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Water production in an ancient sarcophagus at Arles-sur-Tech (France)

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Abstract

It has been claimed, from at least the 16th century on, that a sealed sarcophagus, located in the yard of the abbey of Arles-sur-Tech (France), produces hundreds of litres of water per year. Many hypotheses have been advanced to explain this mystery. After about 3 years of data collection, it is concluded that water production, which amounts to about 200 l/year, arises from a balance between rainwater, dew condensation and evaporation. Defects in the sealing provide an exchange with the atmosphere. Condensation is nearly six times greater than evaporation and accounts for about 10% of the total water production.

Keywords: Water production; Dew condensation; Evaporation; Rainwater

1. Introduction

Artificial dew condensers, such as those in Feodosia (Crimea, Ukraine) and in Trans-en-Provence (France), which collect dew water from the atmosphere, are very rare (Nikolayev et al., 1996). A curious phenomenon is known to occur in Arles-sur-Tech (France) that could be at least partially explained by dew condensation.

The abbey in Arles is known to be the seat of a strange phenomenon that has occurred since the 16th century (and probably earlier, from the end of the 12th

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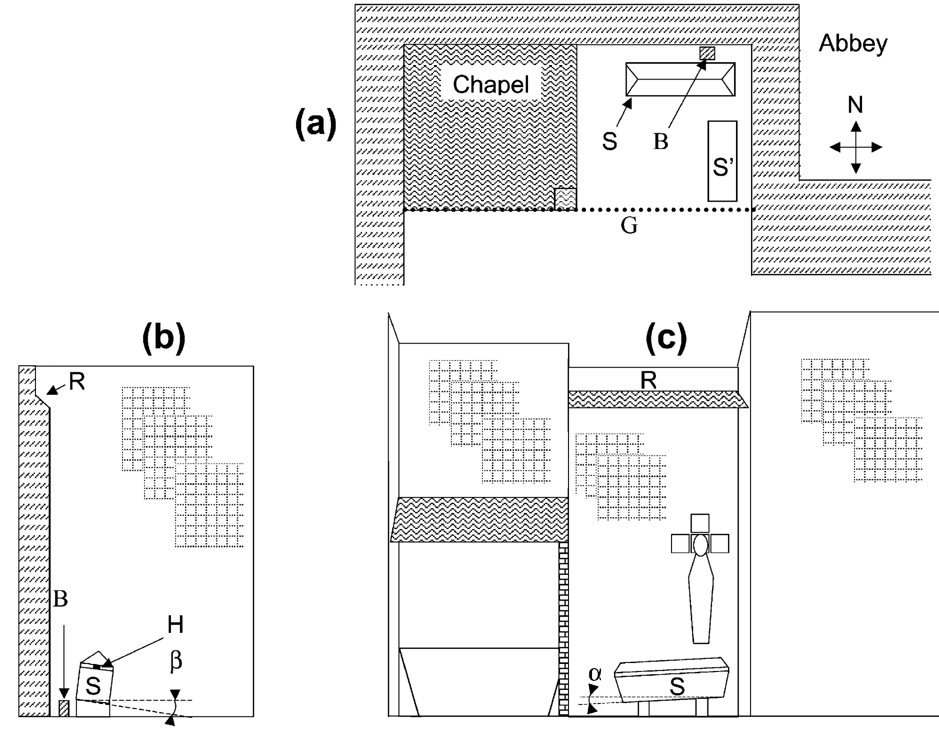


Fig. 1. Schematic view of the sarcophagus location. (a) Top view, (b) side view, (c) front view; (R) roof, (H) water extraction hole, (B) temperature data logger, (S) sarcophagus, (S′) another sarcophagus (bottom opened), (G) grid; $\alpha = 2.7 \pm 0.5°$; $\beta = 4.3 \pm 0.5°$. The sarcophagus is made of white marble and its inner dimensions are—length: $L = 1.76$ m; width: $l = 0.47$ m; height: $h = 0.40$ m. The stone is about 8–10-cm-thick and the maximum lid height is 31 cm. The bottom of the sarcophagus is, on average, 23 cm from the ground. The sides of the sarcophagus are 42 cm from the north wall and 40 cm from the east wall. The sarcophagus is located at 2°38′13″ east longitude and 42°28′40″ north latitude, at 275 m asl.

