Author’s response to editor (May 29, 2024)

Mesoscale permeability variations estimated from natural airflows in the decorated Cosquer Cave (SE France)

EGUSPHERE-2023-2380

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Dear Pr. Gerrit de Rooij,

We appreciate the invitation to revise our manuscript based on the reviewers' comments.

Both reviewers highlighted the lack of explanation for the origin of the pressurization events despite the originality of the phenomenon. This, in turn, led to confusion regarding the presented conceptual model. To address the reviewers’ comments, we applied the corrections we had proposed in response to the reviewers at the end of the *HESS open discussion*.

Revisions made on the manuscript are explained in the following pages, split in two sections:

1. Major changes: This section details the significant revisions made to address the pressurization events, conceptual model, and equations.
2. Line-by-line responses to the reviewers’ comments and other improvements.

We believe these revisions effectively address the reviewers' concerns and significantly strengthen the manuscript. Following the reviewer’s advice, the manuscript was corrected by a native English-speaker. Reviewers’ comments are written in *italic*.

Changes are referenced by line number of the reviewed manuscript.

Yours sincerely,

Hugo Pellet

1. Major changes

1.1. Pressurization events and conceptual model

Both reviewers flagged a lack of clarity in our conceptual model of the Cosquer cave, particularly regarding the mechanism behind the pressurization events and air inflows. To address these concerns and enhance clarity, we made the following revisions to the paper:

l.63-66: we describe and stated the supposed mechanism in the introduction section:

"Cave air pressure increases by the inflow of outside air, during periods with high waves breaking on the cliff of the coastal limestone massif. Waves can produce and force air bubbles to flow along submarine open fissures or karst conduits inside the massif during short periods of time. Since the rock is not airtight, air slowly flows out through the limestone massif over several months."

l.100-105: A paragraph has been added detailing the connection between the cave and the sea through the shallow sumps:

"This pool is connected to the sea outside by karstic conduits that have not been fully surveyed for accessibility and safety reasons. However, the water level in the pool on the cave side varies with waves outside, which indicates that communication with the sea occurs at a shallow depth (Figure 2), and it is suspected that large waves can push air bubbles through the conduits. Expeditions in the cave are never scheduled during rough weather, which makes direct observation of this phenomenon nearly impossible. However, we will show that instrumental records display a strong correlation between episodes of high waves and air input into the cave."

l.126-128: waves data are presented:

"The significant height of waves in front of the cave is the result of simulations provided by the French Naval Hydrographic and Oceanographic Service (SHOM, 2024)."

l.141: the subsection *3.1 Seasonal pressure variations* is split into 2 subsections: 3.1 Overpressure in the Cosquer cave and 3.2 Seasonal variations.

l.141-164 (**3.1 Overpressure in the Cosquer cave**):

In this subsection, the mechanism behind the correlation between cave air pressure and water level is now clearly defined (**l.144-146**):

"Air pressure in the cave and water level of the pools are anti-correlated (Fig. 4A and Fig. 4B). When the air pressure increases, the air is confined by the walls of the cave and pushes down the water table to balance the overpressure."

We made a qualitative description of seasonal cave air pressure variations with emphasize on the pressurization events (**l.150-154**):

"A succession of pressure peaks occurs between October and May (highlighted in grey in Fig. 4) and these are generally absent in summer. These sharp rises in air pressure over tens of minutes to a few hours followed by a rapid pressure decay (over a day or so) are referred to in this paper as pressurization events and the shape of these events will be described in more detail in the following section. Between 20/10/2017 and 30/04/2018, about 30 of these pressurization events occurred. These events generate the cave overpressure by the inflow of outside air."

We now compare the pressurization events periods with daily rainfall (Fig. 4D) and waves significant height (Fig. 4E). This comparison makes it possible to reject the hypothesis of a pressure increase caused by air flushed into the fractures of the unsaturated zone during recharge events and shows a strong relationship with waves height in front of the cave (**l.154-159**):

"They occur systematically during periods with high waves in front of the coastal limestone massif (Fig. 4E). While storms are often associated with rainfall, periods with high rainfall but no high waves occasionally occur (e.g. August 2018, Fig. 4D) and they do not cause pressure variations in the cave (Fig. 4B). On the other hand, some pressurization events are not associated with heavy rainfall, but they are systematically associated with waves (Fig. 4E). Furthermore, the absence of significant wave activity during summer months supports the observation of rising water levels during this period."

