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Front Cover: Lee-side exposure of a fossil parabolic dune viewed from the Grahams Harbour side (west) of North Point, San Salvador, Bahamas. These Holocene carbonate eolianites have been assigned to the North Point Member of the Rice Bay Formation (Carew and Mylroie, 1995). The eolian cross-stratification dips below present sea level, proving that late Holocene sea-level rise is real. Top of the dune is about 7 meters above the sea surface. Photo by Al Curran.

Back Cover: Dr. Noel P. James of Queen's University, Kingston, Ontario, Canada, keynote speaker for this symposium. Noel is holding a carving of a tropical fish created by a local artist and presented to him at the end of the symposium. Photo by Al Curran.

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A COMPARISON OF TIDAL AND NONTIDAL CAVE TEMPERATURES ON SAN SALVADOR ISLAND, BAHAMAS: A PRELIMINARY ANALYSIS

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ABSTRACT

Horizontal and vertical temperature profiles between a non-tidal (Garden Cave, no tidal water present) and tidal (Crescent Top Cave, tidal water present) cave on San Salvador Island, Bahamas were compared. Temperatures were measured and recorded approximately every five minutes for a three and a five day period, using Hobo™ temperature data loggers. Temperatures were recorded simultaneously for a horizontal (cave entrance to back) profile, vertical profile (top of bell hole to floor of cave), and one exterior location (outside cave entrance). Temperature observations indicated that for the non-tidal cave, temperature increased from the entrance of the cave to the back (entrance mean temperature 22.0°C, back mean temperature 23.8°C), while variance in temperature observations decreased from the entrance of the cave to the back. For the vertical temperature profile in the non-tidal cave, temperature increased with height above the floor (floor mean temperature 22.5°C, ceiling mean temperature 24.1°C), creating an atmospherically stable environment. Temperatures within the cave decreased uniformly with the passage of an atmospheric low pressure trough across the island during the study period.

The thermal environment of the tidal cave was different from the non-tidal cave. Temperature increased from the entrance of the cave to the back along the horizontal profile (entrance mean temperature 25.0°C, back mean temperature 25.6°C), while variation of temperature observations decreased from the entrance to the back of the cave. The vertical profile in the tidal cave indicates an atmospherically unstable environment. Temperatures decreased from the floor of the cave to the top of the bell hole (tidal pool mean temperature 27.5°C, ceiling mean temperature 26.1°C). In addition, temperatures directly above and below the tidal water surface displayed a symmetrical, cyclical component which coincided with the tidal cycle. Temperatures rose at high tide, and decreased at low tide. The different thermal environments within the two types of caves indicates a greater complexity and variability in cave micro-climates than alluded to by previous literature. In addition, a two-zone cave climate model may be most appropriate for these tropical flank margin caves. Further, tidal water inside a cave may enhance atmospheric instability. Such instability may

support the dissolution process of condensation-corrosion.

INTRODUCTION

The climatology of caves has received considerable attention due to its impact upon cave morphology, cave biology, cave paleontology, and cave management (Buecher, 1995; Niven & Hood, 1978). Despite the initial belief that cave climate is constant and static, much research has documented the variability of climatic parameters, and a three-zone model has been developed to describe the general zones of climatic variability within a cave (Cropley, 1965; Poulson & White, 1969; Trapasso & Kaletsky, 1994). According to this three-zone model, a twilight zone exists near the cave entrance with greatest variability in climate parameters. Moving from the entrance towards the back of the cave, the influence of exterior climatic conditions diminishes and a middle zone exists in complete darkness with some variability in cave climate. Further in the cave, close to the back, a deep cave zone exists with constant climatic conditions.

One difficulty with the application of this three-zone model is that it has been developed almost exclusively from observations in mid-latitude/temperate regions. For instance, in Wefer's (1991) annotated bibliography of cave climatology, the most extensive listing of literature pertaining to the subject, only three out of 221 sources listed pertain to tropical cave systems. Thus, researchers investigating tropical cave climatology are challenged by the absence of an appropriate cave climate model. Tarhule-Lips & Ford (1998) found the 'Turbulent Pipe Flow' model (Wigley & Brown, 1976) (a refinement of the three zone model developed from temperate cave climate data) requires considerable modification in order to be applicable to caves in Puerto Rico and the Cayman Islands.