century[1]), when a marble sarcophagus reputed to contain the remains of Sts. Abdon and Sennen were placed in the outside yard of the abbey, within about 40 cm of high and massive walls. This sarcophagus (called the "Sainte Tombe" by the inhabitants of Arles and pilgrims) fills with water, even though it is closed by a lid and clearly separated from both the walls and the ground (Fig. 1). Water is collected through a slit between the lid and the body of the sarcophagus; in the past, by a strip soaked in water and, since 1859, by a copper siphon introduced into this slit. The quantity of water has never been measured accurately, but it is estimated at 100–800 l/year (Fitzherbert, 1989; Vallespir, 1972). Perard and Leborgne (1961) undertook the only real scientific study on this phenomenon. After two months without rain, they reported in April 1961, 14 days of

[1] Guillaume de Gaucelme, seigneur of Taillet, who died in 1204, was told to be cured from a face cancer, thanks to applications of the sarcophagus water. The oldest known written report dealing with the production of water is dated 1591 and is from Miguel Llot, a Dominican monk from Claira.

correlated data between the level of water in the sarcophagus and the rainfall. They concluded, after carrying out experiments on the marble cover, that the marble lid was probably porous, involving rainwater migration for 5 days through the lid. We will see in the following that this claim is not founded.

However, from our own discussions with the parish representatives who are responsible for water collection from the sarcophagus, it appeared that the level of water in it does not apparently follow rainfall. In dry seasons, water harvesting occurs and rainfall does not inevitably increases the water level. Condensation (and evaporation) phenomena should also take place. The site is particularly favourable to condensation: humidity is high due to the vicinity of the sea; the churchyard is permanently in the shadow from the high walls; in some places the lid is raised by 1–5 mm from the body of the sarcophagus, allowing air flow and convection. The rain also probably penetrates by the interstices of the lid, since the sarcophagus is tilted to concentrate water in the area of its removal; in addition, a small roof concentrates rainwater in the vicinity of the sarcophagus (Fig. 1). As a matter of fact, we observed, in a period of light rain, drops hanging from the lid in the interstice lid-trunk. Drops can thus run into the sarcophagus.

In order to determine whether this tomb is a “natural” dew condenser, we have therefore measured over a long (almost 3 years) time period the relative contribution on water production of rain, dew and evaporation. The study started on May 31, 1997 and ended on April 26, 2000. It was performed in close collaboration with the parish. It necessitated a very light instrumentation, so as to respect the holy sarcophagus and the beliefs of many pilgrims coming to visit and honour the site.

2. Experimental

In order to carry out measurements of the tomb in the most unobtrusive manner, we set-up a network of four thermocouples. They measured the following temperatures: (1) external air, (2) water in the sarcophagus, (3) the stone outside the sarcophagus, and (4) the stone inside the sarcophagus from 05/31/1997 to 01/24/1998 and (4′) air in the sarcophagus after this date. The probes were connected to a power station of electronic measurement supplied with batteries, the whole located in a small rainproof plastic closet behind the tomb, and invisible from the outside. We also used an electronic thermometer–hygrometer located, until January 1998, in the box of the temperature recorder. Because of the averaging effect of the box, the hygrometer was moved, after 01/24/1998, to within a few meters of the sarcophagus, in a small chapel open in two orthogonal directions. We also checked the relative humidity in the sarcophagus. As expected, when water was present in the sarcophagus, the relative humidity was nearly 100%.

Rainfall was measured, approximately 200 m northeast from the sarcophagus in a small weather station (1), using a classical meteorological funnel of 360-mm height and 116-mm diameter, and recorded daily. The air temperature, the air relative humidity (measured by hair hygrometer) and the atmospheric pressure were recorded in another station (2) about 250 m northeast from the sarcophagus on mechanical drums which are reported weekly.

