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Caves as observatories for atmospheric thermal tides: an example from Ascunsă Cave, Romania

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Abstract: As part of a microclimate study at Ascunsă Cave, Romania, we used Gemini Tinytag Plus 2 data loggers to record cave air temperature variability. At one of the monitoring points we recognized the presence of semidiurnal cycles on the order of a few thousands of a degree Celsius that could be produced under the influence of the semidiurnal tidal components of the Sun (S_2) or the Moon (M_2). Using a Gemini Tinytag Plus 2 data logger with an external probe we measured core rock temperature and showed that it does not influence the cave air temperature on such short time scales. We thus rejected the possibility that Earth tides, mostly produced by the lunar tidal influence on the Earth's crust, would have had a semidiurnal influence on cave air temperature. Moreover, time series analysis revealed a 12.00-hour periodicity in temperature data, specific for the S_2, allowing us to assign these variations to the influence of the thermo-tidal action of the Sun. Using the Ideal Gas Law and assuming a constant volume and amount of air, we calculated that a theoretical change in atmospheric pressure of around 40 Pa was needed to produce the temperature changes we observed. This agrees with published values of atmospheric pressure changes induced by the semidiurnal solar component of the thermal tides ($S_{2(t)}$). We thus can assign the observed temperature changes to semidiurnal atmospheric pressure changes ($S_{2(p)}$) induced by the thermal excitation of the Sun. Our study signals the possibility that readily available data from cave monitoring studies around the world could be used in the study of atmospheric tides. Moreover, it appears that Ascunsă Cave acts as a natural meteorological filter on a short time scale, removing the direct thermal influences of the Sun (especially night and day differences) and preserving only the barometric information from the surface.

Keywords: cave atmosphere, thermal tide, semidiurnal, $S_{2(t)}$, Romania

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As part of a complex monitoring study aimed at understanding how climate signals are transferred through the karst system at Ascunsă Cave, Romania, we recorded cave air temperature at 10 minutes intervals at different points along the main passage of this cave (Drăguşin et al., 2017). For this, we used Gemini Tinytag Plus 2 loggers which, according to the product data sheet, have a reading resolution of 0.01°C or better and an accuracy of about 0.5°C at 7°C (Gemini Data Loggers, 2014). The cave is located at about 1,000 m elevation at 45°00'N / 22°36'E.

At one of the monitoring sites, POM A, we observed semidiurnal cycles in the temperature data, with minima both in the late morning and in the evening, while maxima were observed during the afternoon and in the early morning. The amplitudes are small, around 0.005°C or less, and are superimposed on larger scale variations. When consulted, the manufacturer of the logger, Gemini Data Loggers Ltd., suggested that such variability could be produced by processes pertaining to the electronic components, but did not rule out environmental influences (Blewett, pers. comm.).

These small temperature differences are not explainable by diurnal thermal changes of the surface and/or cave ventilation processes that could be based solely on the radiative forcing of the Sun. Such forcings

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are documented in well ventilated caves, usually at shallow depths. At Ascunsă Cave, we recorded large diurnal variability only at the POM Entrance site, where the proximity to the cave entrance permits exchanges between cave air and outside atmosphere (Drăguşin et al., 2017).

Knowing that there are semi-diurnal periodicities in Earth and atmospheric tides, we expected one of the tidal components to be behind the observed small temperature variations. Earth tides are natural phenomena caused by the combined gravitational action of the Moon and the Sun (Melchior, 1983). Except at the poles, the daily rotation of the Earth on its axis and the relative positions of the Moon and the Sun give two high tides (tidal bulges) per day at any given point on the planet (Baker, 1984).

The most important semidiurnal tidal components are the lunar one (M_2) with a periodicity of 12 h 25 min 14 sec, and the solar one (S_2) with a periodicity of 12 h 0 min 0 sec. Each constituent has a variable amplitude of the vertical and horizontal tidal displacement as a function of latitude.