The purpose of this study was to assess the climate of two types of tropical caves, tidal and non-tidal, on San Salvador Island, Bahamas

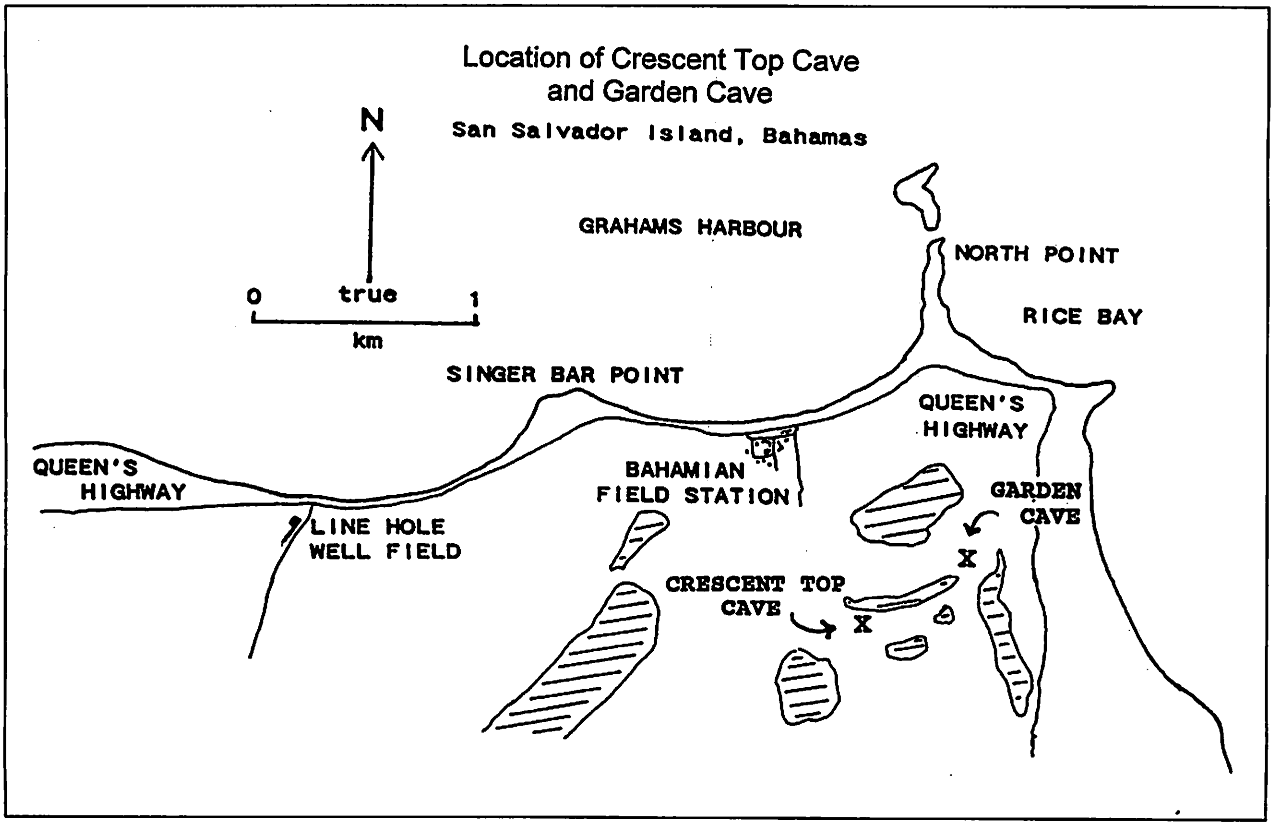

Figure 1. Location of Crescent Top Cave and Garden Cave, San Salvador Island, Bahamas.

and determine the utility of the three-zone cave climate model for tropical cave systems. In addition, temperature observations will be used to assess the potential for the occurrence of condensation-corrosion, a speleogenetic process supported by atmospheric instability within a cave (Dublansky & Dublansky, 1998). Much debate over the validity of condensation-corrosion exists, and this study offers a preliminary analysis of the potential of condensation-corrosion in tropical cave systems based upon microclimate observations (e.g. Frank et al., 1998 vs. Tarhule-Lips & Ford, 1998).