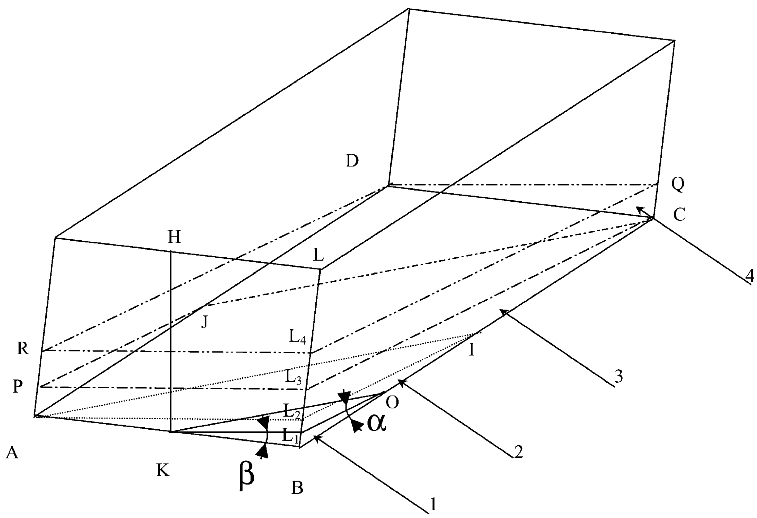


Fig. 2. The different zones (1, 2, 3, 4) of water filling (see text). Here, h is measured along KH, $h_0 = BL_1$, h^* is the water height along BL. The different zones correspond to the following volumes: (1) $KBOL_1$; (2) $ABIL_2$; (3) $ABCJPL_3$; (4) $ABCDRL_4Q$.

There is only one person who is authorised by the parish to collect water. This person measured the quantity of water that he removed and recorded the water level in the sarcophagus, thanks to a cloth attached to the siphon, before and after the water collection.

The amount of water corresponds to the following formulas, where $L = 176$ cm, $l = 47$ cm and the tilt angles $\alpha = 2.7 \pm 0.5°$ and $\beta = 4.3 \pm 0.5°$ (see Fig. 1). Due to the presence of two tilt angles, the relation between the level of water in the sarcophagus and the water content is complex. In Fig. 2, one sees that four different zones of variation can be determined according to the values of $h = KH$, the level measured at the place of water removal. It is easier to express the volume of water (noted V^*) in function of $h^* = BL_i$, the water level along BL. Here, i ranges from 1 to 4 according to the different zones. From simple geometry calculations, one obtains:

$$\text{1st case:} \quad h^* < l\beta, \qquad V^* = \frac{h^{*3}}{6\alpha\beta} \tag{1}$$

$$\text{2nd case:} \quad l\beta < h^* < L\alpha \qquad V^* = \frac{l(6h^{*2} - 6h^* l\beta + 2l^2\beta^2)}{12\alpha} \tag{2}$$

$$\text{3rd case:} \quad L\alpha < h^* < l\beta + L\alpha$$

$$V^* = \frac{1}{6\alpha}\left(\frac{(-h^* + L\alpha)^3}{\beta} + l(3h^{*2} - 3h^* l\beta + l^2\beta^2)\right) \tag{3}$$

$$\text{4th case:} \quad (l\beta + L\alpha) < h \qquad V^* = \frac{1}{2} lL(2h^* - L\alpha - l\beta) \tag{4}$$

The relation between h^* and h is

$$h^* = \frac{h}{\cos\alpha} + h_0 \approx h + h_0, \tag{5}$$

where

$$h_0 = \mathrm{BL}_1 = l\beta/2 \tag{6}$$

$(=1.77$ cm). When $h=0$, water can be present in the sarcophagus, although it is not detected at the measurement location, leading to a maximum "dead" volume (zone 1)

$$V_0 = \frac{l^3\beta^2}{48\alpha} \tag{7}$$

$(=0.26$ l).

In 1950, the sarcophagus was opened 155 years after having been sealed (Fitzherbert, 1989; Vallespir, 1972), and its bottom was found filled with a layer of a few centimeters of dried mud, except in the close vicinity of the siphon location, where the stone was visible. It was reopened recently (September 21, 2000). Water was completely removed with the siphon before the opening, corresponding therefore to the level $h=0$. It was found that the bottom of the sarcophagus was not flat, with a depression at about $1/3$ of the distance from the place of water removal. This depression was filled with water and mud. After having filtered the content, 2.5 l of water was measured, corresponding to an actual "dead" volume $V_0^* = 2.5$ l. We thus simply deduce the volume V from V^* by

$$V = V^* - V_0^*. \tag{8}$$

The Perard and Leborgne measurements were performed in April 1961, within a relatively short period after the 1950 cleaning of the sarcophagus. The authors did not suspect the influence of the dead volume V_0. This volume explains, in our opinion, the 5 days delay of the Perard and Leborgne measurements, which is a far more plausible reason for the porosity of the marble lid and the non porosity of the marble body that they invoked (we think that the marble can be porous for a few-millimeter thickness because of unavoidable ageing, but not within the core).

