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# REVISITING ATMOSPHERIC THERMAL TIDES IN THE 'COSTANTINO DORIA' CAVE (N. 3875 V.G.), TRIESTE: INSIGHTS FROM OLD AND NEW DATA

## RIASSUNTO

*Dal 2 settembre 2023 al 27 giugno 2025, all'interno della grotta "Costantino Doria", situata sul Carso triestino, sono state raccolte serie temporali di temperatura dell'aria e pressione atmosferica mediante uno strumento digitale programmabile, proseguendo le precedenti attività di ricerca. L'elevata frequenza di campionamento (intervallo di campionamento tra 2 e 20 secondi) ha permesso di osservare il comportamento delle grandezze indagate su scala minutale, evidenziando pattern ben definiti con periodicità variabili secondo la stagione. Per la prima volta dall'inizio del monitoraggio, è stato registrato nel segnale di temperatura il periodo di passaggio da un regime prevalentemente diurno (periodo invernale) a uno semidiurno (periodo estivo). È inoltre proposto un modello idraulico euristico per interpretare la dinamica degli scambi termici tra l'aria della cavità e le pareti rocciose, e spiegare l'anticipo di fase del segnale termico rispetto alla pressione. Infine, è stata condotta un'analisi retrospettiva dei dati di pressione atmosferica di fine estate 2020 registrati nella cavità, ipotizzando che le oscillazioni osservate siano riconducibili agli effetti di onde di Rossby.*

## ABSTRACT

*Between September 2nd, 2023, and June 27th, 2025, time series of air temperature and atmospheric pressure were collected inside the "Costantino Doria" cave, located in the Trieste Karst, continuing previous research efforts. The high sampling frequency (sampling interval ranging from 2 to 20 seconds) enabled minute-scale observation of the measured variables, revealing well-defined patterns with seasonally dependent periodicities. For the first time since the beginning of the monitoring campaigns, the transitional phase between a predominantly diurnal regime (winter period) and a semidiurnal regime (summer period) was recorded in the air temperature signal. A hydraulic analogy is also proposed to interpret the dynamics of thermal exchanges between cave air and rock walls, offering an explanation for the observed phase lead of the thermal signal relative to pressure. Finally, a retrospective analysis of atmospheric pressure data from late summer 2020 was conducted, suggesting that the observed oscillations may be attributable to the effects of Rossby waves.*

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## INTRODUCTION

The study presented in this paper builds upon a long-standing tradition of meteorological investigations conducted in the “Costantino Doria” cave (N. 3875 V.G.), a karstic cavity near Trieste, Italy (Fig. 1). Specifically, this work represents a further step in understanding the effects of atmospheric thermal tides on the cave’s air temperature and the physical processes involved. Previous research campaigns have already identified extremely subtle thermal oscillations, presumably linked to atmospheric thermal tides (Bussani, 2005; Bussani, 2007; Bussani, 2022), but some questions remain open—particularly concerning the mechanisms underlying the observed phase lag between air temperature and atmospheric pressure signals. For a detailed overview of the site and its historical background, the reader is referred to the introductory section of the paper by Bussani (2022). Here, we focus on newly acquired data (from September 2023 through June 2025) that shed further light on the behaviour of thermal tides in the cave environment at different time scales (i.e., daily and seasonal). Moreover, a thermodynamic interpretation of heat exchanges is provided, based on a hydraulic analogy. Finally, a brief report about the possible detection of Rossby waves in previously recorded data (August-September 2020) is given.

