Modeling air pressure propagation through Wind Cave and Jewel Cave: How can air pressure signals inside barometric caves be predicted from surface pressure measurements?

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Abstract: Recent speleoclimatological research has shed new light on air pressure dynamics inside barometric caves by identifying pressure-modifying processes and resulting systematic differences between cave and surface air pressure. Based on these new findings, a multi-step quantitative model is developed and explored to predict air pressure inside Wind Cave and Jewel Cave – two major barometric cave systems in the Black Hills of South Dakota, USA – from external surface measurements. Therefore, each identified speleoclimatological pressure process is translated into a mathematical operation. Model evaluation based on Pearson correlation and mean (absolute) deviation between model outputs and control measurements yields good to excellent results: Depending on the location, the presented model predicts 99.2% to 99.7% of measured air pressure inside Wind Cave compared to 90.3% and 99.4% inside Jewel Cave, thus proving that the previously identified and now modeled processes adequately and comprehensively describe the speleoclimatological pressure dynamics inside barometric caves. Slightly weaker model performance is observed at the lower elevator level inside Wind Cave and at Deep Camp inside Jewel Cave due to irregular pressure disturbances caused by elevator operation and unique morphological features in the deeper parts of Jewel Cave, respectively. Comparative spatial analyses of model constants and model accuracies at all investigated locations reveal significant differences in pressure patterns between the caves, thus demonstrating the effect of morphological characteristics on air pressure propagation and resulting modifications. The findings also support earlier research in Wind Cave and Jewel Cave as they provide speleoclimatological background for previously observed differences in airflow dynamics between both caves. Therefore, this study presents an important contribution to understanding the complex speleoclimatology of barometric caves.

Keywords: speleoclimatology, barometric cave, Wind Cave, Jewel Cave, air pressure

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INTRODUCTION

Wind Cave and Jewel Cave are two large and highly complex three-dimensional network caves in the Black Hills of western South Dakota, USA. They were formed in Carboniferous limestone and dolomite of the so-called Mississippian Madison Formation - also known as Pahasapa limestone - during the Tertiary Period (Darton, 1909; Bakalowicz et al., 1987; Palmer & Palmer, 1989; KellerLynn, 2009; Palmer, 2016). As their evolutionary history is considered the most complex of any caves in the world (Palmer & Palmer, 1989), to this day, many questions and controversies surround the formation of the caves, and their origin still causes lively debate (Palmer, 2016). With currently known lengths of 260.2 km and 339.3 km (as of March 2022), Wind Cave and Jewel Cave are the world’s seventh- and third-longest caves, respectively (Gulden, 2022). However, their total volumes and extents, as well as the existence of further cave openings (entrances), are still unknown.

Since their discovery in 1881 and 1900, Wind Cave and Jewel Cave have been famous for their strong bidirectional cave winds, distinguishing them from most other caves of the world. Thus, already the discovery of Wind Cave is closely tied to these cave winds when Black Hills pioneer Tom Bingham was attracted to the Natural Entrance by a whistling
sound of the wind and thereby found the cave (U.S. Department of the Interior & National Park Service, 1931). In 1966, Herb Conn proved the hypothesis of these cave winds being induced by external atmospheric pressure changes and thereby identified Wind Cave and Jewel Cave as barometric caves (Conn, 1966). In contrast to convective caves with a predominant chimney effect (e.g., Cigna, 1968a,b; Bögli, 1980; Atkinson et al., 1983; Faimon & Lang, 2013; Covington & Perne, 2015; Kukuljan et al., 2021), air currents in this type of cave are caused by pressure gradients between the outside atmosphere and the cave. Conn’s findings mark the beginning and still provide the foundation of all speleoclimatological research on barometric caves in the Black Hills.

Although technology available at that time only allowed very basic measurements, Conn identified the fundamental principles and mechanisms of barometric circulation systems. Based on physical airflow models and theories of a balloon-shaped and tube-shaped cave, he provided evidence that airflow inside Wind Cave and Jewel Cave reacts to external barometric changes. Furthermore, differences in the caves’ behaviors were identified as airflow in Wind Cave was observed to be stronger and to reverse more often compared to Jewel Cave.

