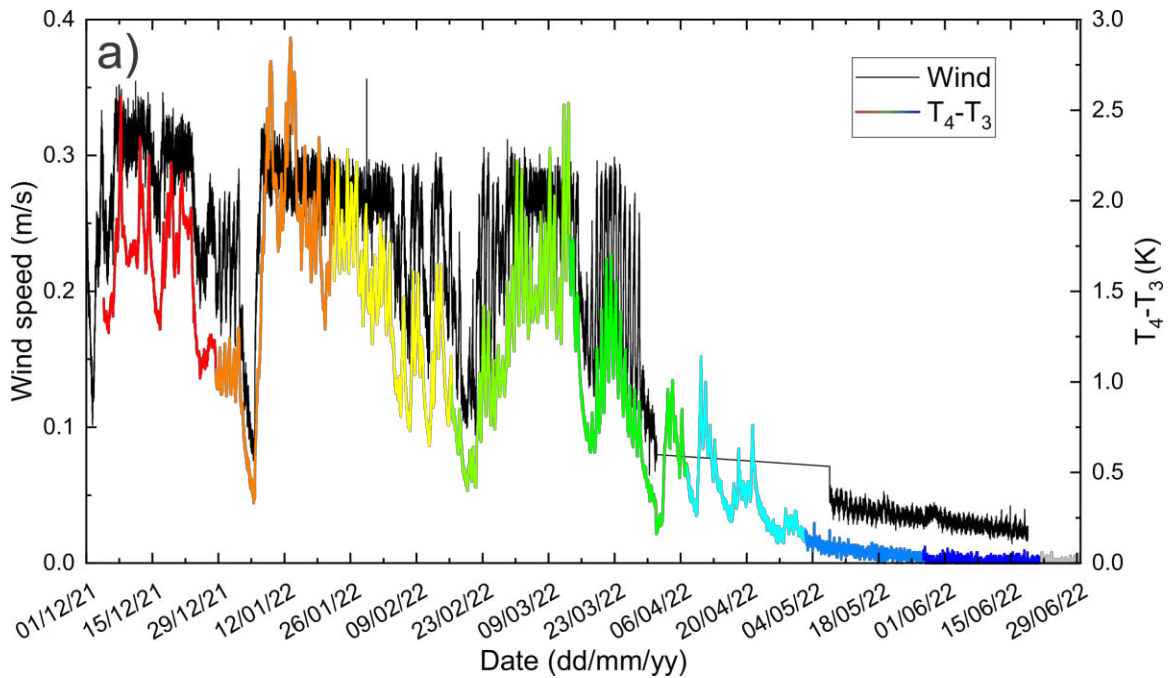
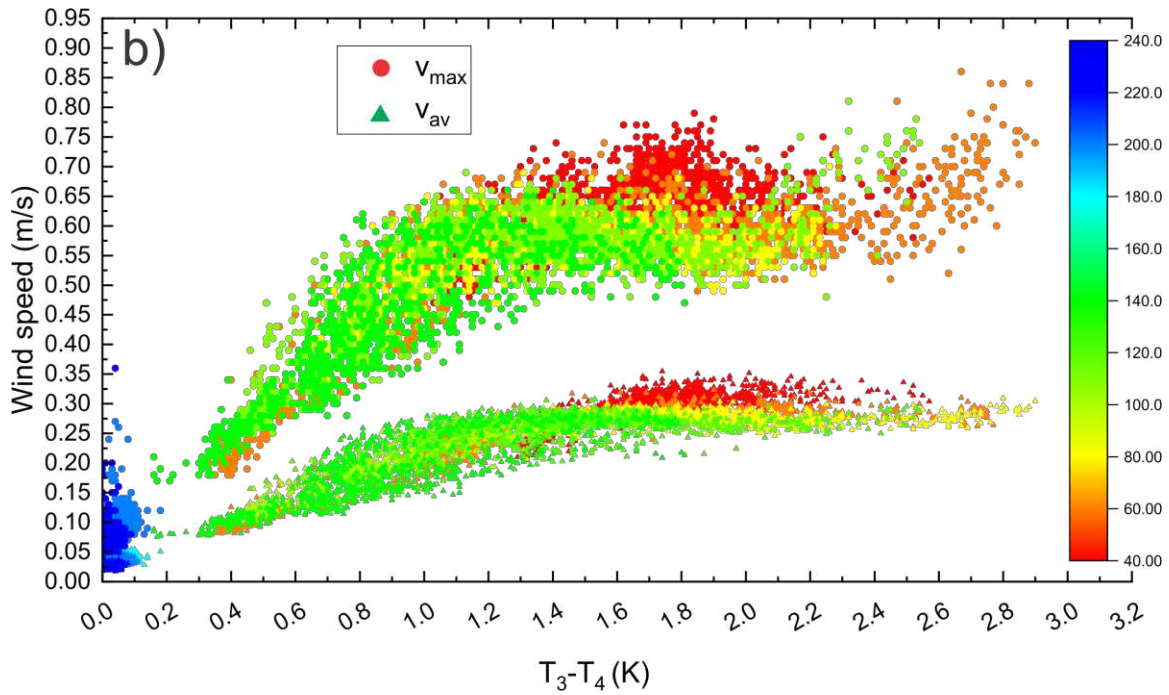