STUDY AREA

San Salvador Island is 640 km East-Southeast of Miami, Florida and is 11.2 km long and 7 km wide (Shaklee, 1994). San Salvador represents one of the small isolated carbonate platforms common to the southeastern Bahamas (Carew & Mylroie, 1997). Due to the carbonate nature of the rock, caves and subterranean voids are common throughout the Bahamas and San Salvador itself. Four general types of caves exist, pit caves, flank margin, banana holes, and lake drains (Mylroie et al., 1995). The two caves included in this study are flank margin caves, which formed in the distal margin of a freshwater lens, under the flank of an eolianite ridge, where fresh water and sea water mix and produce dissolutionally aggressive water (Mylroie & Carew, 1990; Mylroie et al., 1995). Both caves are located at interior locations next to saline ponds in the north-northeast portion of San Salvador (Figure 1). The main chamber of Garden Cave is oriented northwest-southeast with a single entrance facing southeast and the back of the cave to the northwest. The chamber length is 15 m along the northwest-southeast axis and the width is 5 m along the southwest-northeast axis (Figure 2). The entrance is reached by dropping down into a 1.5 m deep banana hole. Inside the cave itself the floor is level from entrance to back (no slope to cave floor) and height from ceiling to floor ranges from 1.5 m near the entrance, and 2 m in the back of the cave.

The second cave, Crescent Top Cave, is oriented north-south with a single entrance facing north-northeast (Figure 3). The cave can be divided into two parts a main chamber and two sub-chambers. The main chamber, where temperature observations were recorded, is 15 m along the north-south axis and 6 m wide on the west-east axis. Within 3 m of the entrance of the cave and the main chamber, the cave floor slopes downward to a depth of approximately 1 m below the cave entrance. After this initial downward slope, the cave floor is level for the remainder of the cave. The distance from the floor of the main chamber to the ceiling is 1.5 m, except for the back of the cave where a pool of water exists, and the distance from the floor of the pool to the ceiling of the cave is 6 m. The two sub-chambers of the cave represent an area that is 8 m along the north-south axis, and 15 m along the west-east axis. The height of these chambers ranges from 0.5 m to 1.5 m. Instruments were only placed in the main chamber of Crescent Top Cave in order to facilitate comparison with Garden Cave due to similar depth, width, and shape. There is potential that the existence of the sub-chambers may cause a different microclimate in Crescent Top Cave's main chamber as compared to Garden Cave. However, since Crescent Top cave is a single entrance cave with no running water or other potential modifiers of cave climate in the sub-chambers, the sub-chambers are expected to have little if any effect upon the microclimate of the main chamber (Smithson, 1993; Wigley & Brown 1976).

METHODOLOGY

Onset Hobo™ data loggers were placed in the two caves in horizontal and vertical transects, programmed to collect temperature observations every one and a half minutes in Garden Cave from 9:00AM December 29, 1997 to 9:00 AM December 31, 1997, and every ten