Two decades later, Nepstad and Pisarowicz (1989) found Wind Cave to be an excellent study site to investigate the effect of cave wind velocity on variations in temperature and humidity due to its vast volume of exchanged air. For some locations inside the cave, they found significant differences between times of inflowing and outflowing air, thus suggesting an effect of barometric airflow on the temperature and humidity regime of Wind Cave. Until today, this study presents the only evidence for a so-directed relationship between airflow and temperature, thus revealing an additional characteristic of barometric caves which distinguishes them from convective caves.

Due to rapid technological progress in measuring instruments and data loggers, as well as the electrification of the caves, a new measuring program was initiated in 2001 to further explore barometric airflow dynamics in Wind Cave and Jewel Cave. Based on highly accurate ultrasonic airflow measurements, Pfliitsch et al. (2010) climatologically investigated the caves’ volumes and extents as well as a potential connection between Wind Cave and Jewel Cave. They found the actual volumes and extents of both caves to be significantly larger than previously assumed. Their extensive qualitative analysis of the relationship between atmospheric air pressure changes and induced cave winds further supported Conn’s (1966) findings on the barometric characteristics of airflow systems.

The first study investigating pressure propagation through barometric caves was presented by Gomell et al. (2021). Based on high-resolution air pressure measurements from various locations inside and outside of Wind Cave and Jewel Cave, the speleoclimatological processes causing the characteristic barometric pressure gradients were explored and quantified. By comparing cave pressure signals with simultaneous surface pressure signals, four systematic modifications were identified: Compared to atmospheric pressure signals at the surface, air pressure inside Wind Cave and Jewel Cave was (1) higher due to lower altitudes of the cave locations, (2) delayed due to a deceleration of the pressure wave at the small opening and narrow cave passages, (3) smoothed, and (4) damped due to long response times of the caves to atmospheric pressure changes.

The authors also found significant differences in the spatial pressure patterns between Wind Cave and Jewel Cave which were attributed to differences in the caves’ morphologies: In Wind Cave, the depth within the cave and the distance to the opening had only a minor effect on the strength of the observed processes. As the differences in temporal shift, smoothing, and damping between the studied sites were very small, the opening and entrance area were identified to provide the greatest obstacle for pressure waves, whereas in the deeper parts of Wind Cave, its high passage density (i.e., its large passage volume per rock volume for current cave boundaries) allowed rapid and almost undisturbed pressure propagation (Horrocks & Szukalski, 2002). In Jewel Cave, however, the reverse pattern was found: Huge differences in temporal shift, smoothing, and damping between the studied sites were observed, thus revealing the majority of the modifications of pressure signals to occur in the deep cave areas due to the lower passage density of Jewel Cave, which impedes pressure propagation.

Based on these previous findings on the processes modifying barometric pressure signals inside barometric caves, in this study, a multi-step numerical model will be developed, which allows predicting air pressure inside Wind Cave and Jewel Cave from surface air pressure measurements and, therefore, air exchange between the cave and outside atmosphere. Considering the difficulties and challenges connected to cave internal measurements, such as long and partly dangerous access routes to the measurement locations or the constantly high humidity often leading to a failure of the measuring instruments, these surface data are considerably easier to obtain. Most importantly, this model will allow exploring the relative and absolute influence of the individual modifications on pressure propagation, their relationship, as well as spatial differences in pressure dynamics within and between the caves. The evaluation will provide evidence of how well the speleoclimatological processes previously identified describe pressure dynamics inside Wind Cave and Jewel Cave and whether additional effects beyond those already known must be assumed.