In order to determine the rate of water production, we had to adapt our determination of the water production rate to the time period between two water removals. This time is of the order of 1–3 weeks. The temperatures within the tomb were collected every 2 weeks. The temperature and humidity measurements at the tomb and at the station are of 3-h periodicity (we, unfortunately, suffered a few breakdowns of the hygrometer and/or the thermometer at the sarcophagus and at the station). Temperature measurements are within ± 0.2 K at the tomb and ± 0.5 K at the station. The humidity measurements are within 5%. The different humidity sensors have been cross-checked, and lead to the conclusion that the dew temperature determination is uncertain within ± 0.5 K and exhibits a positive offset of about 2 K. As the water content of air does not vary appreciably over 250 m from the sarcophagus to the station measurement, we calculated the dew temperature only from the measurements at station 2 (except for a few times when the station hygrometer was not functioning, where we interpolated the data from the hygrometer near the sarcophagus).

We were thus able to determine the amount of rainwater and estimate the extent of condensation or evaporation in the tomb, which are related to the sign of the difference between the atmosphere dew temperature (T_d) and the inner temperature of the sarcophagus.

3. Analysis of data

The difference in temperature between air, stone and water inside the sarcophagus is small and never exceed 1 K, with water temperature always the coldest (this is because water is always at the bottom of the sarcophagus). As a consequence, condensation occurs preferentially on water. As water evaporation is also controlled by this temperature, we therefore only considered the water temperature (T_w) to estimate the sarcophagus condensation and evaporation exchange with the external air. When the sarcophagus is dry, this sensor measures the temperature of the stone inside. The temperature (T_3) of the external stone surface of the sarcophagus lies between T_w and the external air temperature. T_3 only exceptionally reached the dew point.

We first tried to correlate the rainwater precipitation measured at the station (rate dr/dt) with the rate of water production (dV/dt) from the tomb. Here, dt is the time period (expressed in days) between the water collection. The rainfall r is expressed in millimeter per day, with a relative uncertainty $\delta r/r = 1/r$. The volume V is expressed in litres per day and its uncertainty δV comes from a water level measurement error $\delta h = 0.5$ cm. The uncertainty δV is estimated by the difference $\delta V = V(h + 0.5) - V(h)$, where $V(h)$ and $V(h + 0.5)$ are calculated separately. In Fig. 3a, the data are shown as a function of time. Over the period of the measurements, and despite the scatter of data, it is clear that a strong correlation exists between these two quantities. This is made clearer when (dV/dt) is plotted with respect to (dr/dt) (Fig. 3b). A least-square fit to the simple expression

$$dV/dt = a_0(dr/dt) + b \tag{9}$$

with a_0 and b as an adjustable parameter gives $a_0 = (0.107 \pm 0.007)$ m^2 and $b = (0.13 \pm 0.02)$ l day^{-1}. Here, the data have been weighted by the uncertainties δr and δV. The low value of the linear correlation coefficient, $R = 0.23$, reflects the scatter of data. This scatter is mainly due to the presence of condensation (e.g. $dV/dt > 0$ when $dr/dt = 0$) or evaporation (e.g. $dV/dt < 0$ when $dr/dt = 0$). A positive non-zero value for b can be interpreted as the prevalence of condensation over evaporation. The above value for b corresponds to a mean value of (47 ± 7) l/year due to condensation, to be compared with a more complete analysis detailed below, where an average of (22 ± 20) l/year was found. When b is put as zero, one obtains $a_0 = (0.132 \pm 0.005)$ m^2 ($R = 0.22$). The meaning of a_0 is an equivalent surface for rain collection and will be discussed later. A non linear function (square, cubic) that would incorporate the strength of rain does not improve the fit.

