# Cover Letter

Dear Editor,

Thank you for providing detailed reviews of our manuscript ***Physics-informed machine learning for understanding rock moisture dynamics in a sandstone cave***. The reviewer raised concerns about our reasoning regarding the temperature effect. In the response, we provide a data set of **outdoor FDR measurements** with large diurnal variations of temperature to show how to identify the temperature effect, and give evidence of negligible temperature effect of **indoor FDR measurements in our study site inside a cave**. A detailed response to the reviewer is attached in this file.

If there is any problem with the revision, please let me know.

Thank you for your consideration.

Best regards,

Xiao-Wei Jiang

Professor of Hydrology

E-mail: jxw@cugb.edu.cn

# Response to Editor

Dear Authors,

Thank you for submitting your responses to the two reviewers' comments. I greatly appreciate the significant effort you have made to improve this manuscript. I have also noticed a significant improvement in the quality of the English language used throughout the manuscript.

While I am pleased with the authors' detailed and relevant responses to the reviewers' comments, there are still some important issues that need to be addressed. Reviewer #2 has provided a comprehensive report, raising concerns about the authors' reasoning regarding the temperature effect on the measurement signal. The authors claim that this effect is negligible, but Reviewer #2 challenges this reasoning.

Therefore, I kindly request the authors to specifically address this issue raised by Reviewer #2.

Thank you for your attention to this matter.

Response: Thanks for your positive assessment on our study. We have provided detailed explanations and evidence of negligible temperature effect of FDR measurements in our study site inside a cave. We have also revised our manuscript.

# Response to Reviewer#2

I appreciate the considerable efforts made by the authors to enhance the manuscript since the previous round of reviews, and their diligence in addressing all the questions raised.

However, I regret to say that I remain unconvinced by their response to the central point of my critique, namely the impact of sensor sensitivity to temperature. This remains a point of uncertainty for me.

By presenting two instances of two-week periods with elevated FDR readings despite no observable temperature changes (within the figure), the authors draw the conclusion that the sensor's sensitivity can be considered insignificant. First of all, I suggest changing this figure so that the scale of the y-axis for temperature reflects the range of the data which is shown in the figure, currently the difference between minimum and maximum value is too large.

I would like to support my argument again by referring to the state of literature. It is well known that the electrical permittivity of soils (for which the TDR and FDR sensors have been developed) is influenced "by temperature (Roth et al, 1990; Wraith and Or, 1999; Owen et al, 2002; Rosenbaum et al, 2011), (soil) texture (Ponizovsky et al, 1999) and organisation of thin water film layers (Wang and Schmugge, 1980)". (p 648, Jackisch et al 2018). Jackisch et al (2020) also show in their Figure A3 that most soil moisture probes have a high correlation with temperature.

Even with soils, it is considered ideal to calibrate the sensor under controlled conditions for the respective application. As this study relates to a single sensor in a new application and calibration under controlled conditions requires few resources (sensor, stone, scale, thermometer) I would recommend the authors to perform this calibration. In my eyes, this simple measurement would essentially improve their study. Without this calibration the potential temperature effect needs to be a central point of the discussion and needs to be more prominently addressed in every section of the manuscript, including the abstract, introduction, and the conclusions.

My strong recommendation about this aspect is based on the fact that the range measured by the sensor reported in this study is very low (0.010-0.030 over the whole period of observations) while the change in temperature is not negligible (-15 to 14 °C according to Fig. 5; Tsurface 8.4 – 13.6 °C; Tair 10.9 – 21.4 °C between June and September 2021 from the downloaded data).

Additionally, I was suggesting in the first review round to the authors to include a more simple method to measure the relationship between the predictor variables than the LSTM to give a baseline to which the performance of the more sophisticated method can be compared. The authors provided a table with the covariance between the signal of the dielectric permittivity (interpreted as RWC) and the normalized atmospheric conditions in 2020 and 2021. Although this response goes into the right direction, in this context the correlation coefficient is more meaningful than the covariance. Additionally, since my question refers to the necessity of the LSTM, I argue that the same period of time should be considered (June – September). I copy pasted some data out of the pdf provided by the authors (covering summer 2021, please provide .csv ot .txt format in the future when providing data) and calculated the correlation coefficient between predictor variables and the response variable (RWC) (see below). Although the LSTM outperforms a linear model in this study, the linear model would already be doing a very good job (RWC ~ T_surface, r2 = 0.71).