**DATA BASIS AND METHODS**

From August 2017 to March 2020, an extensive long-term air pressure measurement program was carried out to investigate the courses of air pressure inside and outside the caves. High-resolution monitoring of air pressure was conducted at four locations inside Wind Cave, two locations inside Jewel Cave, and at the respective surfaces using a Baro-Sensor (Driesen + Kern DK323/391; measurement range 10 to 1300 hPa,
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Theoretical approach
Given measurements of surface air pressure (i.e., independent variable, input), the speleoclimatological processes identified by Gomell et al. (2021), which lead to air pressure modifications inside barometric caves, are translated into a multi-step quantitative model. Thus, cave air pressure (i.e., dependent variable, output) at all investigated locations inside Wind Cave and Jewel Cave can be predicted. Simultaneous cave air pressure measurements serve as control data to define the model constants for each location and process step and to evaluate the model.

The four consecutively modeled processes include a temporal shift of air pressure (x-axis, time axis), an absolute shift (y-axis, air pressure axis), a smoothing and a damping effect inside the caves. Before each model step is performed, its applicability to the data set is assessed. Afterward, the output of each model step is used as input for the next model step.
Step 1: Temporal shift
In contrast to Gomell et al. (2021), the initial step of model development is the determination of the temporal shift of cave pressure relative to surface pressure to ensure that the same section of the pressure wave is analyzed in the further course of model development. Consequently, all model constants to be determined in the following steps are time-independent and only depend on the spatial position of the investigated location. To verify barometric pressure dynamics, cross-correlation analysis between input data from the surface and simultaneous control data from within the caves is performed for each location:

\[ K(lag) = \int_{-\infty}^{\infty} Input(t) \ Control(t + lag) \, dt \]

where the temporal shift is defined as the value lag for which the integral is maximal (i.e., the correlation between the pressure signals Input and Control is highest). If the lag is positive, the cave pressure signal Control lags behind the surface pressure signal Input, and thus barometric pressure dynamics are to be assumed.

In this case, cave pressure can be modeled as surface pressure Input temporally shifted by the delay calculated before (Fig. 2a):

\[ Model_{1}(t) = Input(t - lag) \]

**Step 2: Absolute air pressure difference**
After the previously described integration of the pressure delay into the model, the same section of the pressure wave is now analyzed in the following process. Consequently, as a next step, the absolute difference between the cave and surface pressure signals due to differences in altitude can be determined and included in the model. To decide whether this process is applicable, the mean of the previously modeled cave pressure signal Model\(_{1}\), is compared to the mean of the measured cave pressure signal Control. If the mean of Model\(_{1}\) exceeds the mean of Control, their difference is added to the previously modeled cave pressure Model\(_{1}\) (Fig. 2b):

\[ Model_{2} = Model_{1} + \text{mean(Control) - mean(Model_{1})} \]

By simply attributing the mean deviation to the difference in altitude, this procedure also takes into account that an exact determination of the depths of the cave measurement locations is not possible due to the extremely complex cave morphologies. This approach is reasonable since the other pressure-related speleoclimatological processes to be modeled (i.e., smoothing and damping) affect the variances but not the means of the pressure signals.

**Step 3: Smoothing**
As a next step, the smoothing is included in the model as the caves have been found to act as low-pass filters on air pressure signals removing Fourier components of pressure variations with frequencies higher than a cutoff frequency (Schönwiese, 2013). If the correlation between the low-pass filtered previously modeled cave pressure signal Model\(_{1}\) and the measurement data Control exceeds the correlation of Model\(_{2}\) and Control, barometric smoothing can be assumed.

An FFT low-pass parabolic filter is found to best model the smoothing effect of the caves. The cutoff frequency is defined as:

\[ f_{\text{cutoff}} = \frac{1}{2n\Delta t} \]

where \( n \) is the number of data points specified, and \( \Delta t \) is the time spacing between two adjacent data points. The transformed data is multiplied with a one-side window, so the above formula is further divided by 2 to account for a two-sided window.

The function to select the frequency components does not jump abruptly at the cutoff frequency but looks like a parabola curve with a maximum of 1 at zero frequency and falling off to zero at the cutoff frequency. The corresponding window function can be expressed by:
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\[ \omega(f) = \begin{cases} 
1, & \text{if } f \leq f_{c1} \\
\frac{(f - f_{c1})^2}{f_{c2} - f_{c1}^2}, & \text{if } f_{c1} < f < f_{c2} \\
0, & \text{if } f \geq f_{c2} 
\end{cases} \]

where \( f_{c1} \) is the pass frequency and \( f_{c2} \) is the stop frequency (cutoff frequency). Further details are provided in OriginLab Corporation (2022).