Fig. 9: a) Record of wind speed and T_4-T_3 between November 2021 and June 2022. Note that the anemometer was placed 75 cm above the floor. Colors denote days since the first observation (24 October 2021). b) Relation between T_4-T_3 and wind speed for 10 min average value of wind speed (triangles) and maximum wind speed in the 10 min interval (circles).

4.2 Properties and dynamics of stratified flow

Intrusion of cold air replaces the cave air with the external air. During the observed rapid cooldown in November 17, 2025, which followed a warm period with external temperatures above T_{sw} , the initial phase of cold-air intrusion lasted about 80 minutes (Figs. 4, 6, 7, 10) and was followed by a relatively stable airflow. Prior to the cooling, the cave air temperatures were approaching T_{sw} , and the early stage of intrusion is dominated by the replacement of warm cave air with colder external air. However, the volume of warm cave air is limited—on the order of a few thousand cubic meters. In an adiabatic system, ventilation would cease once the internal air mass had been replaced by external air. However, the buoyancy driving the counterflow is sustained by the heat exchange between the air and the surrounding rock and sediments. Two main processes can be envisaged: (a) heat exchange between the walls/sediments and the air, and (b) heat exchange between the counterflowing air layers.

Convective heat transfer between the rock/sediment and the air is proportional to their temperature difference. The heat exchange between the counterflowing layers and within them depends on the degree of mixing between and within the descending and ascending air layers. The observed system falls in the context of buoyancy-driven exchange flows in inclined ducts (Lefauve and Linden 2022; Meyer and Linden 2014). However, the cave system differs fundamentally from the classical exchange-flow configuration, when flow is exchanged along the sloping conduit between two infinite reservoirs with prescribed fluid densities. In our case the external atmosphere acts as an effectively infinite reservoir with prescribed properties, whereas the cave atmosphere constitutes a finite air volume whose density field evolves continuously through heat exchange with the surrounding rock and sediments. Consequently, the buoyancy driving the counterflow is continuously regenerated rather than prescribed.

The nearly continuous vertical temperature gradient (Fig. 8) indicates turbulent mixing throughout both the upflowing and downflowing layers. The local reduction of the temperature gradient in the interfacial region (around 1 m from the cave floor) suggests enhanced turbulent mixing there, consistent with an active interfacial shear layer between the counter-flowing streams. Kelvin–Helmholtz-type shear instabilities (Meyer and Linden 2014) may contribute to the initiation of mixing within the interfacial shear layer. The

adjacent upflow and downflow contain turbulent eddies generated by wall shear, interfacial entrainment, and the turbulent energy cascade.

Using reasonable values for air viscosity ($\mu \approx (1.7 - 1.8) \times 10^{-5} \text{ Pa s}$), temperature differences of few Kelvins, the thermal expansion coefficient $\beta \approx (3.4\text{--}3.7) \times 10^{-3} \text{ K}^{-1}$ and characteristic dimensions of the passage, the estimated Grashof numbers ($\text{Gr} \sim 10^9\text{--}10^{10}$) indicate that buoyancy forces greatly exceed viscous damping. The Reynolds numbers in the range $4 \times 10^4\text{--}10^5$ also indicate that the flow is fully turbulent.

