Response to Reviewer #1

This paper investigates the dynamics of rock moisture in a cultural heritage site in China. Based on an analysis of soil moisture sensor measurements, the main outcome of the study is that wetting of the rocks during the summer period is mainly caused by water absorption from the water vapor in the atmosphere. Also a wetting and drying cycle is observed during winter due to freezing and thawing. The interpretation of the results is based on sensitivity analyses of a trained LSTM and an LSTM trained on a set of available direct measurements is compared with an LSTM that is trained on variables that are derived from measurements and that are more directly related to condensation processes such as the wall temperature and dew point temperature. The latter LSTM is called a physics-informed LSTM. The LSTMs are trained on a dataset of one year and are then used to predict the other year.

The obtained insights are interesting and could also be of relevance for the management, protection of the heritage site. I would propose that the authors also give some ideas on how these insights could be used for these purposes.

Response: The water source and formation mechanism in rainy season are concluded in this paper, the vapor concentration is identified as the major control factor of rock moisture in caves, rock heritage protection could be alleviated from the steps of reducing water vapor condensation, rather than rainfall infiltration in this way.

There are a few general questions that need to be addressed.

1) The paper is based on a 2-years time series of rock moisture measurements by only one single sensor. What is the value of such a single sensor time series? Can the results be transferred to other locations? I can imagine that one does not want to disturb such heritage sites with a lot of sensors but wouldn’t it be possible to find a few locations where sensor measurements would not cause a disturbance? Or would you expect a big difference when you place the sensors in a sand layer that you put in thermal contact

with the wall so that the wall temperature of the sand is similar to that of the rock? Is a 2-years period sufficiently long? I think these are questions that need to be addressed and discussed in the paper.

Response: (1) Thanks for your understanding. We were not permitted to install a lot of sensors to disturb the heritage sites in the Yungang Grottes. By installing one FDR sensor in Cave #9, which was the first trial of using the FDR technique to monitor rock moisture, we identified the source of rock moisture in the cave from air vapor for the first time. The aim of the current paper is to report our monitoring scheme and reveal sources of rock moisture. Although we only have one sensor, we believe that this does not undermine the effectiveness of the monitoring scheme and the understanding of mechanisms controlling rock moisture fluctuation in caves.

In fact, to test the universality of this recognition, in July 2022, we implemented rock moisture monitoring in Cave #4. The rock moisture measured in Cave #4 and Cave #9 during 21 July and 21 September 2022 are shown in Fig. S1. The similar patterns of rock moisture addition and depletion in response to vapor concentration in the two caves confirm our recognition on mechanisms controlling rock moisture fluctuation in caves. Unfortunately, the data in Cave #4 is limited, which is not suitable to be included into the current manuscript.

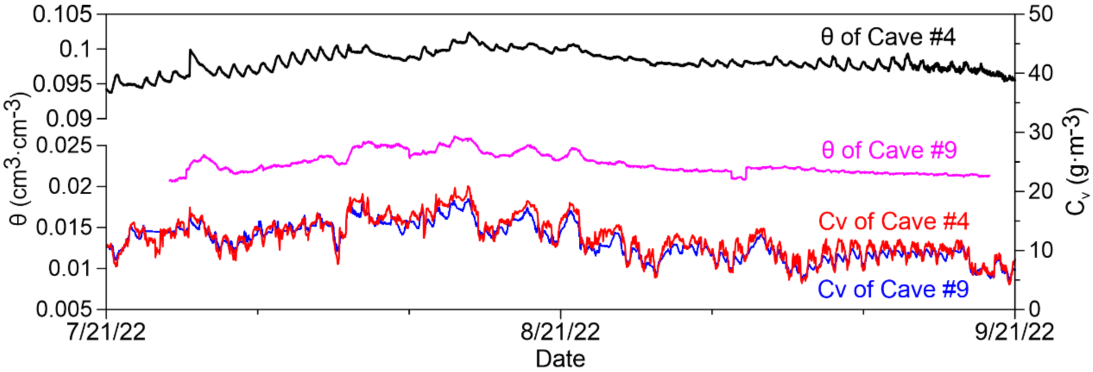

Figure S1. The comparison of rock moisture and atmospheric conditions between Cave #4 and Cave #9 in the summer period of 2022.

