Reply to reviewer 1 in blue

Understanding the processes driving the ventilation dynamics in decorated caves is key to ensure their conservation as even minor shifts in the cave's climatic equilibrium may lead to microbial outbreaks deteriorating the artwork. Pellet et al. present a six-year monitoring study from Cosquer cave, a major paleolithic site on the Mediterranean coast. The only access to the cave is a flooded passage, thus prohibiting any major exchange with the outside environment. The study encompasses air pressure, water levels and cave air temperature. The authors confirm that the cave air pressure is always higher than in the outside atmosphere keeping the water level below the main paintings. Analyzing the effect of tides on the cave air pressure, the authors calculate a cave volume of c. 5000m3. Although largely isolated from the outside, short pressurization events during the winter season reveal sporadic ingress of external air. These events are used to assess the permeability of the host rock and, thus, may serve as reference for low permeable karst volumes in a broader context.

The paper is generally well-written although a cross-check by a native speaker would be recommended (cf. punctuation and use of articles); the figures are of good quality.

First, we would like to express our sincere appreciation to the referee for his thoughtful review and constructive feedback. In the remainder of this document, we aim to address the referee's concerns by responding point by point to his comments and questions.

However, a few points need clarification before being acceptable for publication:

Water level: much of the discussion relates to the air pressure in the main chamber. A key point here is that the higher pressure keeps the water level below the mean sea-level. However, no information is given about how the elevation of the water table inside the cave was determined. Is there an altimetric survey available? If so, please indicate uncertainties. Also, 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 ?

The pressure sensors in the cave are intercalibrated with atmospheric pressure outside the cave ±1 hPa each time data is retrieved from the sensor (more or less every 6 months) using an additional pressure sensor that is brought in the cave in a water-tight and pressure resistant container. When the same pressure is recorded outside and inside the cave the water level is thus the same ± 1 cm.

To investigate the source of air temperature variations within the cave, we will incorporate new data in Figure 4 of the manuscript (Figure 1 in this reply): cave water temperature (see . Temperature is measured with the same probes that measure the cave water level variation. Fig. 1C shows that the air temperature variations are mainly driven by the water temperature variations. Water temperature variations are presumably 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.

Short-pressurization events: the authors associate short pressurization events with wave activity, however without providing any quantitative data with respect to this wave activity. An alternative interpretation would relate the pressurization events to aquifer recharge after rainfall episodes. Although the author state that addressing more closely the effect of sea waves is out of scope of this paper it would make sense at least to address the effect of hydrology. In absence of surface runoff one would expect that the water infiltrates into the subsurface (as shown on Fig.10), thus pushing interstitial air towards the cave. Accordingly, it would be helpful to plot rainfall distribution together with the effective hydrological recharge along the year and discuss correlations (?) with high-frequency pressure changes in the cave.

As the manuscript is focused on the permeability of the limestone massif, we initially preferred to not delve into the origin of pressurization events. However, as pointed out by both referees, the pressurization of the cave is an intriguing phenomenon that requires some explanation. To clarify this point, additional information is provided to show that pressurization events occur when there are waves on the cliff and are not correlated to rain infiltration.

First, it must be clarified that expeditions in the cave are never scheduled during rough weather, and it is forbidden to camp overnight inside the cave. That makes direct observation of pressurizing events nearly impossible. However, records show a strong correlation between episodes of high waves and pressurization events.

To support our assumption of a causal relationship between high waves and pressurization events, the significant height of the waves in front of the cave (data provided by the French Naval Hydrographic and Oceanographic Service, SHOM) and the daily rainfall will be added to Figure 4 in the manuscript (Figure 1 in this reply). While storms are often associated with rainfall, events with high rainfall but no high waves occasionally occur (e.g. August 2018) and they do not cause pressure variations in the cave. On the other hand, some pressurization events are not associated with heavy rainfall, but they are systematically associated with waves. Ongoing statistical analysis suggests a wave height threshold of about 1 m, but this threshold also depends on other factors (sea level, wave direction…). This will hopefully be the subject of a separate publication.