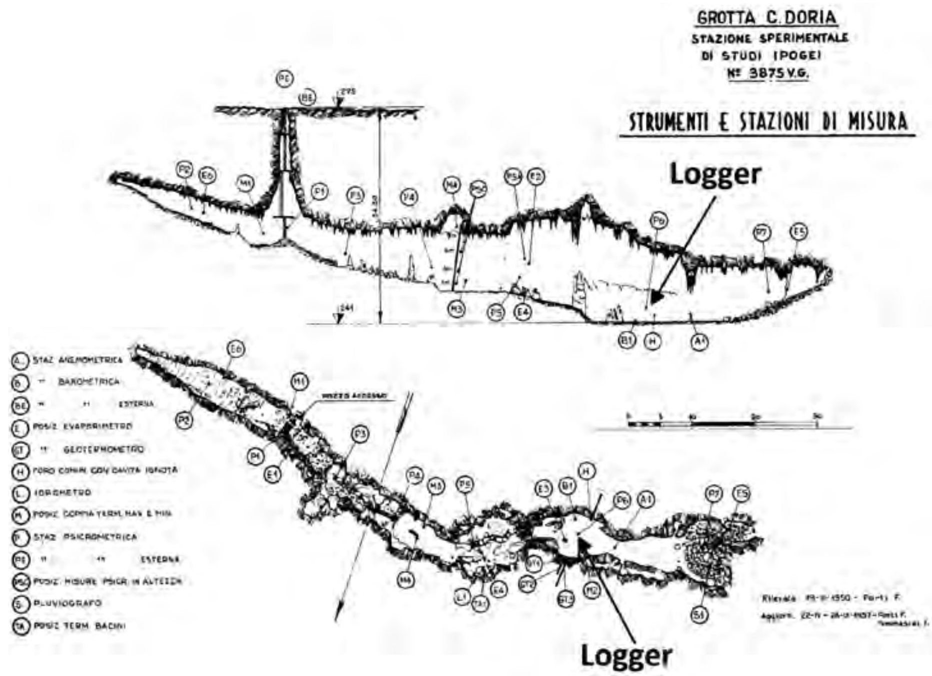

Figure 1 - Logger position in the cave (adapted from Polli, 1969).

## INSTRUMENTATION, DATA COLLECTION AND STATISTICAL ANALYSIS

The data about air temperature and atmospheric pressure of “Costantino Doria” cave were collected by means of a Driesen und Kern Plog 520 programmable data logger (serial number: 521005522). The technical specifications of the instrument are given in Tab. 1 (Bussani, 2007).

| | |
|---|---|
| Length | 200 mm |
| Diameter | 23 mm |
| Memory | 500000 measurements |
| Pressure accuracy | 20 Pa |
| Pressure resolution | 15 Pa |
| Temperature accuracy | 0.1 °C |
| Temperature resolution | 0.003 °C |

Table 1 - Technical specifications of the Driesen und Kern Plog 520 programmable data logger (from Bussani, 2007).

The recordings started on September 2nd, 2023, and ended on June 27th, 2025. The sampling interval ranged from 2 s up 20 s, though for most times it was set to 5 s (see Tab. 2).

| **Data segment** | **Data collection** | **Sampling interval (s)** |
|---|---|---|
| 1 | s: 02/09/2023 19:03  e: 30/09/2023 17:52 | 5 |
| 2 | s: 01/10/2023 04:41  e: 29/10/2023 09:13 | 5 |
| 3 | s: 30/10/2023 00:00  e: 25/11/2023 13:33 | 5 |
| 4 | s: 26/11/2023 00:00  e: 23/12/2023 10:41 | 5 |
| 5 | s: 24/12/2023 00:00  e: 21/01/2024 01:31 | 5 |
| 6 | s: 23/01/2024 00:00  e: 18/02/2024 12:35 | 5 |
| 7 | s: 19/02/2024 00:00  e: 18/03/2024 02:48 | 5 |
| 8 | s: 25/03/2024 00:00  e: 05/04/2024 00:25 | 2 |
| 9 | s: 29/04/2024 00:00  e: 27/05/2024 02:00 | 5 |
| 10 | s: 03/06/2024 04:00  e: 01/07/2024 07:29 | 5 |
| 11 | s: 05/07/2024 05:00  e: 28/07/2024 09:52 | 5 |
| 12 | s: 29/07/2024 00:00  e: 24/08/2024 15:27 | 5 |
| 13 | s: 29/08/2024 00:00  e: 26/09/2024 08:07 | 5 |
| 14 | s: 06/10/2024 00:00  e: 03/11/2024 02:37 | 5 |
| 15 | s: 06/11/2024 00:00  e: 01/12/2024 13:18 | 5 |
| 16 | s: 05/12/2024 13:01  e: 15/03/2025 14:43 | 20 |
| 17 | s: 16/03/2025 18:01  e: 27/06/2025 08:46 | 20 |