For each measurement location, the ideal cutoff frequency is determined by correlation optimization. The correlations between the low-pass filtered input signals and the measured control cave signals are determined for different cutoff frequencies. The highest correlation is obtained for the ideal cutoff frequency, which best describes the smoothing effect of the caves on the pressure signals (Fig. 3).

Based on the previous output \( M_{1} \), and the optimized low-pass filter, including the smoothing effects in the model then yields (Fig. 2c):

\[ M_{3} = \text{ideal Low - Pass Filter} (M_{2}) \]

Step 4: Damping
In addition to removing high-frequency air pressure components, the low-pass filtering performed previously also leads to the attenuation of low-frequency pressure components. Thus, the modeled cave air pressure signal \( M_{1} \) has already been damped compared to the surface pressure signal \( \text{Input} \). Therefore, it is necessary to test whether the cave signal Control has experienced further damping beyond this effect by performing linear regression analysis between the low-pass filtered cave pressure signal \( M_{1} \) and the measured cave signal Control. If the slope of the resulting regression line lies between 0 and 1, the measured cave pressure Control is damped beyond the effect of low-pass filtering already included in \( M_{1} \). In this case, the damping effect is added to the model as an additional process.

By subtracting the mean of the measurement series from each pressure value, the resulting relative pressure fluctuates around zero. It can therefore be mathematically “damped” by multiplication with a damping factor \( D \) with \( 0 < D < 1 \) equivalent to the slope of the regression line. Subsequently, the damped relative pressure signal must be reconverted to absolute pressure. For the entire damping process, this yields (Fig. 2d):

\[ M_{4} = D \ast (M_{1} - \text{mean}(M_{1})) + \text{mean}(M_{1}) \]

RESULTS AND DISCUSSION

Model execution and evaluation
For all investigated locations inside Wind Cave and Jewel Cave, the entire model process, including all four model steps introduced before, can be executed as all tests (orange diamonds in Fig. 2) reveal positive results: In all cases, measured cave air pressure (a) lags behind surface pressure, (b) is higher than simultaneous surface pressure, (c) shows a higher correlation with the smoothed surface pressure compared to the initial signal and (d) exhibits further damping beyond the smoothing of high-frequency components of air pressure. Thus, the model proves that barometric pressure and airflow conditions prevail at all times throughout Wind Cave and Jewel Cave. Due to their large volumes and small openings, instantaneous equilibration of cave pressure to atmospheric variations is impeded, leading to the observed pressure patterns and characteristic compensating currents. While there are other caves of similar cave volume, the small openings of Wind Cave and Jewel Cave, however, provide unique features and therefore distinguish them from most caves in the world. In contrast to other regions, erosion in the Black Hills has resulted in more potential cave entrances being filled than opened. In addition, today, large parts of the cave-bearing Pahasapa limestone are covered by other types of rock. Thus, air exchange between Wind Cave and Jewel Cave and the outside atmosphere is limited to a few small blowholes and the known entrances, while other caves can often breathe through numerous cracks and pores throughout their entire area, allowing nearly instantaneous pressure equalization (Deal, 1962). Thus, less barometric airflow can develop in those caves.

After the previously described positive tests for barometric pressure dynamics and the determination of all model constants summarized in Table 2, the model is executed.

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Representative extracts of model results compared to control measurements are shown in Fig. 4. For better clarity of the results, a period of five days is chosen for each location. As the quality of the model is approximately constant over time, the periods displayed can be considered representative for the entire modeling and measuring period.