We assume that air flows into the cave through shallow fractures and conduits and we propose a mechanism for air inflows through wave-generated bubbles (**l.159-164**):

"The current hypothesis is that breaking waves and waves crashing against the cliff can generate bubbles and then force seawater and air to flow through the limestone massif by shallow fissures and karst conduits (however, the detailed mechanism of how bubbles of air can flow inside submerged karst is outside the scope of this paper). Given the existence of karst pathways at several levels connecting the sea and the cave, air flows through shallow sumps and reaches the cave by upper conduits away from the decorated rooms, and not the lower conduit (human entrance) which is too deep to be the air intake point (-37 m)."

l.165-178 (**3.2 Seasonal variations**):

Quantitative description of seasonal variation of cave air pressure, water level in the cave and cave air and water temperature is made:

"As previously described, air overpressure in the cave decreases during summer. The summer depressurization rate was in average -0.21 cm_{sw} day^{-1} in 2017 and -0.32 cm_{sw} day^{-1} in 2018 (mean over July and August). Conversely, during pressurization events, net air pressure usually increases in the cave, i.e. the air pressure is usually higher after the event than before. Two thresholds are graphically identified in Fig. 4B: (i) maximum air pressure never exceeds 11.5 m_{sw} (1.16 hPa); (ii) immediately after pressurization peaks, the air pressure drops down to an overpressure level between 10.8 m_{sw} (1.09 hPa) and 10.7 m_{sw} (1.08 hPa). Below this level, the pressure decrease rate slows down considerably. The lowest water level is about 1.5 m_{sw} below the seawater level (0.40 m_{sw} above the probe, Fig. 4A) during winter. Thus, at a seasonal time scale, the pressure variation range (Fig. 4A) is around 1.5 m_{sw} (0.15 hPa). […]"

In section 6.2 Air renewal:

l.522: added "shallow submarine karst inception horizons and fractures" for clarity.

1.2. <u>Model and equations</u>

A major concern for both reviewers was about the equations used in the section 4:

l.294: *if you write this in form 1/(1-palTah/pahTaL), equation 6 and 7 would be more obvious:* Eq. (5) modified to match the expected form: $V_l = S_w \, \Delta h_w \frac{1}{1-\frac{P_{al}T_{ah}}{P_{ah}T_{al}}}$

l.314: *Where do you get Qn from. Is it from dn(t)/dt from Eq. 9 ?:*

equation added: "[…] $Q_n = \frac{dn(t)}{dt}$ is the molar flow rate (mol s^{-1}) […]"

l.322: Both reviewers asked about the factor 2 and the P^2 in Eq. (11)*:*

no modification was required in this equation but references (Lang, 1999 and Charbeneau, 2006) are added to support our statement.

l.338: *Refer to my comment to Eq. 11... I am not sure what approximations were used to derive this Equation:*

to pass from Eq. 11 to Eq. 13, no approximation is required.

l.338*: what drives the temperature variations in the cave air? Using a constant Trock is an approximation as we know there are seasonal fluctuations in both, the cave air and the outside atmosphere? what is their effect:*

First, we added the water temperature in the cave to Fig. 4C to show that water temperature in the cave drives the air temperature in the cave (l.174-178):

"Air temperature varies in the range 16°C to 21°C, in a seasonal pattern. The maximum is observed at the end of summer and the minimum at the beginning of spring (Fig. 4C). The air temperature variations are mainly driven by the water temperature variations. Water temperature variations are related to exchange with seawater outside the cave through conduits. Air temperature variations are smoother than water temperature variations, and delayed because of heat exchange with the cave walls, which have thermal inertia."

In the authors' answer to reviewer 1, we made the demonstration that temperature variation is negligeable in the result, but we doubt it is necessary to assess it in the manuscript as the corresponding uncertainty is much smaller that the uncertainty on the air flux measurement.