Table 2 - Air temperature and atmospheric pressure data segments: “s” and “e” stand for measuring start time and end time, respectively; times are given in the dd/mm/yyyy hh:mm format; “sampling interval” is the time elapsed between two consecutive measurements in the raw data (i.e., before computing the minute-average).

The high sampling frequency was aimed at reducing statistical uncertainties associated with the low signal-to-noise ratio, given the thermal tide's small amplitude (approximately 2–3 m°C). The logger was periodically retrieved to download the data (the dataset collected between two retrievals is referred to as a "data segment"); after the download procedure, the logger was again deployed in the same place. The whole procedure usually took one day up to ten days. In April 2024 a misconfiguration of the logger sampling time - mistakenly set to 2 seconds instead of 5 s - led to the memory saturation approximately three weeks earlier than expected, resulting in the failure to record measurements during those weeks. Each data segment underwent an initial cleaning based on visual inspection aimed at removing measurements taken when—following the deployment of the instrument—the temperature of the logger and/or the cave had not yet stabilized. Additionally, measurements recorded when occasional spelunkers entered the cave – clearly evident as a spike in the temperature signal – as well as those captured immediately after retrieval and before data download, were excluded. The cleaned data were then averaged over one-minute intervals.

To improve the clarity of the semidiurnal patterns plotted in Fig. 5, minute-averaged temperature measurements were grouped into 5-minute intervals. This temporal aggregation was performed to reduce sensor noise and highlight broader trends.

Moreover, to analyze the average daily cycle of temperature and pressure residuals inside "Costantino Doria" cave (Fig. 6), we extracted data recorded between May 1st and October 31st, 2024—corresponding to the period with the maximum vertical stability of the air column and, consequently, when changes in the air temperature are at their minimum (Bussani, 2022). The minute-averaged measurements were first grouped into 5-minute intervals to reduce short-term noise. Then, an exponential moving average (EMA) filter with a smoothing parameter $\alpha = 0.01$ was applied to both temperature and pressure datasets to remove long-term variations. The EMA was computed recursively using the formula:

$$\mathrm{EMA}_n = \alpha \cdot x_n + (1-\alpha) \cdot \mathrm{EMA}_{n-1}$$

where $x_n$ is the current measurement and $\mathrm{EMA}_{n-1}$ is the previous filtered value. The first EMA value was initialized to the first 5-minute average to allow recursive filtering. The value \alpha = 0.01 was specifically chosen to ensure a very slow response of the filter, effectively capturing only long-term trends while preserving daily-scale fluctuations such as the diurnal cycle. Residuals, obtained by subtracting the EMA-filtered signals from the raw 5-minute averaged data, were then averaged according to the time of day to extract the mean diurnal cycle. Finally, a circular 10-minute smoothing window was applied to suppress residual high-frequency fluctuations and improve interpretability, while preserving the daily periodic pattern. Each smoothing step was introduced with a specific purpose: the minute and 5-minute averages helped reduce sensor noise and random spikes; the EMA removed long-term trends; and the 10-minute filter refined the residual signal without distorting its natural rhythm.

## RESULTS

1. Air temperature and atmospheric pressure descriptive time series analysis

   During the two-year monitoring period, temperature recordings inside the cave (Fig. 2) displayed a clear seasonal pattern. The warm season, extending roughly from April to October, was characterized by remarkable thermal stability of the cave air, with daily fluctuations limited to just a few hundredths of a degree. This period exhibited a progressive warming trend—initially rapid in spring, then gradually leveling off through summer and early autumn.