The conceptual model summarized in figure 10 does not match with some of the statements and interpretations made along the paper. In particular, the justification for an upper pathway several meters below sea-level is unclear and inconsistent with Figure 2B where the latter is placed at the sea-level. How would waves at the sea-surface propagate into this underwater gallery? Also, Fig 10 suggests there are some water inlets draining from the surface. This makes sense but again raises the question of hydrological recharge on the cave air pressure.

As pointed out by both referees, we will add at the beginning of the paper, in section 2 (after line 99) more explanation about the several paths (or levels) of connection between the sea and the cave through the limestone massif. We will redraw Figure 2B to show that the upper pathway is below the sea-level at a deepest level (so not "placed at the sea-level" as reported by referee 1), and redraw in Figure 10 (conceptual model) the upper pathway at a shallow level (still below the sea-level of course). Given the existence of karst pathways at several levels at the beginning of the paper will help the reader to conceptualize that waves can generate bubbles and then force seawater and air to flow through the limestone massif. The detailed mechanism of how bubbles of air can flow inside the submerged karst is out of the scope of this paper. At the present state of the research, we focus in this paper on the pressure data, and by adding data of wave height and rainfall (previous comment) it should clarify that air enters the cave by the sea.

l.41: 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*"

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

This comment is linked with the previous general comments. In the introduction section, line 63, we will introduce the supposed mechanism. "Cave air pressure increases by the inflow of outside air, during periods with high waves on the cliff. Waves can produce and force air bubbles to propagate by submarine open fissures or karst conduits."

l.91: Cretaceous should be capitalized

Corrected

l.92: “thin sections observations” delete observations

Corrected

l.134: “monitoring” instead of “survey”

Corrected

l.189: tide-related temperature variations “in the cave air” (?)

Added *in the cave*

l.195: 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.

Rephrased : *“*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 remain close to thermal equilibrium.”*

There is no direction implied here.

l.201: Fig 6 suggests that, during low tide, the water level is higher in the cave than at Port Miou. Can you expand on this?

It is because water levels are centered by their mean, see l.176: […] *pressures expressed in meter of seawater (m_{sw}) and mean-centered at a two days scale* […]

l.205: 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 m_{sw}). We will clarify this.

Fig.7: I think I get the point but 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?

Fig. 7 only shows the cave water level (not sea-level). To clarify, we will add line 203: “The highest level recorded in 2017 (water level close to 1,8 meters above the probe in Figure 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.”

The horizontal lines represented the lowest water level reached respectively in 2017 and 2018. It is confusing, the horizontal lines are then removed.

l.241: This variation is

Corrected

l.290: where does the factor 2 on the right hand-side come from?

It is a fundamental property of the gradient operator: $\mathrm{grad}(xy) = x\,\mathrm{grad}(y) + y\,\mathrm{grad}(x)$ or in the case $x = y$, $\mathrm{grad}(x^2) = 2x\,\mathrm{grad}(x)$ (Lang, 1999).

l.307: 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?

Dealing first with the outside temperature variation. Considering an annual temperature oscillation of $\Delta T = 20$ °C for outside air (at the local meteorological station Cassis, https://www.data.gouv.fr/fr/datasets/r/5669e5be-8c67-4fbf-aeae-08cbc2369dd4). Considering the rock massif above the cave is a semi-infinite medium: in this case, the temperature oscillation diminishes with depth like: $e^{-z\left(\frac{\sqrt{\omega}}{2\kappa}\right)}$ (Carslaw and Jaeger, 1959). Where $\omega = \frac{2\pi}{t}$ is the pulsation, t is the period ($t = 1$ year), z is the depth and $\kappa = 0.606\ 10^{-6}$ m^2/s is the limestone thermal diffusivity. At 10 m depth (approximatively the depth of the top of the Grand Puits), the heat wave is diminished by a factor 0.017 and rock temperature variation due to the outside temperature oscillation is 0.34 °C.