(2) As we shown in Figure S1, rock moisture in the summer of 2022 is also controlled by vapor concentration. However, rock moisture addition and depletion in the summer

of 2022 are not as significant as those in the year 2021. Moreover, there was no obvious occurrence of water droplets in the caves in the summer of 2022. Because we had good photos showing water droplets in the caves in the summer of 2021, we believe that the year of 2021 is suitable for analysis and prediction.

In fact, we have monitoring data since 2019. After comparing prediction by using 2020 for training and by using 2019 and 2020 for training, we find the predicted results differ little (Figure S2). Because the aim of the current paper is to report our monitoring scheme and reveal sources of rock moisture, we prefer to use data of 2020 and 2021.

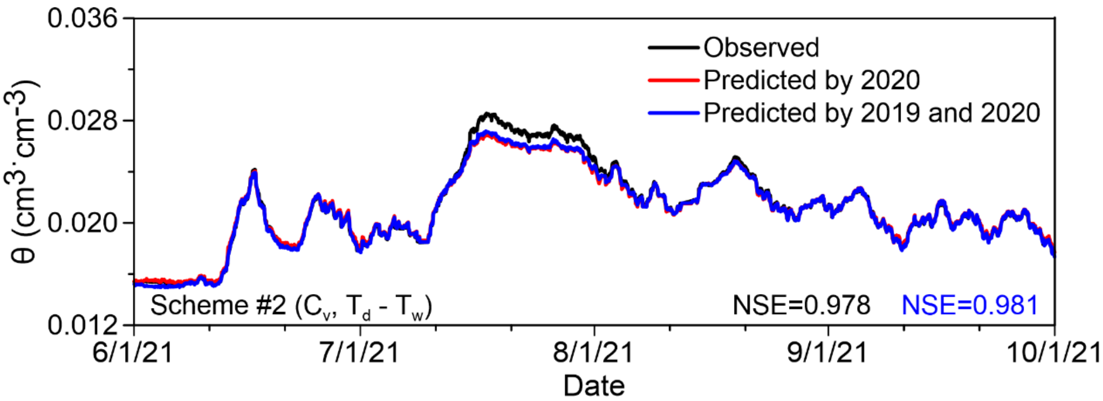

Figure S2. The comparison of prediction results.

2) The description of the LSTMs is not clear and the reason for also presenting the RNN is not clear since it is not used in the paper.

Response: Thanks for your comments. We will add more detailed description of LSTM in the revision.

The LSTM network was developed based on the RNN network, for clarity of describing the structure of the LSTM network, many previous papers on the LSTM network (Gao et al., 2020; Kratzert et al., 2018; Fang et al., 2021) described the structure of RNN before introducing LSTM, even if the RNN network was not used for prediction in their studies. Therefore, we follow these studies and present the RNN in our study. We will state the reason clearly in the revision.

3) The physics-informed LSTM performed a bit better than the other LSTM but the

improvements are not very impressive. Could you find examples where you would expect a much larger improvement? Even though the match between the measurement and LSTM is impressive, they remain a black box and it is not so clear to me why the LSTMs are needed in this paper. What is their role? Doing a sensitivity analyses, you found that precipitation did not explain the rock moisture dynamics and comparing model fits of physics-informed LSTMs with non-informed LSTMs you found that absorption of vapor is the main process. But, can't this be inferred as well from time series analyses, e.g. covariance, wavelet, analyses? If the purpose is to obtain an understanding of the processes, what are the advantages of using LSTMs in comparison with other more classical methods? Could the parameters or weights that are obtained by training the LSTM be interpreted and used to explain the behavior of the system?