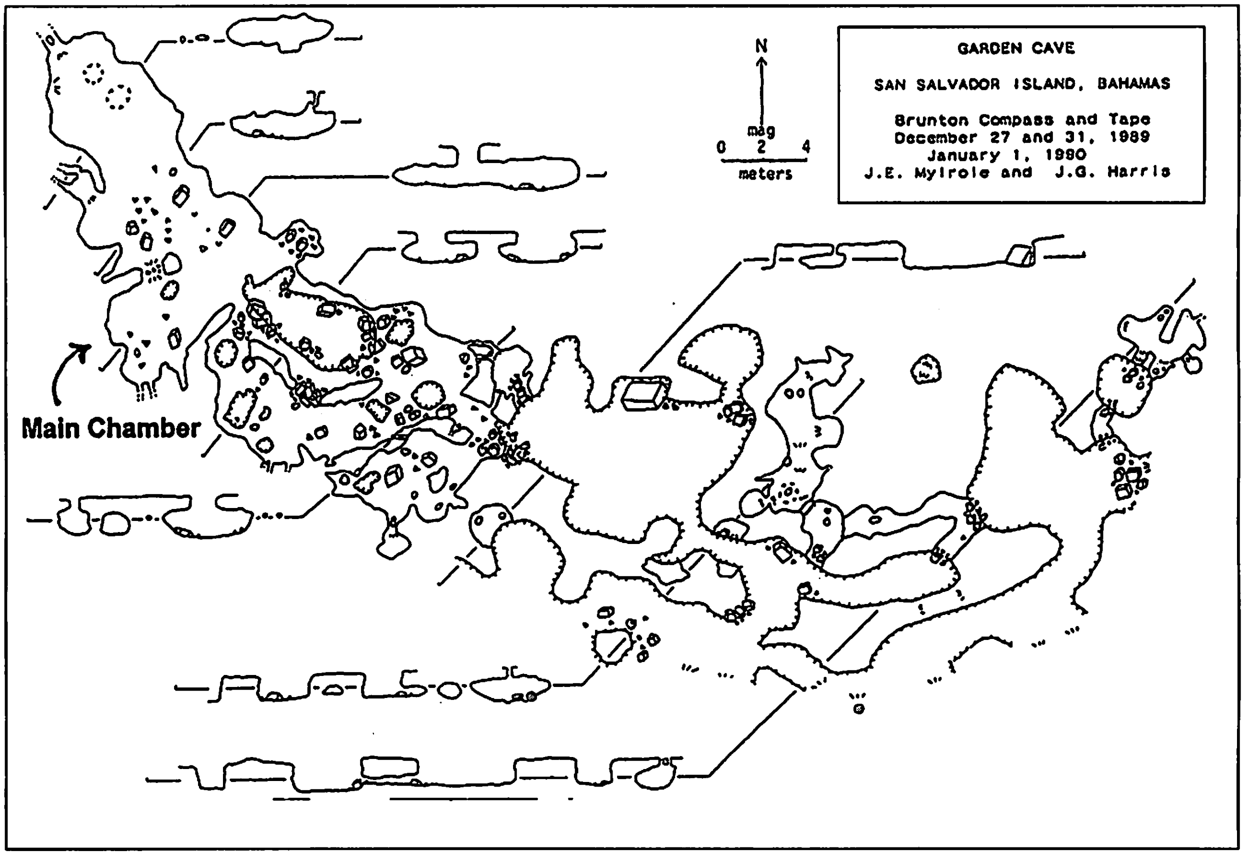

Figure 2. Map of Garden Cave.

minutes 3:00 PM January 2, 1998 to 12:00 PM January 5, 1998 in Crescent Top Cave. In addition one data logger was placed outside each cave entrance to observe external air temperatures during the data collection period. Data loggers were placed approximately every 4 m along the horizontal transects, and attached approximately every 40 cm to a suspended rope for the vertical transect. Sling psychrometer observations were also recorded within the data collection period in order to verify and calibrate data logger observations. At the end of each data collection period, observations were downloaded from the data loggers to a laptop computer, and these observations were imported into various statistical software for analysis.

RESULTS

Garden Cave

Observations from the horizontal gradient indicate cooler conditions near the entrance and warm conditions at the rear of Garden Cave (Figure 4, Table 1). The vertical transect observations indicate cool conditions at the floor of the cave and warmer conditions at the ceiling of the cave (Figure 5, Table 1). Such conditions are expected for winter in a single entrance cave with a down sloping entrance in temperate latitudes (Wigley & Brown, 1976). It is to be noted that even though the floor of Garden Cave is level, air must drop 1.5 m into the banana hole before entering the cave and therefore simulates a downsloping cave (passages below entrance). Statistical analysis indicates that variance in temperature decreases from the entrance to the rear of the cave and from the floor to the ceiling of