As demonstrated by their close agreement (Fig. 4), the final model outputs (i.e., Model₄) adequately reproduce the control measurements and thus the actual cave pressure signals inside Wind Cave and Jewel Cave. Therefore, in general, the multi-step model approach appears appropriate for all investigated locations. However, the quality of the model varies between the locations as the modeled time series at Elevator and Deep Camp deviate more strongly from the control measurements than those at other sites.

Table 2. Constants of multi-step model for all investigated locations within Wind Cave and Jewel Cave, each in ascending distance from the entrance.

| Location       | Model₁ temporal shift [hh:mm:ss] | Model₂ mean difference [hPa] | Model₃ cutoff frequency low-pass filter [1/day] | Model₄ slope linear regression |
|----------------|----------------------------------|------------------------------|-----------------------------------------------|-------------------------------|
| Wind Cave      |                                  |                              |                                               |                               |
| Pearly Gates   | 02:02:20                         | 5.7                          | 5.74                                          | 0.948                         |
| Crossroads     | 02:03:40                         | 6.3                          | 5.46                                          | 0.957                         |
| Elevator       | 02:05:40                         | 8.9                          | 5.27                                          | 0.965                         |
| Lakes          | 02:21:40                         | 15.8                         | 5.01                                          | 0.973                         |
| Jewel Cave     |                                  |                              |                                               |                               |
| Spooky Hollow  | 00:38:20                         | 17.7                         | 15.05                                         | 0.915                         |
| Deep Camp      | 10:26:40                         | 19.3                         | 0.77                                          | 0.812                         |

Fig. 4. Representative extracts of model results and simultaneous control measurements for each model step and all investigated locations inside Wind Cave and Jewel Cave over periods of five days. The four consecutive model steps are presented in columns, and the six locations are presented in rows. Control measurements of cave pressure are shown in orange, corresponding model results in blue, with darker shading indicating more advanced stages of the model.
Most noticeably, the measured cave signal at Elevator shows additional fluctuations of air pressure not predicted by the model (Fig. 4).

As expected, model performance increases by successively including the different pressure-related effects in the model. Thus, predicted and measured air pressure signals converge with each additional step. This finding is further supported by comparing the errors of each model output defined as the absolute value of deviation between the model and control measurement (Fig. 5). With each successive model step, the deviation decreases and therefore converges to the zero line.

The overall high agreement between model outputs and control measurements, as well as the gradual improvement with each included step, indicate that the identified processes of pressure modification all contribute to the actual cave pressure and that their implementation in the model is appropriate.

The differences in cave structure and distinctive morphological characteristics may provide an explanation for these observations: Wind Cave displays a sponge-like structure, characterized by a high density (i.e., large passage volume per rock volume) and closely interconnected passages extending three-dimensionally in all directions. Therefore, air pressure propagates through Wind Cave without significant obstacles and thus can be modeled accurately.

In contrast, within Jewel Cave, a significant decrease in model performance is found in the deep part of the cave. While the model at Spooky Hollow achieves a similar correlation and mean deviation as at the investigated locations within Wind Cave, a significantly poorer result is obtained at Deep Camp with a correlation of 0.9502 and a mean deviation of 1.10 hPa (Fig. 6b, 6d, Table 3). Thus, model evaluation suggests more complex pressure dynamics and processes in Jewel Cave than in Wind Cave, which are not fully reflected by the proposed model.

For Deep Camp (Jewel Cave) to 0.9983 for Crossroads (Wind Cave).

As a second quality measure, the mean deviation between each model output Model, and the corresponding control measurement is calculated for each step and location:

$$\text{Mean Deviation} = \frac{1}{n} \sum_{i=1}^{n} |\text{Model}_i(t) - \text{Control}(t)|$$

where $n$ is the number of values of the modeled and measured time series. Using the absolute values ensures that positive and negative deviations do not cancel each other out. The results are summarized in Figures 6c, 6d, and Table 3.