The plateau, which characterizes $v(\Delta T)$ curve on Figs. 8b and 9b still remains challenging. One possible explanation is that the plateau reflects a regime approaching internal hydraulic control at a critical interfacial Froude number $Fr_i = \frac{v}{\sqrt{g'h}}$, where h is the thickness of the corresponding flow layer and g' is the reduced gravity associated with the density difference between the warm and cold air layers, $g' = g \frac{\Delta \rho}{\rho} = g\beta\Delta T$. When the local interfacial Froude number approaches unity, the flow may become hydraulically controlled (Armi 1986). Under such conditions, additional buoyancy forcing is accommodated partly through enhanced turbulent entrainment, changes in layer thickness and interface position, and increased dissipation, rather than solely through increasing airflow velocity.

The plateau spans over a few degrees K, rather than having a sharp transition, which suggests that hydraulic control may not be confined to a single geometric constriction. Owing to the irregular cave geometry and distributed heat exchange with the surrounding rock, the location of the critical section may migrate with increasing buoyancy forcing, resulting in a range of temperature differences over which the flow remains close to hydraulic control before accelerating again.

The values presented in Table 1 are order-of-magnitude estimates based on representative flow velocities, temperature differences, and characteristic length scale, which are relevant, but non-unique due to complex geometry of the cave. Although the exact values depend on the choice of these parameters, the resulting dimensionless numbers consistently indicate a buoyancy-dominated, high-Reynolds-number turbulent exchange flow operating close to internal hydraulic criticality.

Table 1 Dimensionless numbers for a set of airflow speed and temperature differences $\Delta T = T_4 - T_3$. Gr = Grashof number, Re = Reynolds number, Fr_i = Interfacial Froude number. The Froude number was calculated using the thickness of the lower flow layer ($h=1.2$ m).

ΔT (K)	U (m/s)	Gr	Re	Fr_i
0.50	0.20	2E+09	4E+04	0.89
1.00	0.25	4E+09	5E+04	0.79
1.50	0.28	6E+09	5.50E+04	0.72
2.00	0.38	8E+09	7.6E+04	0.85
2.80	0.51	11E+09	1E+05	0.96

The importance of interlayer mixing is also demonstrated by the cooling of the upflow layer along the flow (Fig. 6d). In the absence of interlayer mixing, warming of the air by convective heat exchange with the cave walls and sediments would be expected to produce a monotonic increase in air temperature along the entire flow path (i.e. along downflow and up. The observed upflow cooling, therefore, provides direct evidence of heat exchange between the counter-flowing layers.

The largest temperature differences are observed between monitoring points T3 and T1 and between points T4 and T2, indicating that interlayer mixing is strongest in the entrance section of the passage, where the counterflow is initially established.

4.2 Thermal inertia and equilibration to steady state

As observed above in Figs. 4–6, when the external temperature rises above T_{sw} after a period of cold air intrusion the system equilibrates to a stable state with “almost” uniform temperature and negligible airflow; details are shown on Fig. 10.

During cold-air intrusion, the airflow cools the sediments and cave walls, producing a nonuniform spatial distribution of rock and sediment temperature. Floor temperatures are lower than ceiling temperatures and increase from the entrance toward the main and lower chambers. This disequilibrium drives the counterflow independently of the external temperature, as seen on Fig. 7, where airflow becomes uncorrelated with external

temperature, but remains a function of ΔT . The counterflow is sustained until the temperature field within the cave equilibrates.