Response: (1) Thanks for acknowledging that our physics-informed LSTM performed better than the non-physics-informed LSTM. Unfortunately, the prediction still underestimates the measurements in July with the highest rock moisture and we cannot figure out a much larger improvement at this stage. We will try to further improve the accuracy of prediction in the future.

(2) We totally agree that a LSTM model capable of high precision prediction is a black box. The combination of the LSTM model and the SHAP (SHapley Additive exPlanations) method leads to not only high accuracy of prediction, but also interpretability of predictions. Therefore, by combining with the SHAP method, the LSTM model is no longer a black box.

We agree that the covariance of two time series can be used to reveal the correlation between the two time series. Table 1 shows the covariance between rock moisture and normalized atmospheric conditions in 2020 and 2021. The results show that each variable has a positive correlation with rock moisture. Vapor concentration (C_v) has the largest covariance while rainfall (P) has the lowest covariance. This is consistent with the feature importance obtained by the SHAP method. Although we did not predict rock moisture by using other classical statistical methods, we believe that the LSTM network, which is an emerging deep learning approach, has its unique advantages over other classical methods when it is combined with the SHAP method.

Table S1. The covariance between rock moisture and atmospheric conditions

	T_a	RH	P	T_w	C_v	T_d-T_w
2020	0.030	0.039	0.001	0.034	0.047	0.030
2021	0.043	0.034	0.001	0.036	0.044	0.022

4) I was confused about the winter period. Was it also used to train the LSTM? There is a discussion on the sensor measurements during the winter period but I could not find a discussion on the performance of the LSTMs for this period.

Response: Sorry for our unclear expressions.

We want to clarify that the winter period was not used to train the LSTM and was not predicted by the LSTM model. In line 235, we pointed out that "Because the period from 1 June to 1 October has the most significant trends of rock moisture addition and depletion, the hourly data during this period in the year 2020 are used to construct the training set, whereas the hourly data in the year 2021 are used to construct the test set".

Abstract:

There were a few points unclear in the abstract.

1) Summer and winter cycles of moisture addition and depletion are mentioned but no information is given about the underlying processes leading to these cycles

Response: We will change the sentence "We identified two major cycles of rock moisture addition and depletion, one in the summer, and the other in the winter." into "We identified two major cycles of rock moisture addition and depletion, one in the summer which is affected by air vapor concentration and condensation, and the other in the winter which is caused by freezing-thawing".

2) LSTMs are used to predict soil moisture. But, it is not clear whether different LSTM's are used for summer and winter and whether different input variables are used for the two different seasons.

Response: We only qualitatively described the cause of fluctuating rock moisture in the winter. The winter period was not used to train the LSTM and was not predicted by the LSTM model.

3) vapor concentration and the difference in dew point temperature and wall temperature are informative input variables to predict rock moisture. It is mentioned that they improved the prediction performance but it is unclear compared to what the predictions were improved.

Response: Sorry for our unclear expression. The improvement in prediction is reflected by the decreased MAE and RMSE, which are labeled in Figure 6 in the manuscript (Figure S3 in the current file).