We also report in Fig. 3b the data from Perard and Leborgne (1961) for V versus r, where V and r stands for, respectively, the cumulated water volume (in litre) in the sarcophagus and the rainfall (in mm), measured each day, for 14 days. Eqs. (1) and (5), which relates V^* and h, applies for the complete set of measurements. We assume here an uncertainty $\delta h = 1$ mm on the water level determination and an error of $\delta V = 0.1$ l, which is added to the preceding error. We do not consider the data where $h = 0$, as they correspond to the dead volume $V_0^* \approx 2.5$ l, which corresponds to make $V = V^*$. As the measurements were performed every day, we can fit directly V versus r as

$$V = a_0' r + b'. \qquad (10)$$

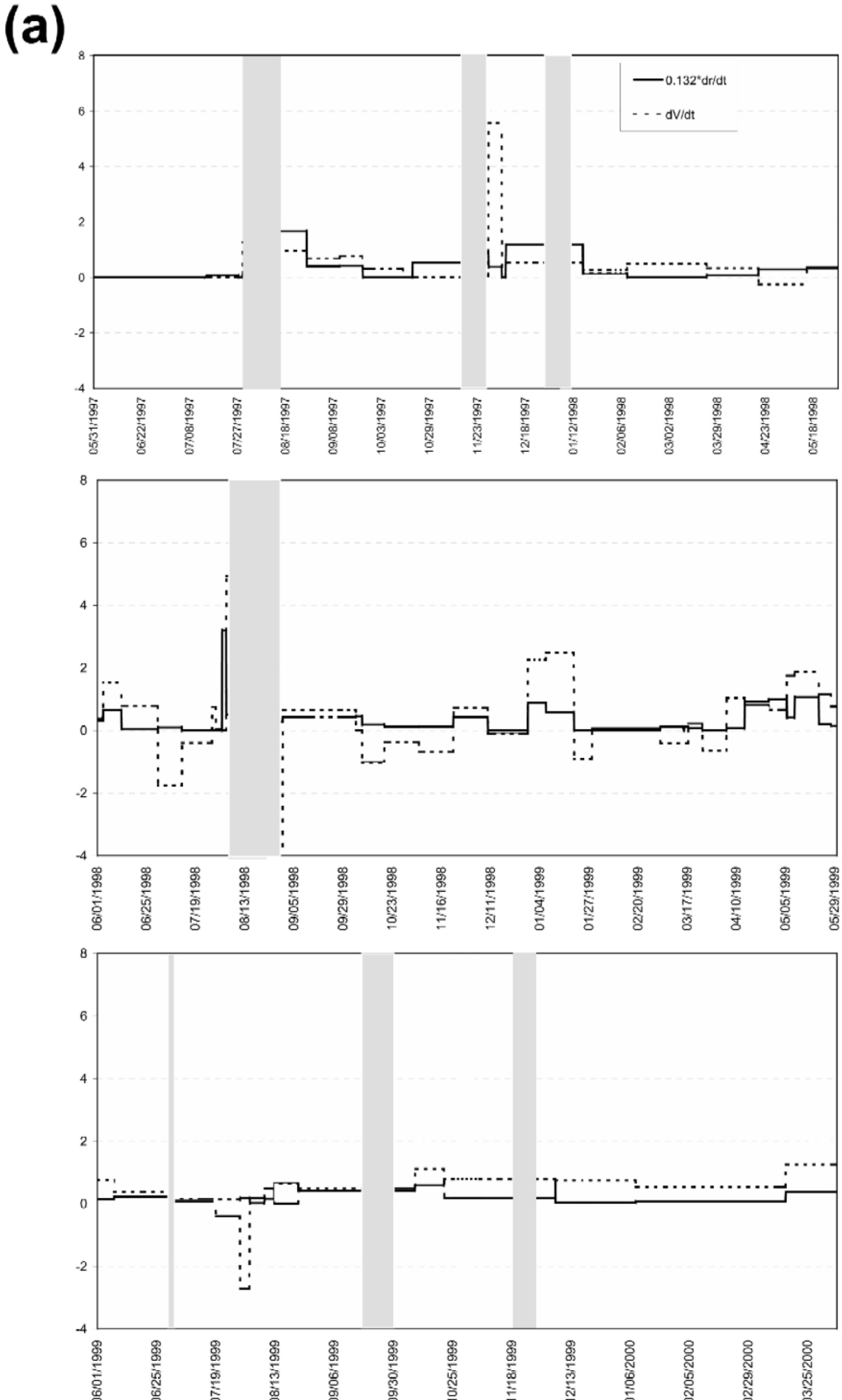
The results are $a_0' = (0.014 \pm 0.003)$ m^2 and $b' = 0.08 \pm 0.09$ l ($R = 0.89$). It is important to note that condensation is detected because V increases at constant r-values ($\mathrm{d}r/\mathrm{d}t = 0$). The low value of a_0' when compared to a_0 ($a_0' \approx a_0/10$) has no special meaning, since the evaporation process is likely to be more important in this period than for the yearly average (data were collected in April). The b' value has also no meaning as it is related to the dead volume.