In addition to these visual qualitative observations, the model results are further evaluated by quantitative measures. First, Pearson correlation between each model output and the simultaneous control measurement is calculated (Fig. 6a, 6b, and Table 3). The analysis shows that there is no change in the correlation coefficient neither between Model, and Model, nor between Model, and Model, as these functions only perform a vertical shift (e.g., shift of y-axis intercept of corresponding regression line) and a change of slope of the regression line describing the linear relationship, respectively. For the final output Model, the correlation coefficients range from 0.9502 to 0.9983 for Deep Camp (Jewel Cave) to 0.9983 for Crossroads (Wind Cave).
be more complex and thus more difficult to predict. In addition, the constants determined during model development (Table 2) allow a deeper comparison of speleological pressure processes and patterns between Wind Cave and Jewel Cave.

As already discussed in Gomell et al. (2021), most pressure modifications inside Wind Cave occur in the upper part of the cave, where the small Natural Entrance and the narrow entrance area provide the strongest obstacles at which pressure waves are modified. In Jewel Cave, by contrast, the large majority of these changes in air pressure signals appear to occur in the deeper parts of the cave, where a series of constrictions causes a highly smoothed and lagged signal.

For an advanced comparative analysis of speleoclimatological processes that modify air pressure inside Wind Cave and Jewel Cave, the influence of location choice is minimized compared to previous studies: The delay and the smoothing of pressure signals at all investigated locations are no longer only examined and compared in absolute values but in relation to their position. Since an exact determination

Intra- and inter-cave comparison of model results

The evaluation of model performance has already revealed differences between the studied caves, as air pressure dynamics inside Jewel Cave were found to

As first introduced by Ringeis et al. (2007), the deeper parts of Jewel Cave between Spooky Hollow and Deep Camp, on the other hand, can be described as a series of large and wide halls connected by narrow passages restricting air exchange and, therefore, rapid pressure equalization between them. Due to large volumes of air inside these halls, they function as a long chain of "internal barometric sub-caves". Depending on the frequency of external pressure fluctuations, atmospheric pressure waves penetrate Jewel Cave to different depths, causing air to flow back and forth through the sub-caves in opposite directions. These highly complex pressure and airflow dynamics between Spooky Hollow and Deep Camp can exceed the modeled processes and superimpose air pressure signals, thus resulting in lower model accuracies.

Table 3. Quantitative quality measures for model evaluation: Pearson correlation R and mean deviation [hPa] between model and control measurements for all investigated locations.

| Location               | Model 1 | Model 2 | Model 3 | Model 4 | Model 1 | Model 2 | Model 3 | Model 4 |
|------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Wind Cave Pearly Gates | 0.9964  | 0.9964  | 0.9981  | 0.9981  | 5.66    | 0.43    | 0.31    | 0.24    |
| Wind Cave Crossroads   | 0.9965  | 0.9965  | 0.9983  | 0.9983  | 6.28    | 0.44    | 0.31    | 0.25    |
| Wind Cave Elevator     | 0.9934  | 0.9934  | 0.9963  | 0.9963  | 8.90    | 0.45    | 0.34    | 0.32    |
| Wind Cave Lakes        | 0.9958  | 0.9958  | 0.9978  | 0.9978  | 15.82   | 0.42    | 0.30    | 0.28    |
| Jewel Cave Spooky Hollow| 0.9965  | 0.9965  | 0.9968  | 0.9968  | 17.73   | 0.50    | 0.48    | 0.30    |
| Jewel Cave Deep Camp   | 0.9191  | 0.9191  | 0.9502  | 0.9502  | 19.36   | 2.10    | 1.37    | 1.10    |
of the distance from the opening is not possible due to the highly complex cave structures, instead, the altitude-dependent absolute difference between cave and surface signals is used as a proxy for depth. All other pressure-related speleoclimatological effects only affect the measures of dispersion (variance, range) but not the means of the pressure signals. Therefore, the mean absolute barometric pressure shift can be attributed to the difference in elevation.

For each investigated location, the delay determined by cross-correlation analysis and the ideal smoothing period determined by correlation optimization are normalized by absolute air pressure shift. The smoothing period is derived from the reciprocal of the cutoff frequency introduced before and is used because of its positive correlation with the degree of smoothing. Because the damping of air pressure directly results from the delay and smoothing, it does not provide any further insights and is therefore excluded from this analysis. For the dependence of smoothing and damping on the delay, see Supplementary Figure S1.