Additionally, the strong correlations between RWC and both temperature measurements (0.84 & 0.82) underline the point that a proper validation (under controlled conditions) that the sensor is not mainly influenced by temperature would be recommendable (or this aspect needs to be highlighted).

I think the authors can still substantially improve the quality of their research and this manuscript by addressing the above mentioned points.

Response: We summarize that the reviewer still has three concerns of our study. The first is whether there is temperature effect associated with the FDR measurements, the second is the necessity of sensor calibration, and the third is the necessity of the LSTM model.

**1. On the temperature effect**

We agree that the FDR measurement is sensitive to temperature, especially when the temperature spans a large range. In the references you listed, the temperature variations are really large. For example, the temperature ranges between 5 and 65°C in Wraith and Or (1999), between 0 and 70°C in Owen et al (2002) and between 5 and 40°C in Rosenbaum et al (2011). We acknowledge that the FDR readings which have temperature effect cannot represent the rock water content, however, we have evidence to prove that temperature effect of FDR sensors inside the caves in this study is negligible.

To demonstrate that the sensor installed in Cave #9 free from sunshine exposure has negligible temperature effect, we first compare our latest measurements carried out in an outdoor sandstone which is exposed to sunshine and in the indoor sandstone inside Cave #9. In the outdoor sandstone, as a result of the large temperature variations induced by solar radiation, there is obvious diurnal variation of FDR signal (Fig. S1a); in the indoor sandstone, as a result of the small temperature variation, there is not obvious diurnal variation of FDR signal, especially in September and October (Fig. S1b).

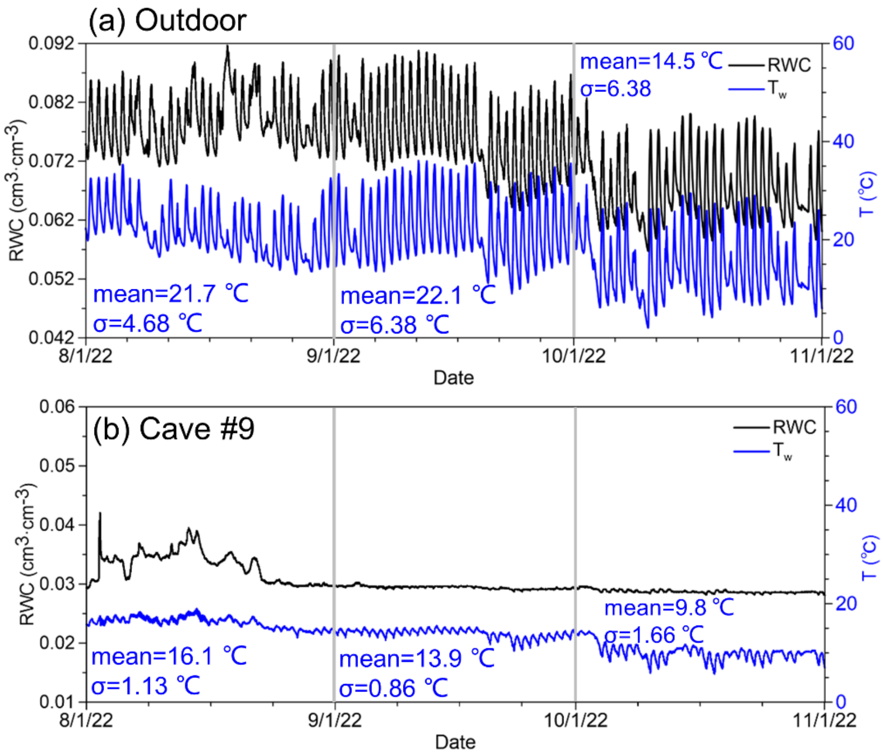


Figure S1. The fluctuating RWC and $T_w$ in August through October of 2022. (a) Outdoor sandstone and (b) Indoor sandstone inside Cave #9. Note that a and b have the same scale.

For the FDR sensor installed in outdoor sandstone exposed to sunshine, there is a linear correlation between RWC and $T_w$, with $R^2$ being as high as 0.92 and 0.996 in September and October (Fig. S2a), respectively. However, this does not mean that the correlation between RWC and $T_w$ is enough to reveal the temperature effect. By defining $\Delta RWC = RWC_t - RWC_{t-1}$ and $\Delta Tw = T_t - T_{t-1}$, we find a high correlation between ΔRWC and ΔT, with $R^2$ being as high as 0.96 and 0.98 in September and October, respectively (Fig. S2b). In August, $R^2$ of correlation between ΔRWC and ΔT is also as high as 0.67. Therefore, outdoor FDR measurement has temperature effect, which can be revealed by using a plot of ΔRWC versus ΔT.