When looking at Fig. 3a, one sees that there are some periods of time where there was no rain, but still with water production ($\mathrm{d}V/\mathrm{d}t > 0$). In other periods, there was no rain and water diminution ($\mathrm{d}V/\mathrm{d}t < 0$). It is thus clear that condensation and evaporation play a significant role in water production. Therefore, in a second attempt to fit the data, we express the rate of water production by accounting for condensation and evaporation with the following expression:

$$\mathrm{d}V/\mathrm{d}t = a(\mathrm{d}r/\mathrm{d}t) + k_c(T_d - T_w) \qquad \text{if } T_d - T_w > 0 \qquad (11)$$

$$\mathrm{d}V/\mathrm{d}t = a(\mathrm{d}r/\mathrm{d}t) + k_v(T_d - T_w) \qquad \text{if } T_d - T_w < 0 \qquad (12)$$

In these expressions, the proportionality to $\mathrm{d}r/\mathrm{d}t$ corresponds to the rain capture. The other contributions (Nikolayev et al., 1996) correspond to the linearisation versus temperature of the condensation and evaporation contributions (strictly speaking, we should have taken the difference in saturation pressures). The parameters k_c and k_v stand for the exchange coefficient corresponding to the condensation and evaporation processes, respectively. These coefficients are a function of the shape of the condenser and cannot be expressed simply. We choose to determine the above coefficients over a time period when there was no rain. From 03/25/99 to 04/05/99, $(\mathrm{d}r/\mathrm{d}t) = 0$ and on-average evaporation occurred; from 02/10/98 to 03/23/98, $(\mathrm{d}r/\mathrm{d}t) = 0$ and condensation occurred on average. From a least-square fit to the data and an iteration for the free parameters (Figs. 4 and 5), we find $k_c = (0.50 \pm 0.09)$ l day^{-1} K^{-1}, $k_v = (0.080 \pm 0.003)$ l day^{-1} K^{-1}. Here, and in the following, the uncertainties on the parameters were calculated from the curvature near the minimum (see Fig. 5), with a root mean square error taken as 3.5 10^{-4}. This value was calculated from the uncertainties on V and r and is the same as in the fit (Eq. (9)). We then imposed the above k_c and k_v values in Eqs. (11) and (12) to fit the whole set of data, and found $a = (0.180 \pm 0.0075)$ m^2 (Fig. 5). As noted above, a can be understood as the surface of sarcophagus that effectively collects rain. Using the simplest assumption that the rain,