Inside Wind Cave, the greatest relative pressure changes in terms of delay and smoothing per depth occur in the upper part of the cave. With increasing depth, the depth-dependent rate of air pressure modifications is found to decrease (Fig. 7a). Thus, a delay per absolute shift of 00:21:37 hour/hPa is observed at Pearly Gates, which then gradually decreases to 00:08:57 hour/hPa at Lakes. The ideal smoothing period per absolute shift behaves analogously with a gradual decrease from 00:44:20 hour/hPa at Pearly Gates to 00:18:11 hour/hPa at Lakes (Fig. 7a). The results suggest that in Wind Cave, a large proportion of the cave volume is located near the entrance in the uppermost part of the cave above Pearly Gates. Due to its dense sponge-like structure described earlier, fluctuations of external pressure thus reach the entire cave within a few hours.

Jewel Cave, however, exhibits the opposite trend: At Spooky Hollow, pressure delay and ideal smoothing period per absolute shift are as low as 00:02:10 hours/hPa and 00:05:24 hours/hPa, respectively, but increase to 00:32:22 hours/hPa and 01:36:17 hours/hPa at Deep Camp (Fig. 7b). Thus, in contrast to Wind Cave, the degree of pressure modifications per depth significantly increases with depth, indicating that much of the volume of Jewel Cave must be located far from the entrance below Spooky Hollow. Despite the relatively large altitude difference and, therefore, distance to the entrance, only very weak pressure modifications occur above that location owing to the significantly larger opening, allowing fast and less disturbed pressure propagation.

The analysis reveals that the extraordinary pressure changes at Deep Camp cannot be explained solely by its long distance from the entrance. Even in relative terms of modifications per depth, pressure changes at Deep Camp far exceed those at all other investigated locations (Fig. 7). This finding provides further evidence for the strong pressure-modifying effect of the unique morphological structure of Jewel Cave, characterized as a long chain of barometric sub-caves separated by constrictions. Both the relative and absolute strength of pressure changes at Deep Camp provide evidence that there are no other previously undiscovered openings close to this area.

For further insights into the smoothing and damping processes inside Wind Cave and Jewel Cave, dominant frequency components of the cave’s internal smoothing effect on air pressure are located and compared. Therefore, FFT spectrum analysis is performed, converting the difference functions of cave and surface pressure signals in the time domain into their counterparts in the frequency domain (e.g., Cooley & Tukey, 1965; Cochran et al., 1967; Cooley et al., 1967, 1969; Nussbaumer, 1981; Frigo & Johnson, 2005). With the transformed data, the amplitude is computed as $\sqrt{Re^2 + Im^2}/n$

where Re and Im are the real and imaginary parts of the transform data and n is the length of the input sequence. The results for all locations are displayed in Figure 8. Additionally, all original FFT spectra of the cave and surface signals after the application of the time shift are shown in Supplementary Figure S2.
Once again, the results support the previous findings that the strength of the smoothing effect and its frequency distribution are relatively constant throughout the investigated locations inside Wind Cave. Across the cave, the strongest smoothing occurs at frequencies of 2/day, connected to periodic pressure components caused by atmospheric tides (e.g., Chapman & Lindzen, 1970; Forbes & Garrett, 1979; Lindzen, 1979). At this frequency, the smoothing amplitudes range from 0.15 to 0.19 hPa (Fig. 8a-8d). Additionally, the analysis reveals similar smoothing of low-frequency pressure fluctuations with periods of several days caused by alternating high- and low-pressure systems (i.e., anticyclones and cyclones). Smoothing of air pressure fluctuations in this frequency range causes the observed damping effect on the cave pressure signal. Thus, the transformed data prove that a large majority of the smoothing and damping effect inside Wind Cave occurs in the uppermost part of the cave. In contrast, pressure waves between Pearly Gates and Lakes propagate without experiencing significant smoothing and damping.