2. Line by line responses

[1] Following the reviewer's advice, the manuscript was corrected by a native English-speaker. These corrections are not detailed below but are visible in the track-change file.

Reviewer 1

[2] l.37: "2" replaced by "two".

[3] l.42: *underline that the stronger airflow in winter is valid for a descending conduit. In ascending conduits, this would likely happen in summer*:

Modified sentence: "These flows are subject to seasonality, with generally stronger flows in winter and stratification of air masses in summer for descending conduits and conversely for ascending conduits".

[4] l.63-65: *please state the supposed mechanism driving this airflow. Obviously, this wouldn't happen without an external force if the cave is over-pressured*:

the supposed mechanism is stated: "Cave air pressure increases by the inflow of outside air, during periods with high waves breaking on the cliff of the coastal limestone massif. Waves can produce and force air bubbles to flow along submarine open fissures or karst conduits inside the massif during short periods of time."

[5] l.58: added: "(southeastern France)".

[6] l.81: space between numbers removed: "32500" and "19000".

[7] l.86: corrected sentence: "The sea was lower back then".

[8] l.86-87: space between numbers removed: "20000" and "8000".

[9] l.91: *Cretaceous should be capitalized*: corrected.

[10] l.92: *"thin sections observations" delete observations*: deleted.

[11] l.123-125: *However, no information is given about how the elevation of the water table inside the cave was determined. Is there an altimetric survey available?:*

added: "[…] pressure sensors of air inside and outside the cave are intercalibrated. When the same pressure is recorded inside and outside the cave, the water level in the cave is thus equal to the sea level.".

[12] l.144: *"monitoring" instead of "survey"*: "survey" replaced by "monitoring".

[13] l.174-178: *what is the source of the temperature fluctuations measured in the cave air? Does it correlate to the seawater temperature and are these temperature fluctuations compensated in the pressure analysis ?:*

water temperature is added to Fig. 4C and temperature variations are described l.174-178 : “Air temperature varies in the range 16°C to 21°C, in a seasonal pattern. The maximum is observed at the end of summer and the minimum at the beginning of spring (Fig. 4C). The air temperature variations are mainly driven by the water temperature variations. Water temperature variations are related to exchange with seawater outside the cave through conduits. Air temperature variations are smoother than water temperature variations, and delayed because of heat exchange with the cave walls, which have thermal inertia.”

[14] l.218: *tide-related temperature variations “in the cave air” (?)*:

Corrected: “Tide-related temperature variations in the cave air are observed”.

[15] l.222-l.224: *phrasing: According the cave air temperature measurements it is rather the wall which stays close to equilibrium with the cave air rather than the opposite*:

modified sentence: “These observations indicate that thermal convection is very active at least in the decorated rooms of the cave and that at the tide time scale, the air in the cave and the walls remains close to thermal equilibrium.”

[16] l.225: *Fig 6 suggests that, during low tide, the water level is higher in the cave than at Port Miou. Can you expand on this?*

Water levels are centered by their mean, see l.205-206: [...] pressures expressed in meter of seawater (msw) and mean-centered at a two days scale [...]

[17] l.225: *In Fig 6, you show that the cave water level is c. 5 cm lower than the sea level whereas the fluctuations shown on Fig 7 range in the order of 1 m. What do I get wrong?*

Fig. 6 compares tide-related water level and sea level variation (around few centimeters) whereas Fig. 7 presents the annual amplitude of cave water level (up to 1.5 msw). See the next comment for clarifications.

[18] l.232-234: *you may want to explain better why the sea-level was c. 0.25 cm higher in 2018 than 2017. What do the horizontal lines (red and black) represent on the figure?*:

sentence added : “The highest level recorded in 2017 (water level close to 1,8 meters above the probe in Fig. 7) was an exceptionally high water level in the cave, equivalent to the sea-level for a few days. A scaled photo of the Horses panel is added to the figure. It illustrates how high the water level can rise and flood the artwork.”. Horizontal lines on Fig. 7 were confusing and are thus removed.