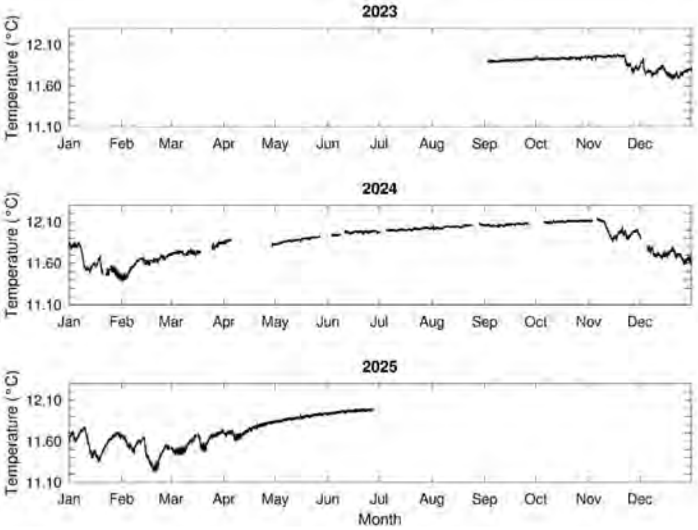


Figure 2 - Air temperature in the "Costantino Doria" Cave, September 2023 – June 2025.

The onset of the cold season was abrupt and typically occurred in November, marked by the intrusion of denser outside air and the subsequent breakdown of vertical thermal stratification. This transition introduced increased thermal variability, which manifested in two distinct phases: a pronounced cooling period from November to February, resulting in a temperature drop of approximately 0.6–1 °C; and a short transitional warming phase between February and April, still marked by significant fluctuations. With the return of spring, the air column progressively regained vertical stability, which then persisted through the following warm season. These observations are consistent with previous findings reported by Bussani (2022).

In addition to air temperature, atmospheric pressure was monitored as well (Fig. 3) in

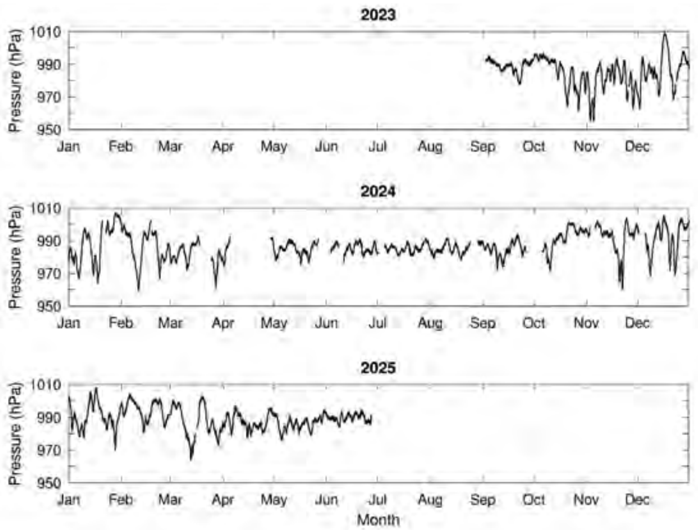


Figure 3 - Atmospheric pressure in the "Costantino Doria" Cave, September 2023 – June 2025.

order to assess the presence of seasonal trends or distinctive features. The pressure time series revealed a clear alternation between two regimes: from April to October, pressure variations inside the cave were markedly smaller whereas from November to March the signal exhibited pronounced and frequent fluctuations. This seasonal pattern mirrors the dynamics of external atmospheric pressure, suggesting a strong coupling between the cave interior and the outside meteorological conditions. Unlike temperature, however, no additional pressure-specific patterns were observed within the cave environment.

2. Daily cycle of air temperature in particular winter conditions

Fig. 4 illustrates the temporal evolution of cave air temperature across three distinct periods: late January to early February 2024, early March 2025, and April 2025. Within each panel, specific intervals stand out for the clarity of their thermal signal: namely, the final days of January and the beginning of February 2024, the first ten days of March 2025, and the first ten days of April 2025. These time intervals are characterized by a pronounced diurnal temperature cycle, with daily amplitudes ranging from approximately 0.05 °C to just under 0.1 °C. The signal is notably regular and well-defined, distinguishing itself from surrounding days where the thermal pattern appears less coherent.