(a)
0.132*dr/dt
dV/dt

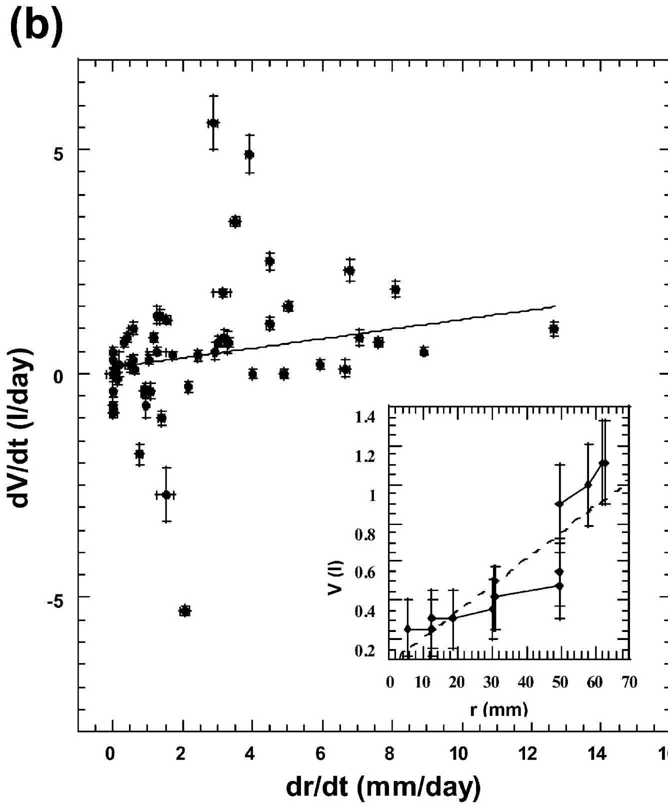
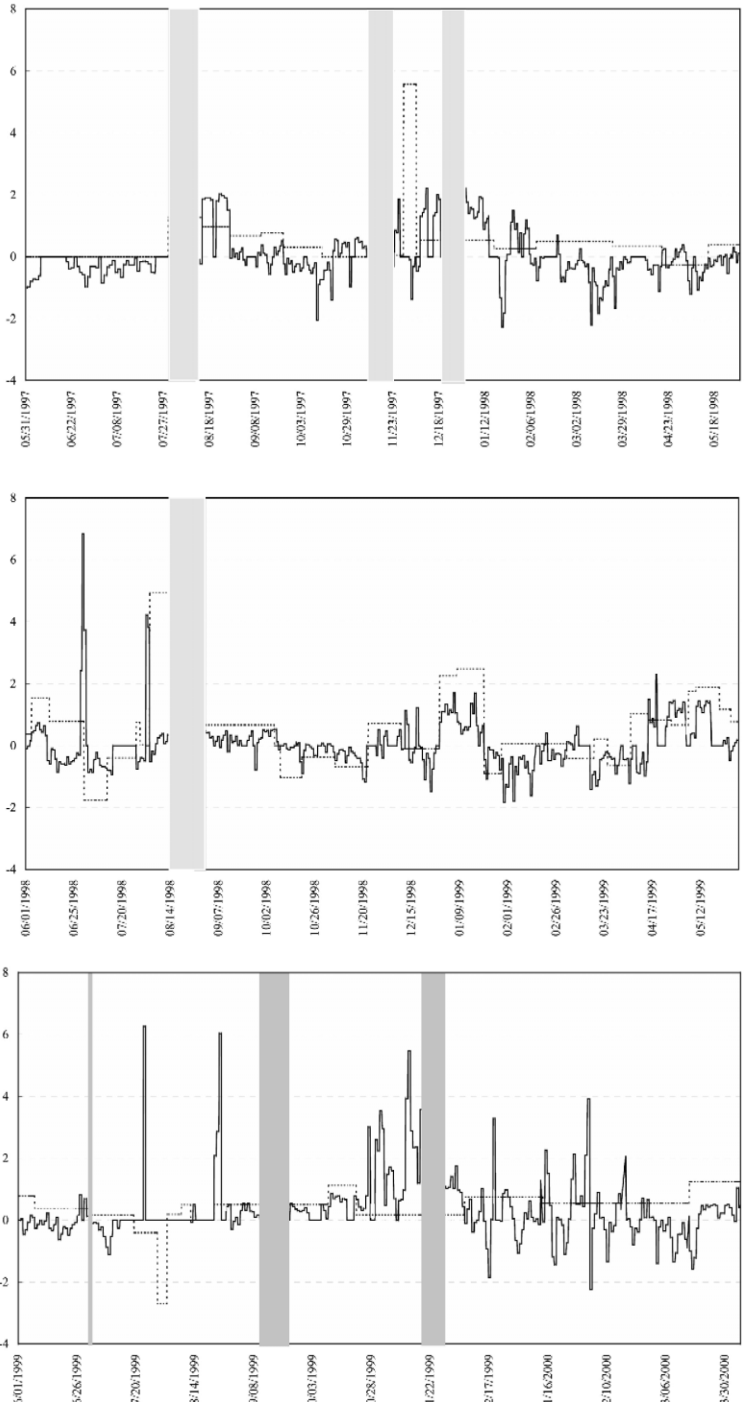


Fig. 3. (a) Sarcophagus water production (dV/dt) (l day^{-1}, dotted line) compared to the rescaled rainfall data $0.132(dr/dt)$ (mm/day, solid line) between May 31, 1997 and April 26, 2000. The multiplication factor of (dr/dt) comes from a fit to Eq. (9) ($b = 0$). The grey regions correspond to the time periods where data were not available. (b) Correlation between the sarcophagus water production (dV/dt) (l day^{-1}, full symbols) and rain water (dr/dt) (mm/day). The line is the best fit (see text). The inset refers to the Perard and Leborgne measurements (Perard and Leborgne, 1961) (see text).

collected by the north-half of the lid, penetrates by the inclined slit between the lid and the body of the sarcophagus (Fig. 1b), we find an *equivalent* surface capture of an order of 25% the half lid area (0.7 m^2), which is a quite reasonable value (note that the slit is large enough to collect rainwater: a simple calculation shows that even a 0.1-mm slit thickness is able to collect the biggest rainfalls).