[19] l.271: *This variation is :* corrected.

[20] l.322: *where does the factor 2 on the right hand-side come from?*: See section 1.2 of this document.

[21] l.335: *what drives the temperature variations in the cave air? Using a constant Trock is an approximation as we know there are seasonal fluctuations in both, the cave air and the outside atmosphere? what is their effect?* See comment [13] for the source of temperature variations in the cave air. Water temperature in the cave is added to the Fig. 4C.

[22] l.339: added “much”

[23] l.358: *please edit: ‘equation will, in most cases, yields …’*:

Corrected: “In most cases, eq. (15) yields a correct order […]”

[24] l.379-386: *unclear please edit*:

paragraph rephrased to improve clarity: “[…] Using this latter value, the calculated air-filled volume of the cave was the same in 2017 and 2018, within the range of uncertainties, as expected. It shows that using data of the two summer months, volume can be calculated by the method proposed. Table 2 summarizes mean cave water level measurement and volume calculated over the two summer months for years 2015 to 2020. Mean summer cave volume over the 6 years was 5000 m^3 for an average water level of 1.54 cm_{sw}. This mean volume was maximal in 2020 when the mean water level was minimal, and was minimal in 2016 when the mean water level was maximal. Using the complete dataset available from years 2015 to 2020, the 6-year average water level was 1.33 m_{sw} and yields an average air-filled volume of the cave of 5184 m^3."

[25] l.415: *missing article:*

corrected: "[…] when the air […]"

[26] l.438-442: *unclear, please rephrase: are your referring to the rapid pressure decay or the slow depressurization:*

rephrased: "[…] Similarly, the cumulative net annual air outflow during rapid pressure decays varied from 7720 m^3 (year 2015) to 18260 m^3 (year 2020) with an annual average of 13270 m^3. The budget gives a remaining outflowing air volume (6-year average, 4320 m^3) corresponding to the cumulative net annual air outflow during slow depressurization periods."

[27] l.471: *have been*: corrected

[28] l.486: *you may want to specify that this is during summer*: corrected: "Over the two summer months, there is a slow decrease […]"

[29] l.488: *the pools' reference surface (?)*: Corrected

[30] l.491: *should be "and during years"*: Corrected

[31] l.490-491: *waves where not addressed yet, did they? Wouldn't it rather be associated with groundwater recharge?*

Waves and rainfall are now presented earlier. We showed the correlation between pressurization events and waves height. see Section 1.1 of this document.

[32] l.490: *Wave heights and direction were not discussed so far*. See previous comment

[33] l.538: *This upper conduit was not introduced yet*.

A paragraph has been added l.100-103, detailing the link between the cave and the shallow sumps. We postulate that air passes through these sumps during high waves periods. See section 1.1 of this document for the details.

[34] l.587: *not connected to the cave. But what about the epikarst, flushing air into the fracture during recharge events?*

See section 1.1 of this document

Reviewer 2

[35] l.42: *This depends on the shape of the cave; downsloping cave would be active in winter, and vice versa:*

*c*orrected: "[…] for descending conduits and conversely for ascending conduits […]".

[36] l.63-65: *What kind of events ?*:

Pressurization events and the supposed mechanism are presented. See section 1.1 of this document.

[37] l.94: *I guess you mean intergranular porosity?:*

modified: "[…] carbonates do not display neither macro nor micro porosity."

[38] l.110: *It would be helpful to add another perspective of the cave. I guess this is a DMR of ground; why don't you add a side perspective to get a feeling of the volume. I guess that the scale on Figure 2a does not apply for Figure 2b.*

Figure 2B is not based on a 3D model, it's a drawing showing a cross-section of the Cosquer cave in its environment (sea, cliff). We believe Fig2B is more useful to understand the case study than a cross-section of the main rooms with archeological artwork (the totality of the cave is not yet available in 3D). See below for Figures and tables changes.