Second, temperature variation affects dynamic viscosity of air therefore the massif permeability to air. For an ideal gas, dynamic viscosity $\mu(T) \sim \sqrt{T}$ and $\mu(T) \approx \mu' \sqrt{\frac{T}{T'}}$ (Chapman and Cowling, 1990), therefore permeability $k(T) \sim T^{\frac{3}{2}}$ and $k(T) \approx k'(T) \left(\frac{T}{T'}\right)^{\frac{3}{2}}$, where μ (Pa.s) is the dynamic viscosity and k (m^2) the permeability at the temperature T (K) and μ' the dynamic viscosity and k' the permeability at T'. Assuming in the worst case that rock temperature ranges the same as cave air temperature (from 16°C to 21°C), then permeabilities would varies of a factor about 0.990 (at 16°C) to 1.015 (21°C). We may explain that in the revised manuscript, but doubt it is necessary as the corresponding uncertainty is much smaller that the uncertainty on the air flux measurement.

l.325: please edit: ‘equation will, in most cases, yields …’

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

l.345: unclear, please edit

Edited: “*Using data recorded in summer 2018, mean volume is 4967 ± 78 m^3 for a mean cave water level observed $\overline{h_w}$ = 1.53 m_{sw}., which would be equivalent to 4915 m^3 for the reference level h_w = 1.60m. Using this latter value, calculated air-filled volume of the cave is 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.*”

l.350-351: unclear, please edit. How does this compare with figures in the previous sentence?

Edited : “*Applying Eq. 3, the average annual volume of the cave can be estimated from the average volume of the cave and the average water level during summer (V = 5000 m^3 and h_w = 1.54 cm_{sw}). The average water level for years 2015 to 2020 is 1.33 m_{sw} and yields an average volume of the cave of 5184 m^3.*”

l.380: missing article: when the air

Corrected

l.405: 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 varies from 7720 m^3 (year 2015) to 18260 m^3 (year 2020) with an annual average of 13270 m^3. *Therefore, air outflow outside the pressurization events can also be calculated by subtracting the cumulative annual net air inflow with air outflow during rapid pressure decays. This leads to the cumulative net annual air outflow during slow depressurization periods (4300 m^3 on average).*”

l.435: have been

Corrected

l.450: you may want to specifiy that this is during summer

Corrected: "*Over the two summer months, there is a slow decrease* […]"

l.452: the pools' reference surface (?)

Corrected

l.455: should be "and during years"

Corrected

l.476: waves where not addressed yet, did they? Wouldn't it rather be associated with groundwater recharge?

See previous comments about the correlation between rainfall, waves and pressurization events

l.490: Wave heights and direction were not discussed so far

Waves heights will be addressed earlier in the manuscript (in sections 2 and 3) according to the new information provided in previous comments.

l.502: This upper conduit was not introduced yet

The upper conduit was poorly introduced l.99. The new information provided in previous comments should clarify the issue.

l.550 not connected to the cave. But what about the epikarst, flushing air into the fracture during recharge events?

See previous comments about the correlation between rainfall, waves and pressurization events

Table1 Please provide also numerical estimates and reference to it if these are used in further calculations

Known model input values e.g. P_0, T_0, S_w, g, R, γ, ρ_{sea}, h_0 will be added to Table 1.

Fig.2a: the 3D projection is difficult to read and a classical speleological survey would probably be more helpful here. In particular, it is unclear how P2 is connected to the rest of the chamber. Is this a small "island" in the middle of a pool? What is the grey-scale of the 3rd dimension? Adding some elevation quotes would be useful, or even better, draw some isolines.

Modification to increase readability (such as isoline instead of grey scale elevation) will be provided to Fig. 2A. The probe P_2 is moored in the water to a speleothem, the *island* is in fact a column.

Fig. 2b please add a vertical scale to this (nice) illustration

Vertical scale will be added

Fig.4C Please plot also the seawater temperature

See Figure 4C updated (= figure 1C in this document)

Fig. 11 interesting figure, but one would also like to see how hydrological recharge correlates with cave Pair rises during the winter months, resp. get an idea of rainfall distribution along the year.