Note that there is a large difference (a factor of 6) between the coefficients of evaporation and condensation. The sarcophagus simply works as the natural glacier pits (Tigaud and Rigaud, 1988). During the night, the outside air, colder than the pit, falls down and cools the pit bottom, and during the day, the outside air, warmer than the pit, enters only at the top. This configuration permits condensation while minimising evaporation.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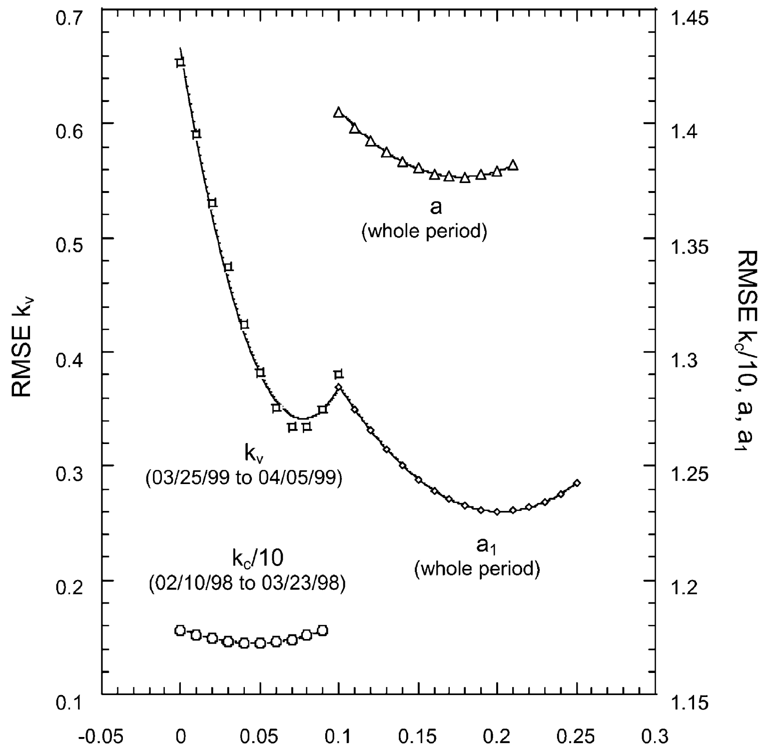

Fig. 5. Minimisation of the root mean square error (RMSE) between $(\mathrm{d}V/\mathrm{d}t)$ and their fit to Eqs. (11) and (12) when the values of the parameters a, a_1, $k_c/10$, k_v are iterated (see text).

We can estimate the role of condensation with respect to that of rainfall. An average rough estimation can be found by comparing the coefficient (a) obtained with condensation and evaporation ($k_c \neq 0$, $k_v \neq 0$, Eqs. (11) and (12)), and that (a_1) obtained without condensation ($k_c = 0$, $k_v \neq 0$, Eq. (12)). We find (Fig. 5) $a_1 = (0.200 \pm 0.007)$ m^2, which gives a condensation contribution of $(a_1/a - 1) = 0.11 \pm 0.1$.

Although the uncertainty on the precise value of the yearly contribution of condensation is large, the phenomenon of condensation does exist and is not negligible. The sarcophagus works as a massive dew condenser similar to the Knapen condenser (Knapen, 1929) in Trans-en-Provence (France), and to a lower extent, since this latter is partially cooled by nocturnal radiation, to the Zibold condenser in Feodosia (Crimea) (Nikolayev et al., 1996). These “massive” condensers are known to have low or mediocre yields (Nikolayev et al., 1996).

Fig. 4. Daily water production rates $\mathrm{d}V/\mathrm{d}t$ (l day^{-1}) (dotted line) and best fit (solid line) according to Eqs. (11) and (12) with parameters $a = 0.18$, $k_v = 0.08$ and $k_c = 0.5$. The grey regions correspond to the time periods where data were not available.

4. Concluding remarks

After collecting thermo-physical and meteorological data over nearly 3 years, the phenomenon of water collection in the Arles-sur-Tech sarcophagus can be understood as a balance between infiltrating rain between the sarcophagus body and its cover, dew condensation, and its complementary process, evaporation. A total water production of nearly 200 l/year was measured, with a contribution from dew that amounted to about 10% of the whole production, i.e. 20 l/year.

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