[39] l.135: *do you mean transmissivity and permeability of rock with respect to the air:*

“Air intrinsic transmissivity” changed to “Intrinsic transmissivity to air”

“Air intrinsic permeability” changed to “Intrinsic permeability to air”

[40] l.144-147: *Since you are mentioning the phenomena and previous works, maybe mention what is the idea of mechanism behind it...:*

Paragraph modified: “Air pressure in the cave and water level of the pools are anti-correlated (Fig. 4A and Fig. 4B). When the air pressure increases, the air is confined by the walls of the cave and pushes down the water table to balance the overpressure. Conversely, between late spring and early autumn, there is a slow decrease in cave air pressure and the water level simultaneously increases.”

[41] l.157: *These events are highly interesting. I guess you should tell something about their origin already at this point:*

See section 1.1 of this document.

[42] l.231: *Cumulative ?:*

“cumulated” replaced by “cumulative” throughout the manuscript.

[43] l.257: *Here you probably mean air filled volume:*

Corrected throughout the manuscript

[44] l.294: *if you write this in form 1/(1-palTah/pahTaL), equation 6 and 7 would be more obvious.*

Corrected, see section 1.2 of this document.

[45] l.313: *Where do you get Qn from. Is it from dn(t)/dt from Eq. 9 ?*

See section 1.2 of this document.

[46] l.322: *Explain P^2 in the right-hand side. It looks like that P from the left equation goes into the argument of grad.*

See section 1.2 of this document.

[47] l.326: *I don't get the meaning of "defining the percolation threshold":*

this sentence was incomplete and confusing. The last part has been deleted “[…] low water saturation to host a continuous gas phase.”

[48] l.335: *I cannot get the sense from this sentence. Please reformulate*:

Sentence modified: “[…] it follows from Eq. (11) that the total flux depends linearly on the difference of the squared pressure between the boundary conditions.”

[49] l.338: *Refer to my comment to Eq. 11.... I am not sure what approximations were used to derive this Equation.*:

See section 1.2 of this document.

[50] l.341-343: […] *Initially tell clearly that you assume three different geometries shown on Fig. 8., so that the reader is not confused*: modified: “The interpretation of the air effective transmissivity coefficient λ_a, which has dimension of m^3, can vary based on the geometrical configuration. Three geometries are considered: a porous rock volume (Fig. 8A), a single fracture (Fig. 8B) and a pipe (Fig. 8C).”

[51] l.512-517: *You have not directly shown what causes the pressurization events. Nevertheless, I miss this clear statements in the introductory part. What I can get is that you have multiple pressurization events in the cold season with relaxation of this overpressure through the summer season. Could you relate pressurization events to some other outside atmospheric or oceanographic data (observation of winds/waves).*:

See section 1.1 of this document.

[52] l.525-523: *see my previous comment... can you show some correlation between pressurization and external events*:

See section 1.1 of this document.

[53] l.538-543: *Although this is somehow central for the manuscript, it is hard to understand what you want to say. How is the air "pushed" by the waves and why does this happen only in the upper conduit and not in the lower one. Events though this is said to be outside the scope of the paper, one would still need some concept that relates the waves with air inflow.*

See section 1.1 of this document.

Tables and figures

[54] Table 1: reviewer 1 asked to add to Table 1 a column for numerical estimates and a column for references. Among the 35 variables presented in the Table 1, only 9 of them are constant values (P_0, T_0, S_w, g, R, γ, ρ_{sea}, h_0, μ), most of the new columns would thus be empty, we therefore preferred to not add them. However, all the model input values are presented in the text.

[55] Table 1: gravitational acceleration unit corrected

[56] Fig. 2A: modifications are provided to improve the readability of the map.

[57] Fig. 2B: the upper sump is redrawn to emphasize that it is submerged. An approximative scale and approximative elevation are added.

[58] Fig. 2B: *It would be helpful to add another perspective of the cave*:

we do not have a better cross-section of the cave yet.

[59] Fig. 4: Daily rainfall (Fig. 4D) and waves significant height in front of the Cosquer cave are added to support our assumptions and conceptual model.

[60] Fig. 7: Horizontal lines are removed for better clarity.

[61] Fig. 10: modified to better match the statements and interpretations made along the paper.