See Figure 4D updated (= figure 1D in this document)

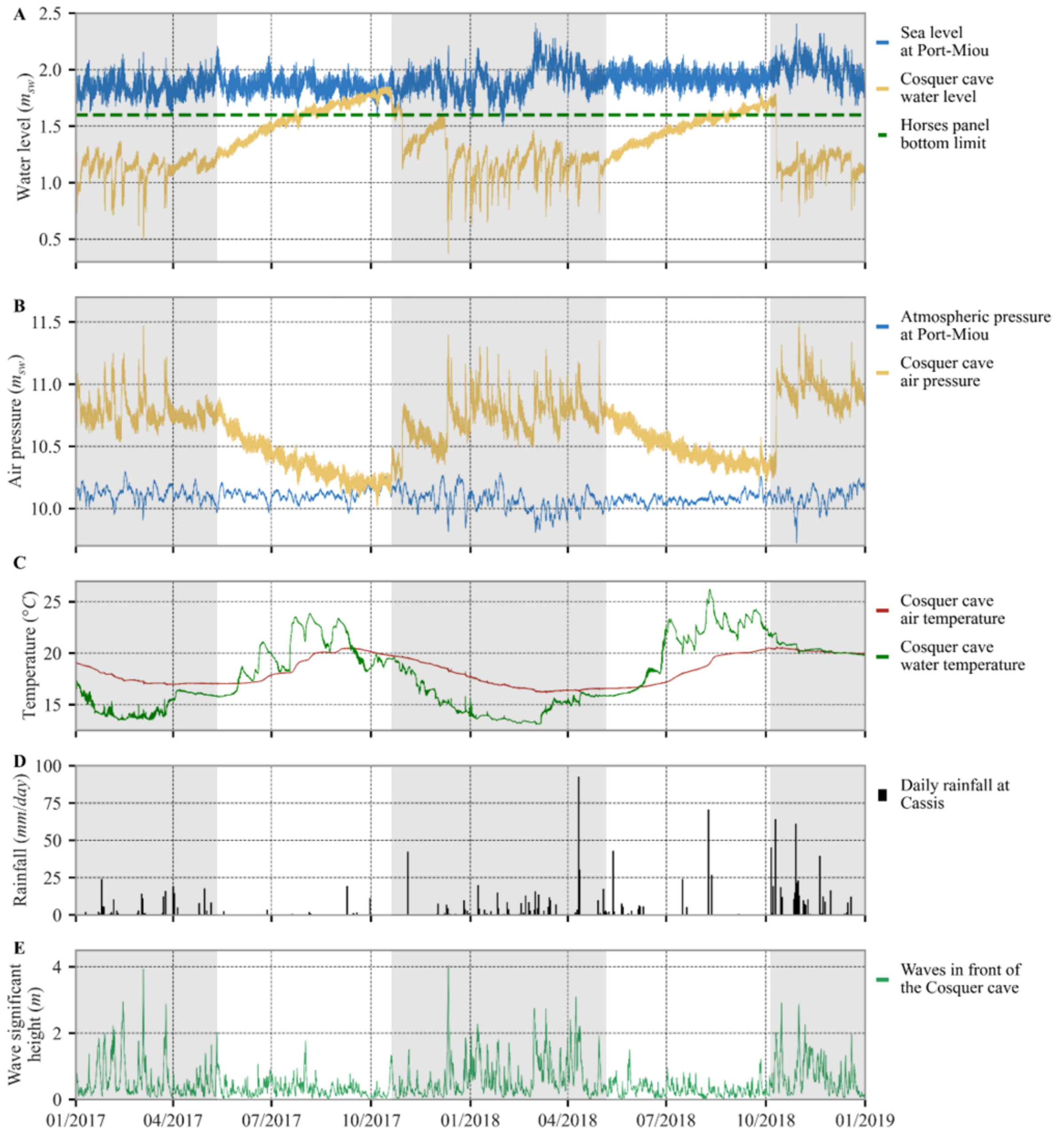

Figure 1: Pressure, water level and temperature time series recorded in the Cosquer cave and at the Port-Miou observatory for years 2017 and 2018: (A) Sea level at Port-Miou (h_s) and Cosquer cave water level (h_w), expressed in column of seawater (m_{sw}) above the probe with the same reference level. The green dashed line shows the bottom of the horses panel (paleolithic decorated wall). (B) Atmospheric pressure (P_{atm}) outside the cave and cave air pressure (P_a). (C) cave air temperature (T_a) and cave water temperature in Room 1 (T_w). (D) daily rainfall and (E) waves significant height in front of the Cosquer cave. Pressurization events periods are highlighted in grey.

Bibliography

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