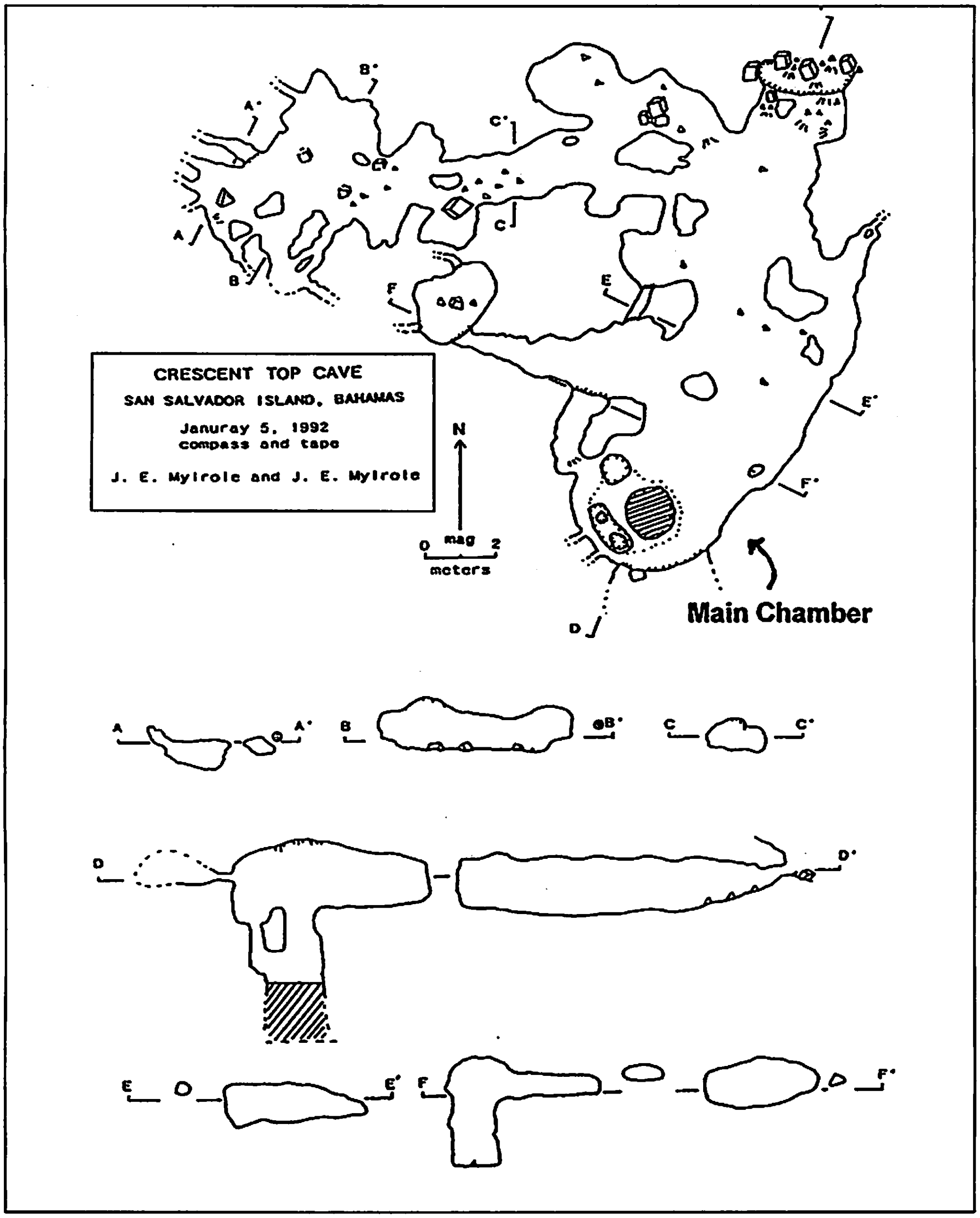

Figure 3. Map of Crescent Top Cave.

the cave (Table 1). Such decrease in variance fits the temperate three-zone model and represents a decrease in the influence of the exterior climate from front to rear, and floor to ceiling. In addition, linear regression analysis indicates that exterior temperatures explain less variance in cave temperatures moving to the rear and ceiling of the cave (Table 1). Again such patterns support the temperate three-zone model and the dampening of exterior conditions influence deeper in the cave.

However, despite the decrease in the influence of exterior conditions deep in the cave, all portions of the cave displayed influence from a storm as it passed across the island the night of December 31, 1997. The passage of an atmospheric trough brought behind it a cool, dry air mass from the continental United States, causing a drop in temperatures across the Bahamas. This decrease in temperatures can be seen in the observations recorded by each data logger (Figure 4 & 5). The largest drop in temperature was at the cave entrance and floor, while the smallest drop in temperatures was at the rear