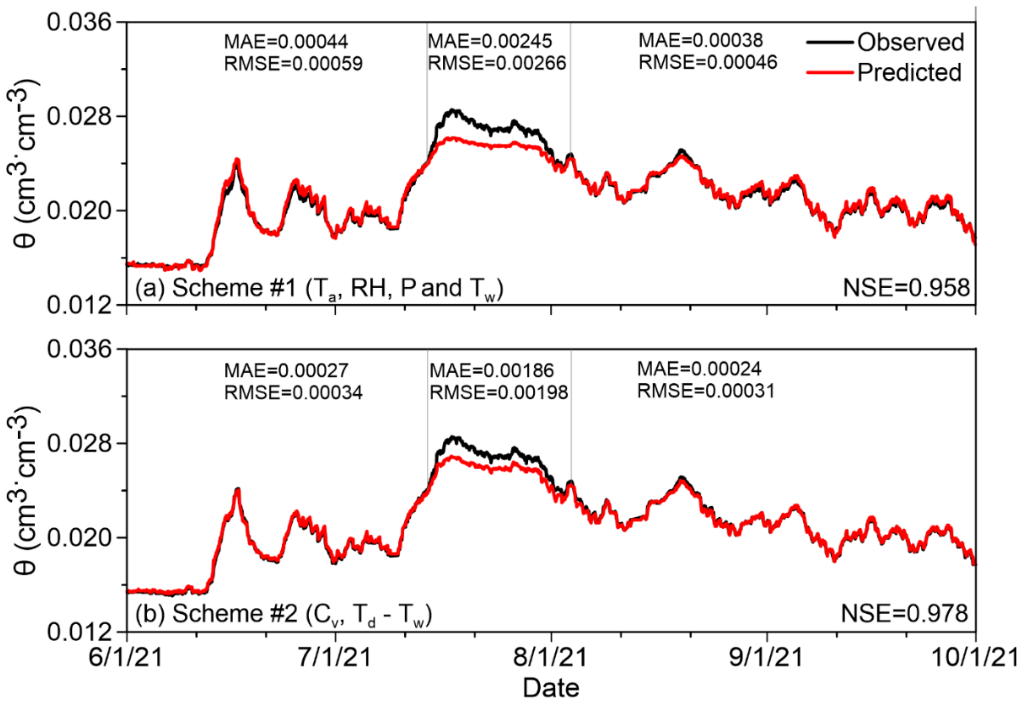

Figure S3. The predicted and measured rock water content obtained by two schemes with different input variables. (a) Scheme #1 using four directly measured variables; (b) Scheme #2 using two calculated variables controlling vapor condensation. Also shown are NSE of the whole time series, MAE and RMSE of three different stages.

4) What are ‘multi-diurnal fluctuations’?

Response: It should be “multiday fluctuations”. Sorry for our misuse of the word.

5) Causal factors of rock moisture fluctuations were identified. But, it is not clear which fluctuations the authors are referring to. Fluctuations in a season or diurnal fluctuations? Can explaining the moisture fluctuation in a season be used to explain the diurnal fluctuations?

Response: Sorry for our unclear expression. Diurnal rock moisture fluctuations should have causal factors different from seasonal fluctuations. The term "multi-diurnal fluctuations" in the abstract should be changed to "multiday fluctuations".

Introduction:

I was confused by the word use 'cave'. It can be either an underground camber or it can be a cavity in a face of a cliff. Looking at the pictures later, it seems that the latter definition is the one applicable here. This difference is important to understand where air temperature, humidity is measured or defined. Furthermore, are air humidity and temperature measured in these caves or in the free atmosphere at some distance from the caves? I suppose that there will also be an exchange of moisture and sensible heat between the free air and the wall of the cliff and that the humidity temperature in the cavities will be different from that in the free atmosphere. I think you need to elaborate on this and explain better where air humidity, atmospheric conditions, etc. are measured and how those measurements are influenced or influence the rock moisture.

Ln 57: You want to investigate the relation between atmospheric conditions and the rock moisture content in caves. But where are the atmospheric conditions measured? In the caves or above the soil surface in the free atmosphere?

Ln 70-75: Make clear here whether you are referring to air temperature and humidity in the caves.

Response: According to the UNESCO World Heritage Centre (https://whc.unesco.org/en/list/1039), "cave" is used officially to represent the "cavity" with rock carvings.

We totally agree that the humidity and temperature in the caves are different from that in the free atmosphere outside the caves, and there is exchange of moisture and sensible heat between the free air and the wall of the cliff. In our study, air humidity and temperature are measured next to the wall of the cliff (the pink points shown in Figure 2 in the manuscript). We will describe this more clearly in the revision.

Study site and methods:

I think that a conceptual figure that shows the 'different forms of water' and the different 'sources of these forms' would be helpful.