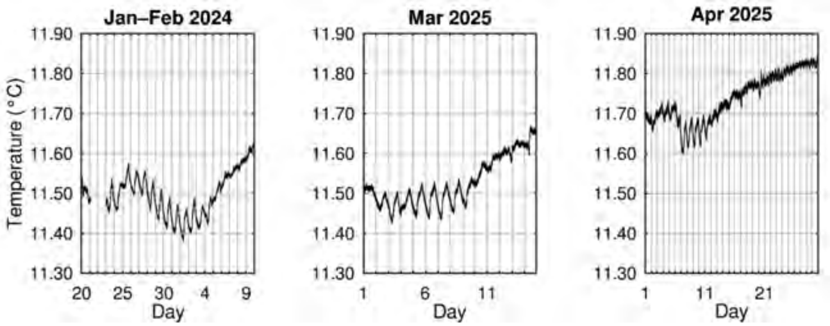


Figure 4 - Evidence of pronounced diurnal patterns in the air temperature signal from the "Costantino Doria" Cave, observed over consecutive days spanning three distinct time periods.

Meteorological data from OSMER (Osservatorio Meteorologico Regionale, station at Trieste – Molo Fratelli Bandiera) indicate that these well-defined diurnal cycles correspond to days with high solar irradiance, associated with clear or nearly cloudless skies. This correlation is further supported by the timing of the temperature extrema within the cave: minimum values typically occur near sunrise, while maximum values coincide roughly with sunset. Interestingly, these days did not exhibit significant increases in external air temperature, and wind conditions were generally weak to moderate, with the sole exception of April 6, 2025, which was marked by strong wind.

These observations suggest that the emergence of a distinct diurnal cycle within the cave is primarily driven by solar radiation under fair-weather conditions. While the mechanism appears consistent, further monitoring is required to better understand the processes governing the onset of such thermal response of the cave environment to external atmospheric forcing.

Additionally, Fig. 5 reveals a noteworthy transition, occurred in the last ten days of April 2025, from the diurnal cycle described in Fig. 4 to a semi-diurnal pattern in the temperature signal, associated with the establishment of a stable air column within the cave. Due to experimental issues, this transition had not been previously observed. It is particularly interesting to note how rapidly this shift takes place, suggesting that the transition between these two regimes may be critically sensitive to minimal variations in air temperature.

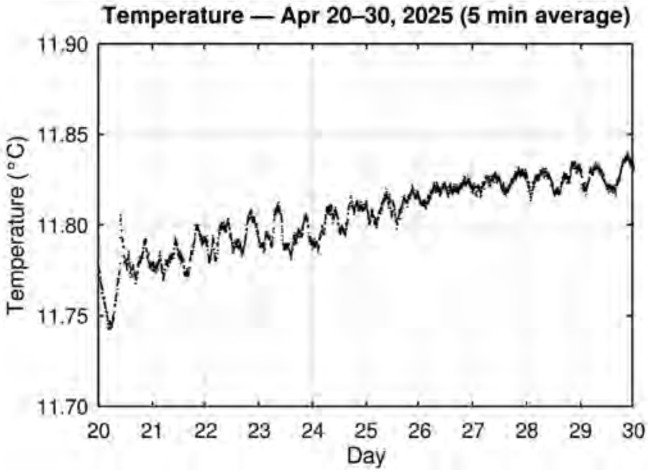


Figure 5 - Semidiurnal patterns in the air temperature signal from the “Costantino Doria” Cave, observed over consecutive days at the onset of the vertical stability of the air column.

3. Phase-lag between air temperature and atmospheric pressure in summer conditions

During the warm season—when the cave’s air column is vertically stratified and temperature fluctuations are minimal—a pronounced semidiurnal oscillation emerges in the smoothed temperature residuals, with an amplitude of approximately 2–3 m°C (Fig. 6).