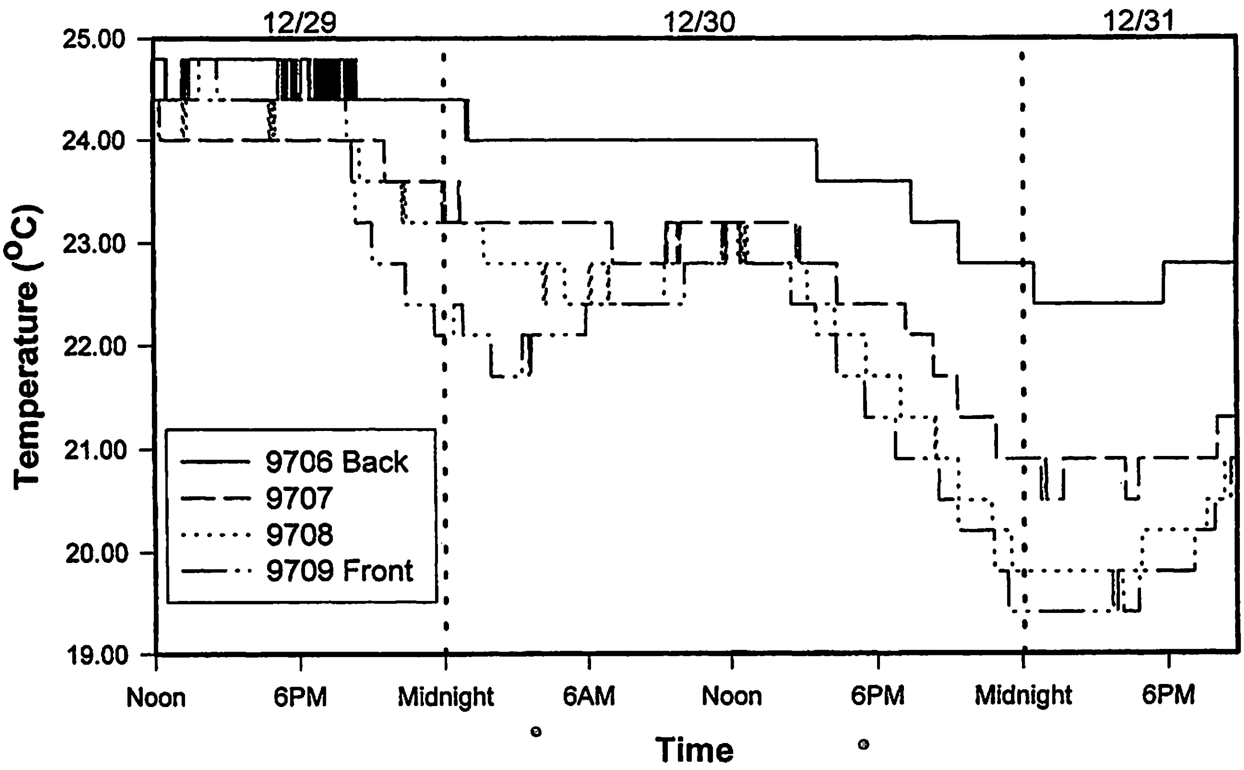

Figure 4. Garden Cave, Bahamas: horizontal transect temperature observations.