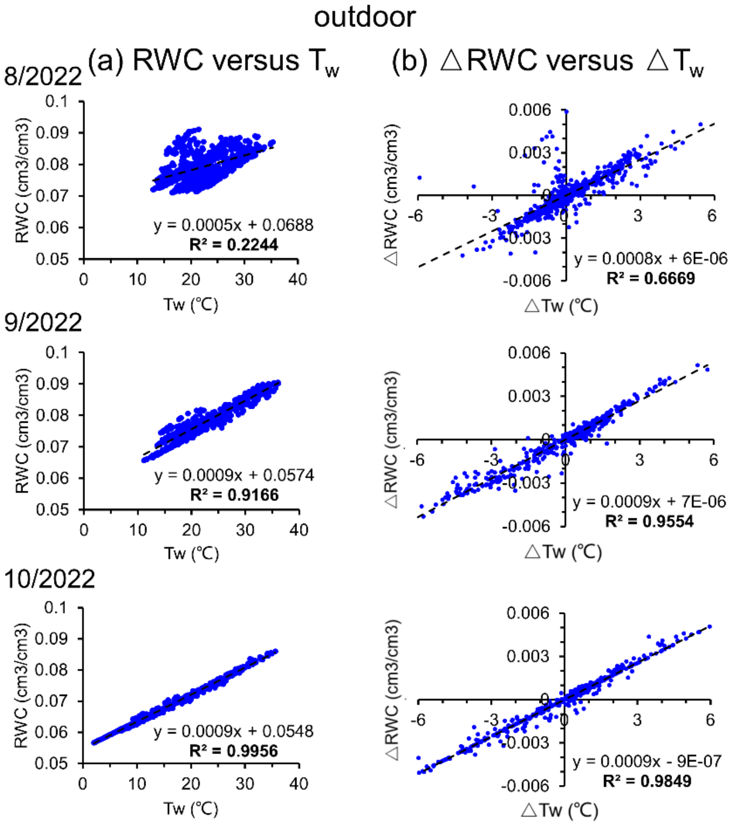


Figure S2. Plots of RWC versus $T_w$ (a) and of hourly variation in RWC, ΔRWC, versus hourly variation in $T_w$, $\Delta T_w$, (b) in the outdoor sandstone in three months.

However, in our manuscript, the sensor was installed inside Cave #9 that is not exposed to sunshine. In the revision, we use plots of ΔRWC versus ΔT in four months (Fig. S3b) to exclude the possible occurrence of temperature effect. Although there is correlation between RWC and $T_w$ in September (with $R^2$ equals 0.78, Fig. S3a2), there is no obvious correlation between ΔRWC and ΔT (Fig. S3b2), indicating that an instantaneous change in temperature does not cause an instantaneous change in FDR signal. Moreover, there is no correlation between ΔRWC and ΔT is all other months. Therefore, we want to clarify that the correlation between RWC and $T_w$ cannot be used as an indicator of the temperature effect.

In the revision, we use plots of ΔRWC versus $\Delta T_w$ to illustrate that the temperature effect is negligible.