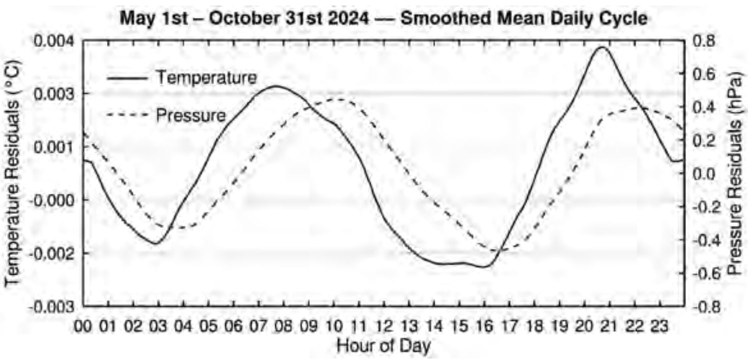


Figure 6 - Phase-lag between air temperature and atmospheric pressure (smoothed mean daily cycles) in the “Costantino Doria” cave when air column is vertically stable (warm season).

The second trough is noticeably broader and flatter, whereas the second peak attains a higher, more sharply defined maximum. The pressure residuals exhibit a parallel semidiurnal cycle of amplitude slightly under 1 hPa, reflecting alternations of compression and expansion in the cave air driven by atmospheric thermal tides. A clear phase lag is evident between the two series: pressure consistently lags temperature by about one hour in the pre-dawn hours, increasing to approximately up to two hours later. These timing offsets corroborate the findings of Bussani (2022). A qualitative discussion of the mechanisms behind this phase delay is presented in Section 4 of the "Results" chapter. However, such mean diurnal cycle breaks down during the cold season, when the air column becomes unstable and temperature fluctuations become considerably larger. Under these conditions, the temperature signal can no longer resolve patterns on the order of one thousandth of a degree.

4. Hydraulic analogy to explain heat transfer processes between cave atmosphere and cave rock walls

In order to provide a qualitative, heuristic explanation for the phase lag observed between the semidiurnal temperature and pressure residuals (see section 3 of "Results" chapter), we introduce a simple hydraulic analogue. In this model, two communicating vessels represent the cave air and the surrounding rock walls, respectively. The water volume in each vessel corresponds to either the internal energy (i.e., heat content) of air or rock, or the work done by atmospheric tides, while the water level represents temperature in either system (air or rock). A narrow conduit connecting the vessels models thermal conductivity, allowing energy to flow back and forth depending on the temperature gradient.
A sinusoidal pump is attached to the air vessel to represent the time-varying power delivered to the cave atmosphere by thermal atmospheric tides, via periodic compression and expansion. The pump modulates the flow rate sinusoidally, mimicking the periodic energy exchange due to atmospheric pressure variations. The pump's amplitude corresponds to the strength of the tidal forcing, and the conduit width reflects the thermal conductivity of the rock. The vessel volumes are proportional to the respective heat capacities of air and rock. As the pump approaches its lowest (but still positive) flow rate—meaning it is still adding fluid, but at a decreasing rate—the head difference between the two vessels causes the conductive flux into the rock to exceed the pump's input. As a result, the water level (i.e., air temperature) in the air vessel begins to decline, even though the pump is still supplying fluid.
Translated back into thermodynamic terms, this moment corresponds to a phase in which the developing temperature gradient between cave air and rock walls drives conductive heat loss at a rate that temporarily exceeds the instantaneous power input from atmospheric tidal forcing. In other words, the rock absorbs heat more rapidly than the atmosphere can supply it. Consequently, the air temperature begins to fall before the pressure minimum is reached.