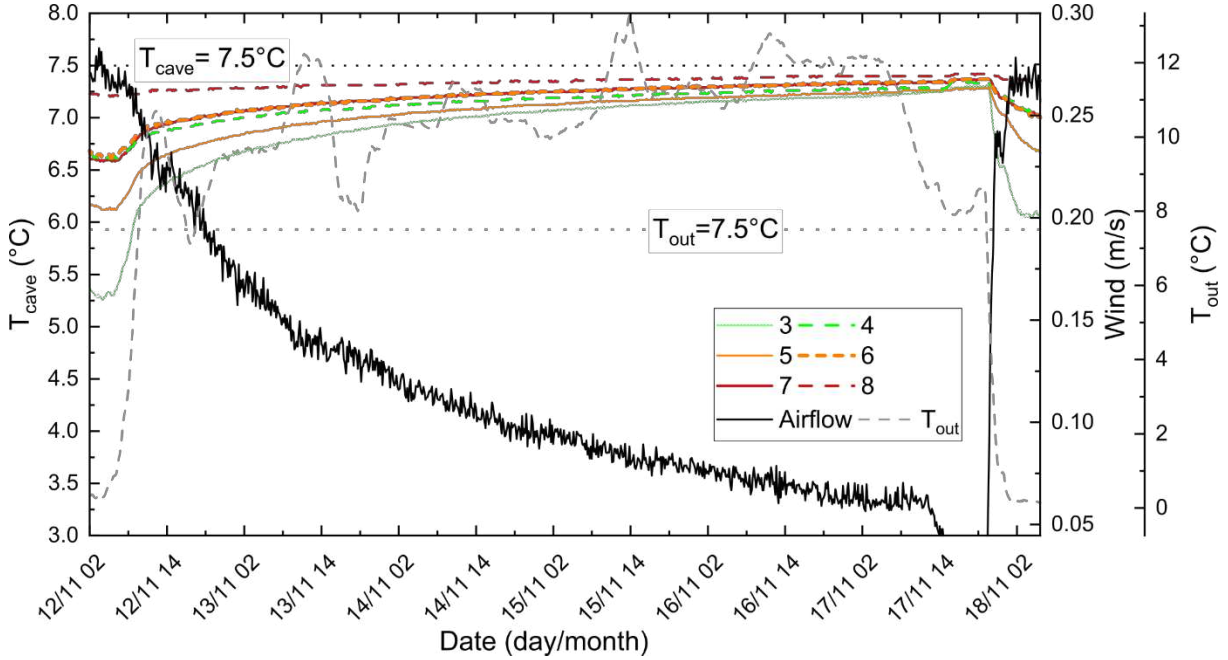


Fig. 10: Airflow speed, cave and external temperature during equilibration, when $T_{out} > 7.5^{\circ}\text{C}$.

4.3 On thermal length scale and seasonal evolution of airflow

Cooling of the sediment–rock layer surrounding the void has several consequences. As shown by Gabrovšek (2023), cooling of the walls promotes deeper penetration of cold air into the cave. In a simple situation with a straight tube connecting two entrances at different elevations, cooling of the walls reduces buoyancy because it allows cold air to penetrate deeper into the passage, thereby reducing the density contrast between the warmer cave air and the colder external air (Fig. 11a, case 1). In a V-shaped passage (Fig. 11a, case 2), which is a closer analogue to the present case, the situation is more complex. Here, buoyancy increases with penetration length because it depends on the thermal disequilibrium between the inflow and outflow limbs. As cold air penetrates deeper, this disequilibrium grows until a new equilibrium is established between airflow velocity, penetration length, and buoyancy forcing. Under counter-flow conditions (Fig. 11a, case 3), additional complications arise from heat exchange between and within the counterflowing air masses. The magnitude of this exchange depends on the flow regime and on the thickness of the mixing layer separating the two flows.