The effects of Earth or atmospheric tides on cave environments is less studied. A significant influence regarding fluid flow in karst systems was reported by Maucha & Sárváry (1970), Williams (1977), and Bayari & Ozyurt (2014), while Van Ruymbeke et al. (2004) demonstrated that in an underground environment variations in rock temperature are closely influenced by the M_2 tidal component.

While the Sun's influence on the atmosphere has both a tidal and a thermotidal dimension (Chapman & Lindzen, 1969), the thermal component is dominant. These oscillations are excited in different ways, including the absorption of solar radiation (mostly by water vapor and ozone), while the restoring force acting on the tides is Earth's gravity (Oberheide et al., 2015). The thermal excitation mechanism leads to changes in temperature, density, and pressure.

A question rises about the possible influence of lunar tides on cave air, via rock temperature. To assess this relationship, we installed in March 2017 another Gemini Tinytag Plus 2 data-logger with an external PB-5001 temperature probe that was buried inside the limestone cave wall. The PB-5001 probe has a diameter of 6 mm and a length of 150 mm. For the installation, we drilled a 6 mm diameter hole to accommodate the probe and we enlarged it towards the exterior in order to house the handle too. The free space left around the handle was filled with cement. In this way, the probe is in direct contact with the rock over its entire surface and is isolated from interacting with the cave atmosphere.

Between early March and late April 2017, core rock temperature rose from 7.035 to 7.052°C (Fig. 1). Cave air temperature followed this variability and rose by 0.035°C, from 6.990 to 7.025°C. Higher rock temperature suggests that cave air values are controlled to some extent by those of the surrounding rock. Further study could clarify the relationship between cave air, rock and outside temperature, but most important for our present study is that we did not distinguish in the rock temperature data the same semi-diurnal variability as seen in cave air. Thus, we can state at the moment that the surrounding rock might control air temperature on monthly timescales, but not semi-diurnal ones. Hence, the influence of lunar tides on cave air temperature is insignificant and neglected for the moment.

If cave air temperature is not influenced by the surrounding rock or by air advection from the outside, we could consider a possible control by surface air pressure changes, under the Sun's influence. By regarding the cave as a closed volume, we can use the ideal gas law to calculate what pressure change is needed for the observed temperature shifts. The equation describing this law is written as