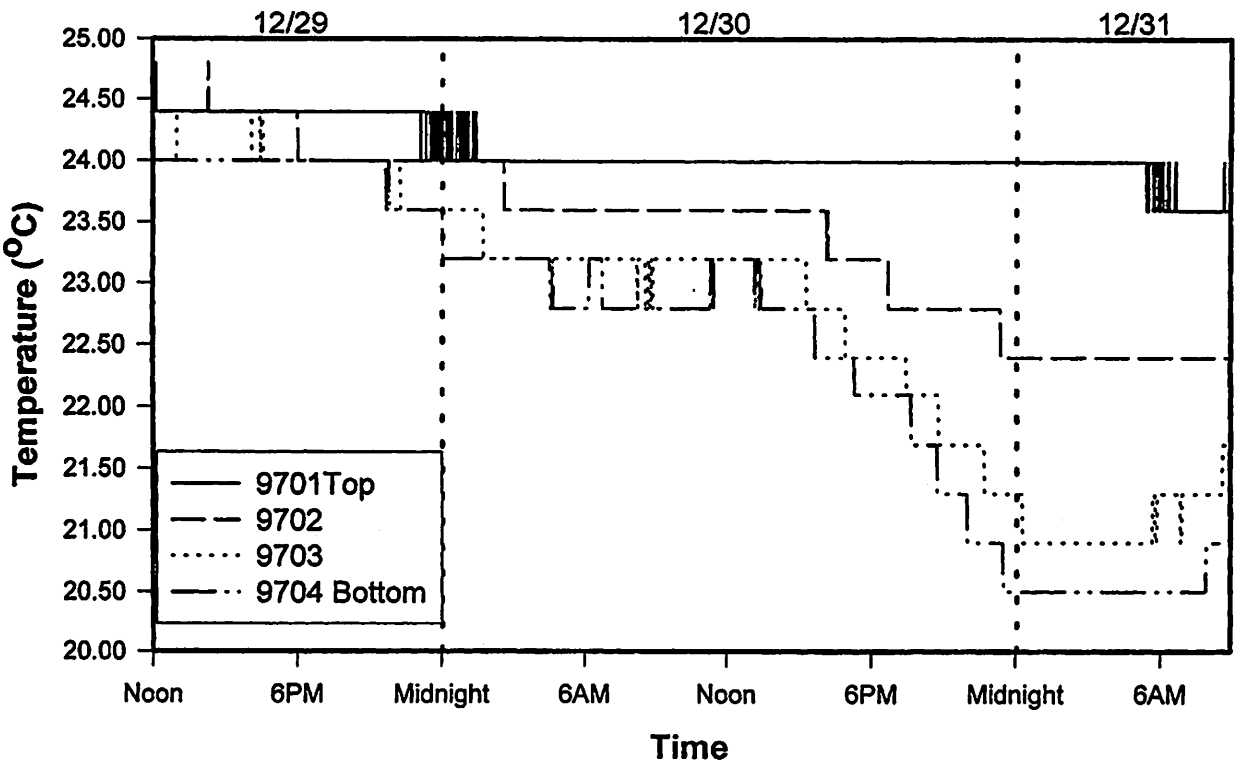

Figure 5. Garden Cave, Bahamas: vertical transect temperature observations.

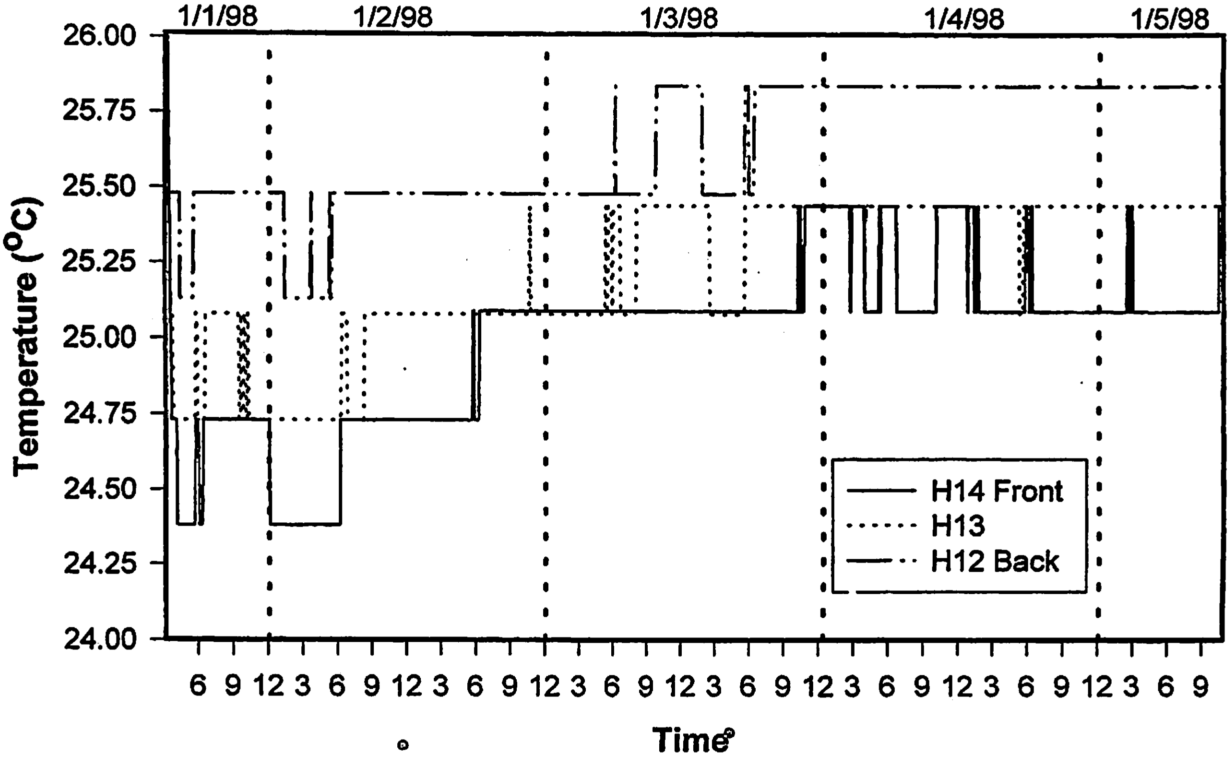

Figure 6. Crescent Top Cave, Bahamas: horizontal transect temperature observations.