Inside Jewel Cave, significant amplitudes of power spectral densities differ considerably between the investigated locations: At Spooky Hollow (Fig. 8e), the smoothing effect on the semi-diurnal atmospheric tides (frequency = 2/day) is much less pronounced than in Wind Cave with smoothing amplitudes of only 0.06 hPa. Also, over other frequencies, only weak smoothing occurs, which agrees with the very high cutoff frequency of the corresponding ideal FFT filter (Fig. 3, Table 2). As expected from previous analyses, the frequency distribution of the smoothing function at Deep Camp, however, shows a completely different pattern (Fig. 8f): Here, much stronger smoothing of low-frequency variations is obtained as pressure fluctuations with a period of 6.3 days exhibit a smoothing amplitude of 1.6 hPa, thus highly exceeding smoothing at any other location and causing the strong damping found at Deep Camp. Considering the large distance between Spooky Hollow and Deep Camp and their enormous difference in pressure modifications, further research on sites located in between is needed for a better understanding of the dynamics of pressure fluctuations.

Fig. 8. FFT transfer functions (amplitude over frequency) of difference functions of cave and surface pressure signals for all investigated locations inside Wind Cave (a-d, top and middle) and Jewel Cave (e-f, bottom). The frequencies of dominant amplitude differences indicate frequencies of strong smoothing.
propagation between the two locations.

Interestingly, the findings of this study are closely related to previous speleoclimatological research from the Black Hills, as they can offer an explanation for previously observed differences in airflow dynamics between Wind Cave and Jewel Cave. Conn (1966) and Pflitsch et al. (2010) found airflow at Wind Cave to be stronger and to react almost directly to external pressure changes, resulting in frequent reversal of airflow direction at the Natural Entrance. Airflow at Jewel Cave, on the other hand, was weaker and experienced longer periods of consistent flow direction as its reaction to external pressure changes was delayed.

These different airflow dynamics result from the differences in pressure patterns throughout Wind Cave and Jewel Cave analyzed and described in this study. Due to Wind Cave’s morphological structure, pressure equalization is faster compared to that of Jewel Cave, resulting in smaller pressure changes being sufficient to reverse airflow direction, thus producing airflow patterns as found by Conn (1966) and Pflitsch et al. (2010).

CONCLUSIONS

Based on recent findings on speleoclimatological air pressure dynamics, this study shows the possibilities and limitations of predicting air pressure inside barometric caves from surface measurements. For four locations inside Wind Cave and two locations inside Jewel Cave, a gradual quantitative model was developed from quantification of previously identified speleoclimatological pressure modifications and their transfer into mathematical operations. Due to the huge morphological complexity of the investigated caves, prior data collection at the locations of interest was necessary to determine the model constants.

The model was tested and gradually evaluated on the basis of Pearson correlation and the mean deviation between predicted and measured cave pressure signals. Good to excellent results could be achieved across all locations, proving that the previously identified and now modeled processes adequately and comprehensively describe the speleoclimatological pressure processes inside barometric caves. For Wind Cave, the presented model was able to explain 99.2% (Elevator) to 99.7% (Crossroads) of measured air pressure compared to 90.3% (Deep Camp) and 99.4% (Spooky Hollow) for Jewel Cave.

The exceptionally strong absolute pressure modifications at Deep Camp had already been identified and discussed in previous studies. Until now, however, it could not be clearly proven that these are not only due to the location’s great depth, but also to the unique cave structure of Jewel Cave consisting of a long chain of large halls connected by narrow constrictions, which function as individual barometric sub-caves. This study has now revealed significant differences in speleoclimatological pressure dynamics between the two studied caves independent of location choice, thus providing evidence for the effect of morphological characteristics on air pressure propagation and resulting modifications. The new findings integrate well with previous research in the Black Hills caves, as they provide speleoclimatological explanations for observed differences in airflow dynamics between Wind Cave and Jewel Cave. Considering the fundamental relevance of airflow for almost all elements of speleoclimatology, this study significantly contributes to a better understanding of the complex climate systems inside barometric caves.

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