$$PV = nRT \qquad (1)$$

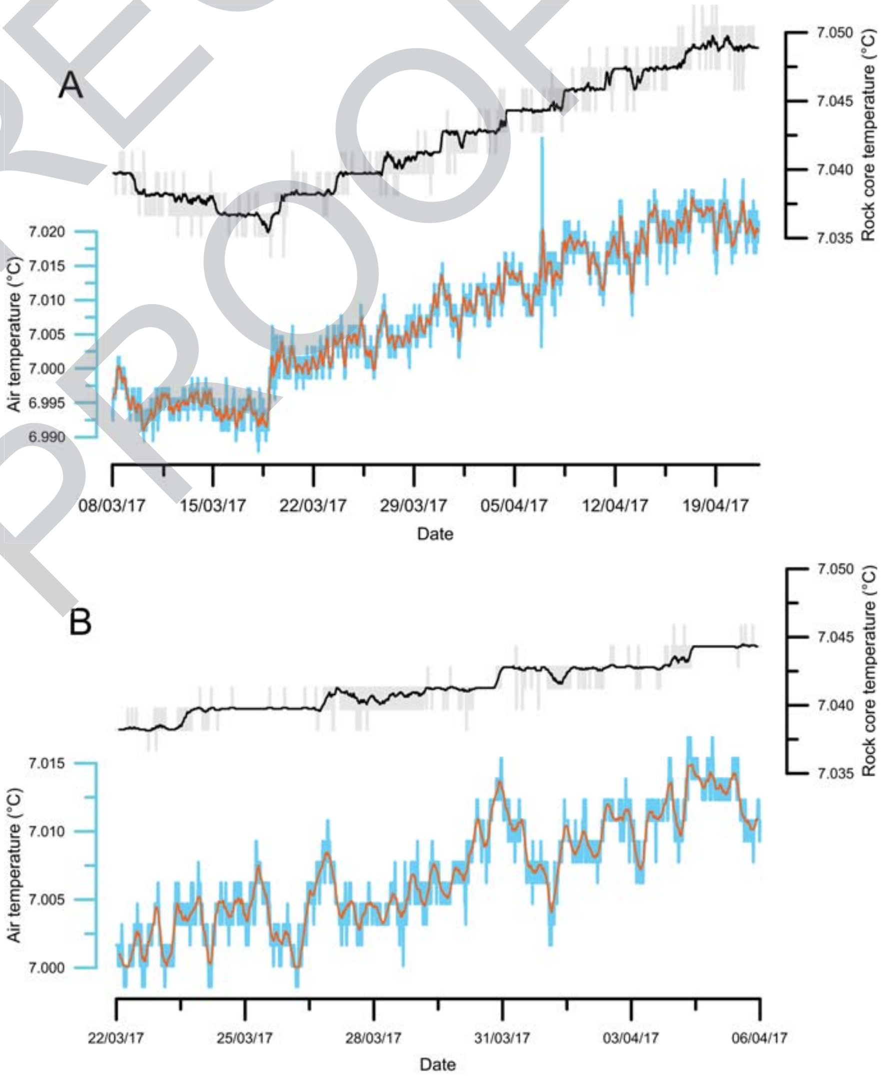

Fig. 1. Comparison between cave air (blue) and core rock temperature (gray). The running average, calculated using a three hour window, is shown for each dataset. A) Variability over the studied period; B) Detailed view of a 9 day period.

where P is the air pressure expressed in kilopascals (kPa) , V is the volume in liters (L), n is the amount of substance of gas in moles (mol), R is the ideal gas constant (8.314 kPa L mol^{-1} K^{-1}) and T is the absolute temperature of the gas in Kelvin (K).

We take as example a change in temperature observed on 22nd April 2016, from 7.035°C at 15:00 to 7.040°C at 21:00. If we consider the volume (L) and amount of air (mol) to be constant, the initial air pressure at 15:00 can be calculated as

$$P_0V = nT_0R \qquad (2)$$

where P_0 and T_0 represent the air pressure and the temperature at 15:00. Further, the air pressure at 21:00, P_1, is calculated as:

$$P_1V = nT_1R \qquad (3)$$

where T_1 is the temperature at 21:00.

Solving equations (2) and (3) shows that the 0.005°C temperature rise can be explained by a rise in atmospheric pressure of 40 Pa. Similar values for the amplitude of the $S_{2(p)}$ are given for our latitude by Chapman & Westfold (1956), Dai and Wang (1999) or Schindelegger and Ray (2014).

Surface pressure data from the Drobeta Turnu Severin meteorological station, situated 40 km to the south at 77 m asl, can be used for a direct comparison between cave air temperature and surface air pressure variability on semidiurnal scales. For our analysis, we used hourly surface pressure data available at NOAA-NCDC (2017).

For a comparison between the cave and the meteo station, we reconstructed air pressure variability for two random periods during June and July 2015. First, we translated the Drobeta pressure data to local time, from UTC to UTC+2. Then we calculated the temperature change from 03:00 to 09:00, 09:00 to 15:00, 15:00 to 21:00, and finally 21:00 to 03:00 of the next day. Using the ideal gas law, we transformed the temperature variation into theoretical pressure values (Fig. 2). Further, we calculated the surface pressure differences at Drobeta for the same 3-hour intervals. From the graphical representation in Figure 2 we can already see a similar variability of the two datasets, with the best fit at 15:00, the time of day with the greatest thermal excitation. We also note that the six hour variability is better expressed at Ascunsă Cave, which appears to act as a natural meteorological filter on a short time scale, removing the direct thermal influences of the Sun (especially night and day differences) and preserving only the barometric information from the surface. Further study should detail why the amplitude of S_2 is much smaller inside the cave whereas S_1 is completely filtered-out.