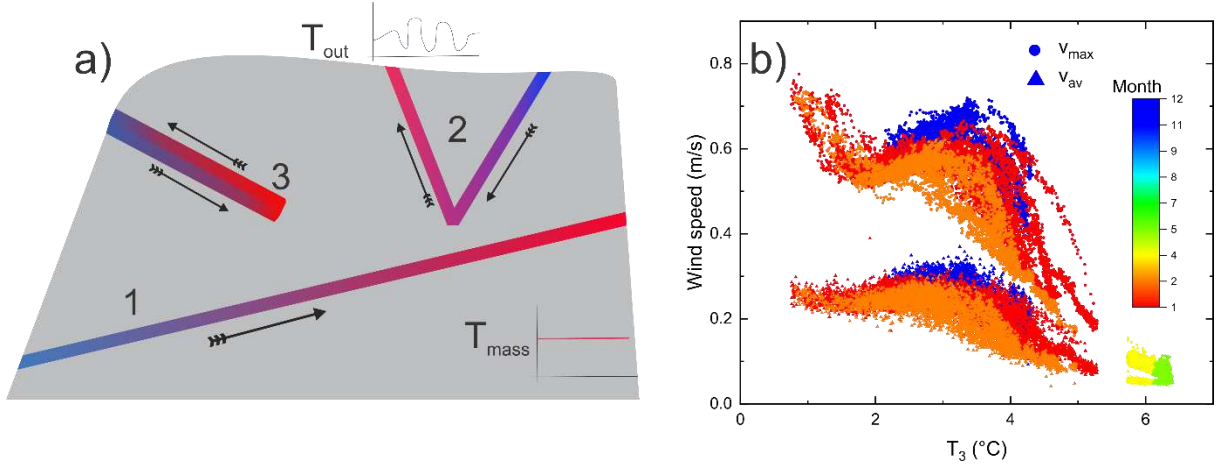


Fig. 11: (a) Conceptual comparison of winter ventilation in (1) a straight passage connecting entrances at different elevations, (2) a V-shaped passage, and (3) a single-entrance cave with counterflow. (b) Airflow velocity (10 min average (triangles) and 10 min maximum (circless) as a function of near-floor temperature T_3 during the 2021/2022 season. Circles denote maximum and triangles average wind speed within 10 min intervals. Colors indicate the month of the year.

To illustrate the seasonal evolution of the airflow, Fig. 11b shows the relationship between the near-floor temperature (T_3) and wind speed. During the latter part of the cold season (February-March; Fig. 11b, orange), the same near-floor temperature is attained at lower airflow velocities than earlier in the season (December; Fig. 11b, blue). This indicates that, as the surrounding rock cools over the winter, the incoming cold air is warmed less efficiently along its flow path, allowing it to penetrate farther into the cave.