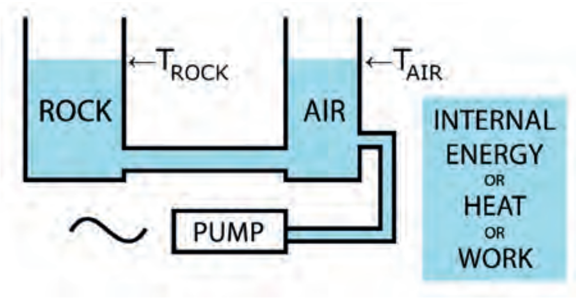


Figure 7 - Hydraulic analogy of heat exchanges between cave air and rock walls, based on the principle of communicating vessels.

This mechanism explains the observed phase lead of temperature relative to pressure. It reproduces the counterintuitive timing documented in the literature (Chen, 2003; Wu, 2003; Bussani, 2005; Bussani, 2007; Bussani, 2022) and in our latest measurements.

5. Possible observation of Rossby waves

To conclude the results section, we present a brief retrospective analysis of atmospheric pressure measurements collected during the previous research campaign (Bussani, 2022), which had not been thoroughly examined until now. Data recorded from late August through the end of September 2020 reveal a recurring pattern of fluctuations with a periodicity of approximately five days (Fig. 8). This regularity suggests the presence of a dynamic process influencing the local pressure field. Although such oscillations are not exclusive to cave environments and can also be observed in open-air measurements, their detection within the cave underscores the added value of continuous cave-based monitoring—not only for studying internal dynamics, but also for capturing broader atmospheric phenomena. The timing of these fluctuations closely matches the quasi-5-day Rossby mode (Salby, 1981), offering a plausible meteorological explanation for the pressure variations recorded inside the cave, although more data and a more refined analysis will be necessary to confirm this interpretation.

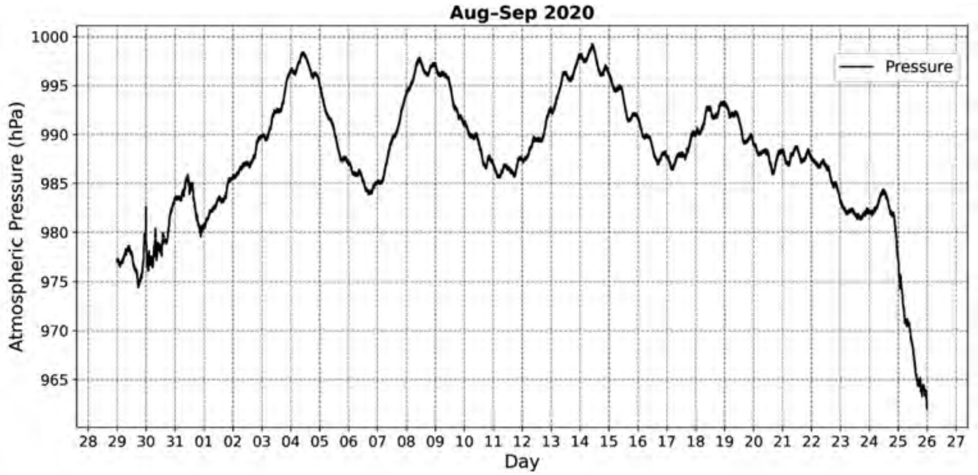


Figure 8 - Atmospheric pressure observed at the end of summer 2020 in the "Costantino Doria" cave.

## CONCLUSION

The two-year monitoring campaign has revealed a complex interplay between cave air temperature, atmospheric pressure, and external meteorological conditions. Seasonal transitions govern the thermal stability of the cave, with distinct regimes emerging during warm and cold periods. Diurnal and semidiurnal cycles—driven respectively by solar irradiance and atmospheric tides—manifest under specific conditions, with clear phase relationships and amplitude modulations. A hydraulic analogy offers a plausible explanation for the observed phase lag between temperature and pressure. Moreover, the detection of low-frequency pressure oscillations suggests that cave environments might serve as a sensitive observatory for broader atmospheric dynamics, including Rossby waves. These findings underscore the value of high-resolution cave monitoring for both microclimatic and atmospheric research. Further investigations will be essential to refine the mechanisms and expand the interpretative framework.

## ACKNOWLEDGMENTS

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