A semi-diurnal component of temperature variability can be better identified using spectral analysis and we chose to employ two independent methods for the period June-July 2015. The period was chosen thanks to its lack of major temperature fluctuations (Drăguşin et al., 2017), thus making the detrend step easier and more reliable.

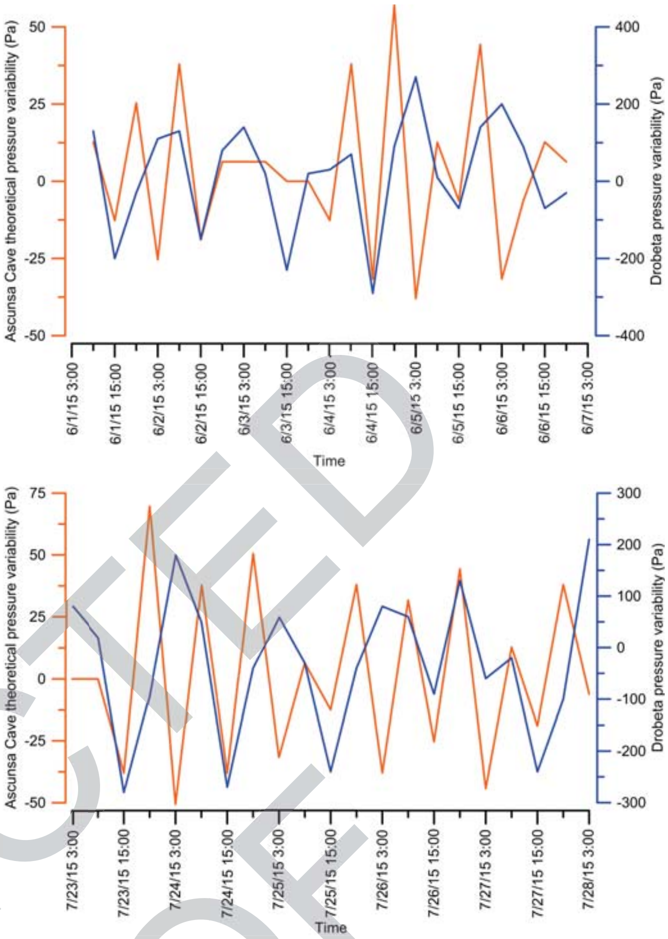

Fig. 2. Comparison between three hour surface air pressure variability at Drobeta meteorological station (blue) and theoretical air pressure variability inside Ascunsă Cave (orange).

Using Fourier analysis, between 01 June 2015 and 31 July 2015 we identified a 12 hour periodicity in cave air pressure variability (Fig. 3, left panel), while surface pressure clearly shows two periodicities of 12 and 24 hours (Fig. 3, right panel).

Further, we used the Morlet wavelet, which provides insight into the non-stationary nature of a time series and can identify localized and intermittent periodicities (Torrence & Compo, 1998). This shows