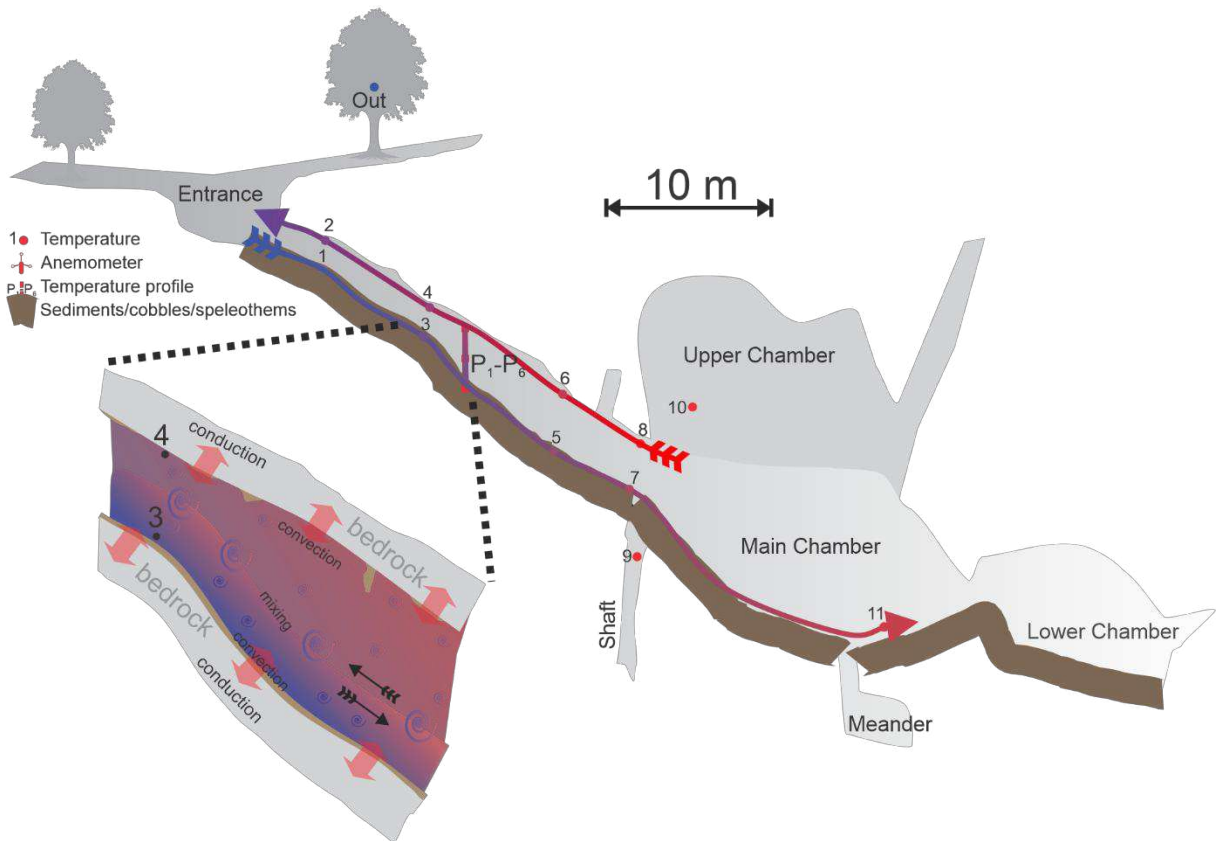


Fig. 12 Extended cross-section of Koševka Cave with colors showing a qualitative temperature profile along the airflow. Arrows indicate airflow direction; temperature is presented on a blue–red colour scale. Excerpt shows a section of the main passage with (qualitative) temperature distribution and heat exchange mechanisms.

5 Conclusions

We present and discuss results from a relatively simple cave, where buoyancy drives a two-layered flow along an inclined passage. Within the cave, the density field evolves continuously owing to heat exchange between the air and the surrounding rock and sediments. Consequently, the airflow, heat transfer, and buoyancy become dynamically coupled. The results also indicate heat exchange between the upflowing and downflowing air layers, as well as within each layer. The processes are summarized in Figure 12.

The measured relationship between buoyancy proxies and airflow velocity exhibits a sigmoid behaviour. When the external temperature rises above the switch temperature—

the temperature at which the external air is approximately in thermal equilibrium with the cave massif—cave temperatures are no longer directly influenced by external conditions. However, owing to the thermal inertia of the surrounding rock and sediments, the temperature disequilibrium between the floor and ceiling continues to drive airflow until thermal equilibrium within the cave is reached.

Estimated Grashof, Rayleigh, Reynolds, and internal Froude numbers indicate that cave ventilation represents a high-Reynolds-number, buoyancy-driven turbulent exchange flow operating close to internal hydraulic criticality. This framework provides a physically consistent interpretation of the observed counterflow, enhanced turbulent mixing within the interfacial shear layer, and the non-linear dependence of airflow velocity on buoyancy. The broad velocity plateau may indicate a regime approaching hydraulic control, with the critical section potentially migrating through the irregular cave geometry as buoyancy forcing increases.

In this work, we limit ourselves to a qualitative description of the observations and highlight the underlying physical mechanisms. Nevertheless, the results demonstrate the richness of processes that can arise even in a relatively simple geometry. They also illustrate how thermal inertia, buoyancy, and turbulent mixing interact to govern natural ventilation in confined subsurface environments.

Several open questions remain and require more detailed investigation. The flow structure across individual cave cross-sections could be examined using laser-sheet visualization and particle image velocimetry. Additional temperature measurements within the surrounding rock and cave sediments would improve understanding of the thermal coupling between the different media. Ultimately, the goal is to develop a quantitative model capable of reproducing the observed flow and heat-transfer dynamics.

Although this study focuses on a single cave, similar ventilation patterns are observed in many karst systems but remain poorly documented and only partly understood. More broadly, the results demonstrate that caves provide unique natural laboratories for studying the interaction between buoyancy-driven flow, turbulent mixing, and heat transport in confined environments. We hope that the observations presented here will stimulate further

field, experimental, and modelling studies and contribute to a more general understanding of natural ventilation and subsurface climate dynamics.

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