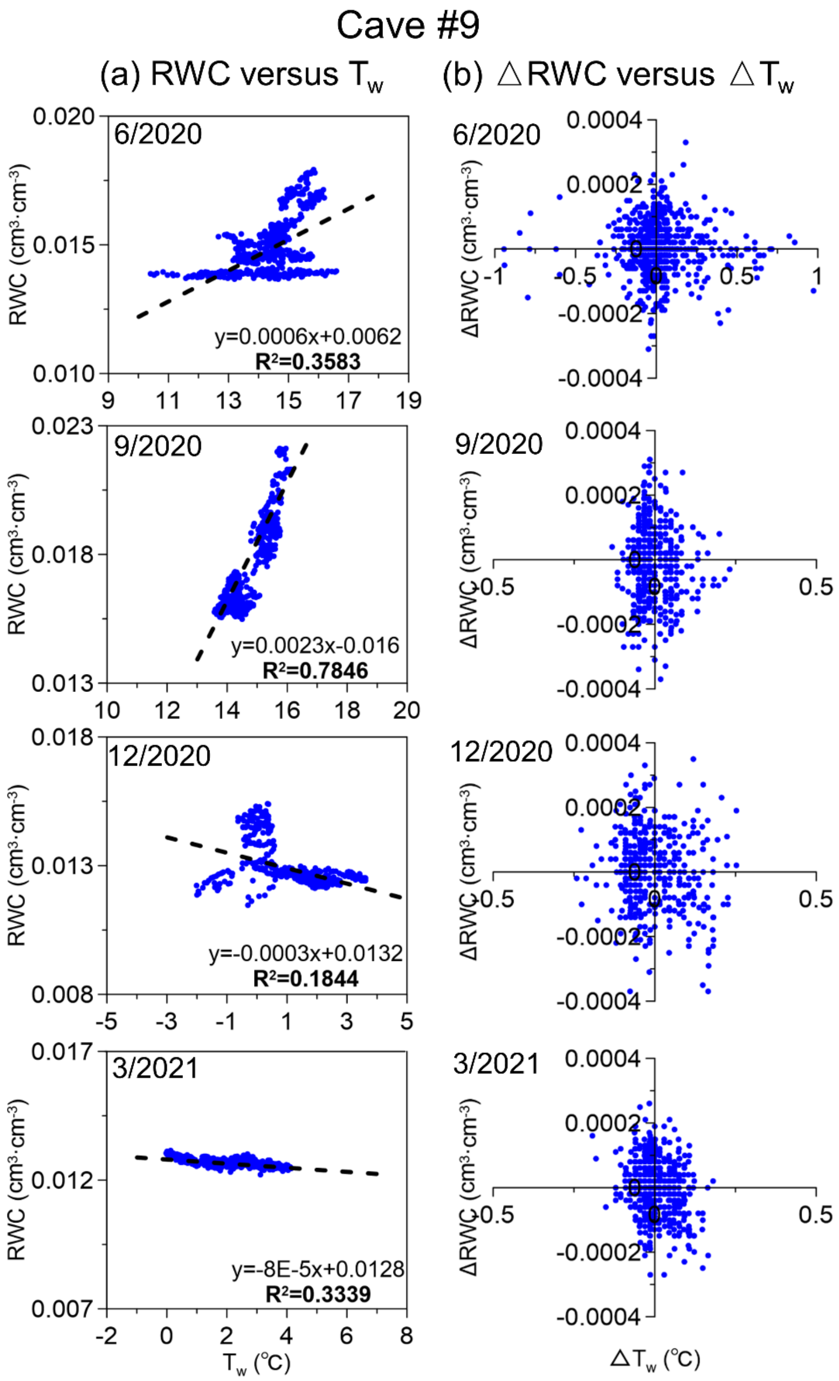


Figure S3. (a) Plots of RWC versus $T_w$ in Cave #9; (b) Plots of $\Delta$RWC versus $\Delta T_w$ in Cave #9.

## 2. On the necessity of sensor calibration

We totally agree that sensor calibration is important. However, as pointed out by Reviewer #2, calibrating rock water content measurements in the field remains a challenge so far.

We have tried to calibrate the rock water content of rock samples in the laboratory. By weighing rock samples, we can establish a linear relationship between FDR readings and rock water content. However, in the current study, the FDR sensor is installed into a rock wall, the weight of which is impossible to be weighed. Moreover, we cannot collect a large rock sample to install a FDR sensor and conduct sensor calibration.

Because the possible occurrence of temperature effect has been excluded, we believe that direct reading of FDR measurements can be used to understand the dynamics of rock moisture.

**3. On the necessity of the LSTM model**

As indicated in the title of our manuscript "Physics-informed machine learning for understanding rock moisture dynamics in a sandstone cave", the aim of our study is to improve understanding of causes of rock moisture dynamics with the aid of a machine learning model. The cause-and-effect relationship between rock water content and vapor concentration is the precondition of high precision prediction.

We totally agree with the reviewer that a simple linear model can do a good enough job to predict rock moisture. However, it is impossible to have high $R^2$ by using other traditional models. In our study, the LSTM model leads to high $R^2$ equaling 0.985 and 0.996 for schemes #1 and #2, respectively, illustrating that the LSTM model outperforms a linear model. In our opinion, a high $R^2$ close to 1 predicted by the LSTM model is a robust indicator showing that the fluctuating rock moisture is caused by water vapor condensation.