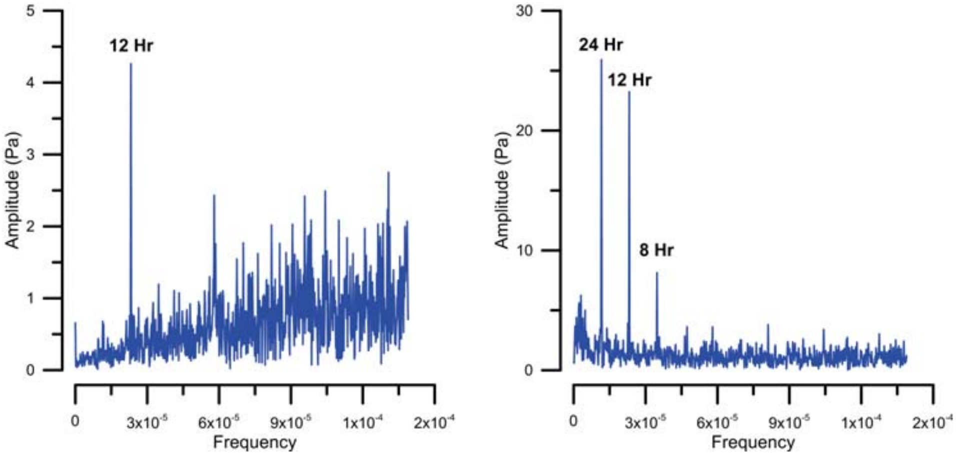

Fig. 3. Periodicities identified in the theoretical air pressure variability.

clear periodicities at 12 and 24 hours in surface air pressure at Drobeta, and a faint 12 hour signal at Ascunsă Cave (Fig. 4).

A possible phase lag between the two datasets was also investigated, analyzing each dataset separately, in reference to their starting time. We obtained a phase lag of 12 minutes for Drobeta and ~24 minutes for Ascunsă Cave. We note that we did not calculate the uncertainty related to these figures. The roughly 12 minute difference between the two sites is small and could be induced by data sampling or by differences in site conditions.

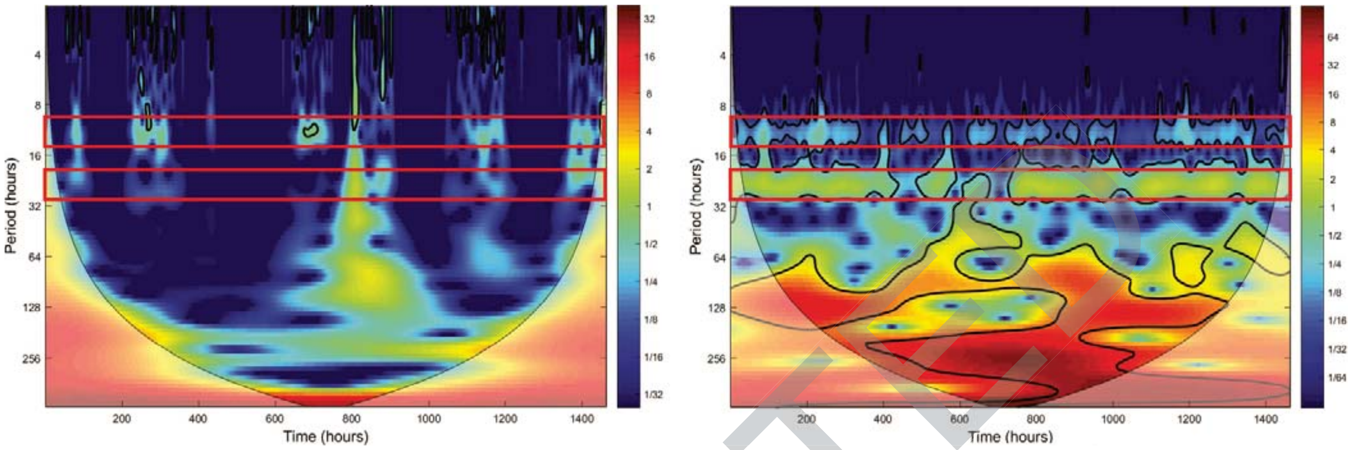

Fig. 4. Wavelet analysis of the theoretical air pressure variability at Ascunsă Cave (left panel) and air pressure variability at Drobeta meteorological station (right panel). Red quadrangles indicate the 12 and 24 hour periods.

Our present study shows how detailed temperature monitoring can help in the cost effective identification of stable underground sites for the placement of geophysical equipment that is sensitive to temperature or pressure. Moreover, as Schindelegger & Ray (2014) show that global numerical models do not reproduce very well the local variations in pressure due to atmosphere tides, an approach such as the one presented here can help in the monitoring of atmospheric tides at local/regional levels, especially thanks to the fact that caves can occur in regions and altitudes that lack direct observations from meteorological stations.

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