Response: Thanks for your suggestion. We will try to plot a conceptual figure in the revision.

Figure 3 and Figure 4 should be made conform with each other. An output layer is missing in figure 4. The notation in the text should match with the notation used in figures 3 and 4. The equations in the text were mixed up.

Response: Thanks for pointing out the problems. We will fix these problems in the revision.

Ln 155: Dimensions of the weight matrices should be given.

Response: Thanks for your suggestion. We will give the dimensions of the weight matrices in the revision.

Ln 185: equations for mean absolute error and root mean square error are not correct.

Response: Thanks for pointing out the problem. We will fix the errors in the revision.

Results:

Rock moisture increases with increasing vapor concentration, also when wall temperature is higher than the dew point temperature. Is that caused by the fact that the water potential in the rock is much lower than the water potential of free water? The dew point gives the temperatures at which vapor starts condensing on a flat surface. But, wouldn't vapor also condense in a dry porous medium when the temperature is above the dew point temperature but the vapor concentration is above the equilibrium vapor concentration in the free air space that is in contact with the water in the porous medium? This equilibrium vapor concentration would be calculated from the water potential in the porous medium using the Kelvin equation.

Response: We totally agree with you. Following your approach, we have calculated the equilibrium vapor concentration in the porous medium from the water potential and wall temperature by the Kelvin equation.

As shown in Figure S4, the period with air vapor concentration being higher than the equilibrium vapor concentration in the porous medium corresponds to the period when condensation occurs. We will also add Figure S4 into the revision.

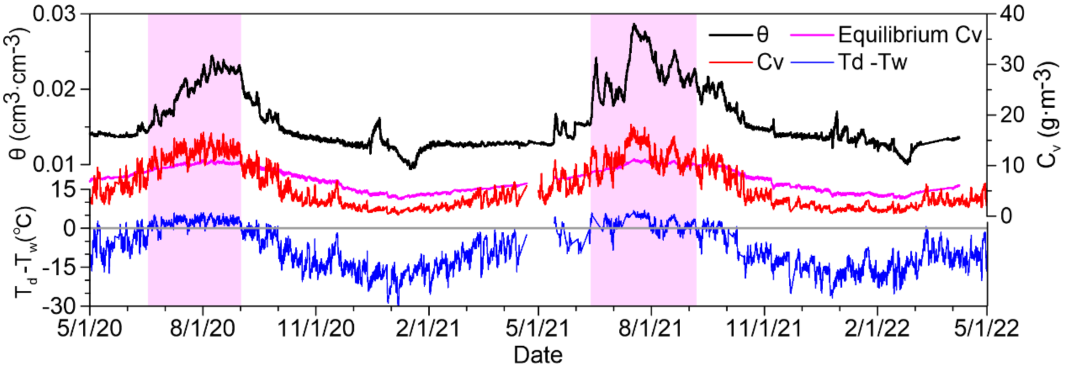

Figure S4. The equilibrium vapor concentration in the porous medium.

Reference:

Gao, S., Huang, Y. F. Zhang, S., Han, J. C., Wang, G. Q., Zhang, M. X. and Lin, Q. S.: Short-term runoff prediction with GRU and LSTM networks without requiring time step optimization during sample generation, J. Hydrol., 589, 125188, https://doi.org/10.1016/j.jhydrol.2020.125188, 2020.

Kratzert, F., Klotz, D., Brenner, C., Schulz, K. and Herrnegger, M.:Rainfall–runoff modelling using Long Short-Term Memory (LSTM) networks, Hydrol. Earth Syst. Sci, 22, 6005–6022, https://doi.org/10.5194/hess-22-6005-2018, 2018.

Fang, Z. C., Wang, Y., Peng, L. and Hong H. Y.: Predicting flood susceptibility using LSTM neural networks, J. Hydrol., 594, 125734, https://doi.org/10.1016/j.jhydrol.2020.125734, 2021.