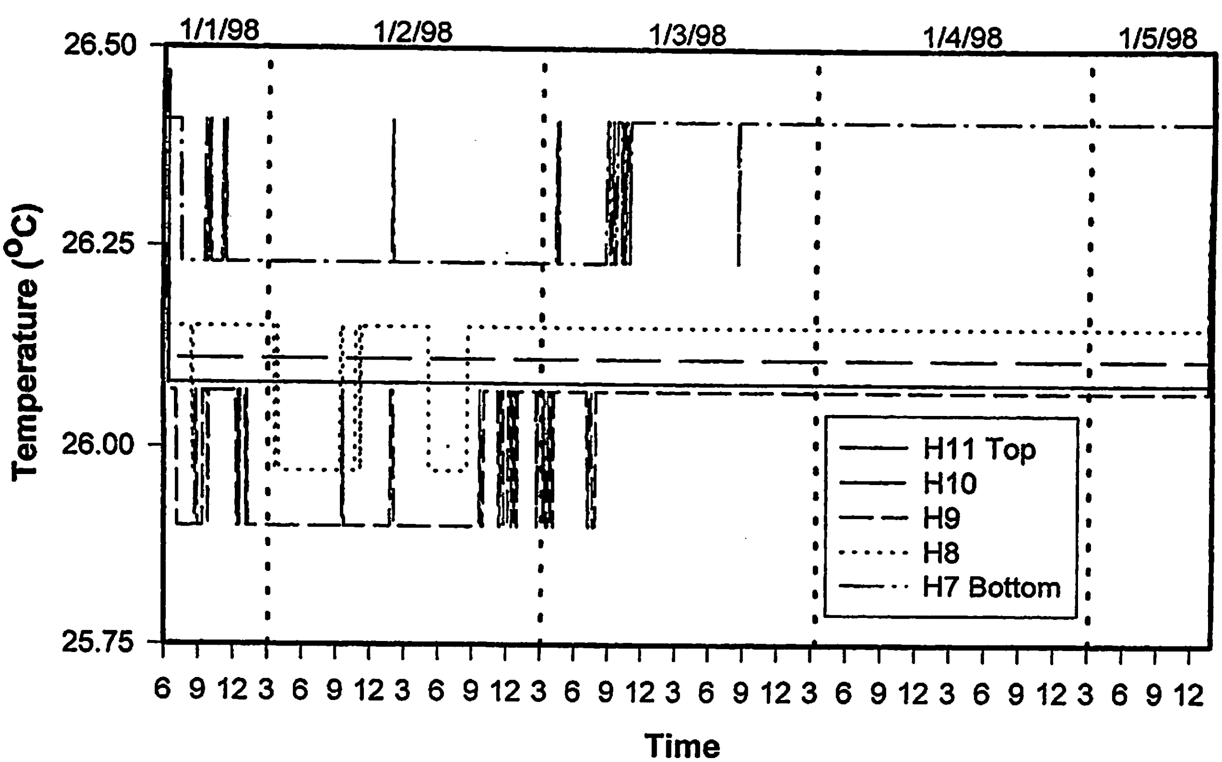

Figure 7. Crescent Top Cave, Bahamas: vertical transect temperature observations, nontidal component.

A) Horizontal Transect:

Data Logger	Mean Temp (°C)	Coefficient of Variance	Linear Regression with Exterior Temperature (r^2)
9706 (Back)	23.75	0.0324	0.74
9707	22.67	0.0507	0.74
9708	22.26	0.0669	0.80
9709 (Front)	21.97	0.0742	0.90
9710 (Exterior)	21.53	0.1340	

B) Vertical Transect:

Data Logger	Mean Temp (°C)	Coefficient of Variance	Linear Regression with Exterior Temperature (r^2)
9701 (Ceiling)	24.09	0.0091	0.39
9702	23.42	0.0290	0.73
9703	22.81	0.0491	0.75
9704 (Floor)	22.52	0.0560	0.72

Table 1. Summary statistics for Garden Cave temperatures.

A) Horizontal Transect:

Data Logger	Mean Temp (°C)	Coefficient of Variance	Linear Regression with Exterior Temperature (r^2)
H12 (Back)	25.64	0.0086	0.25
H13	25.23	0.0103	0.32
H14 (Front)	25.00	0.0116	0.27
H15 (Exterior)	22.94	0.0488	

B) Vertical Transect:

Data Logger	Mean Temp (°C)	Coefficient of Variance	Linear Regression with Exterior Temperature (r^2)
H11 (Ceiling)	26.08	0.0015	0.0034
H10	26.11	0.001	0.0009
H9	26.03	0.0031	0.0800
H8	26.13	0.0023	0.0500
H7	26.34	0.0034	0.1200
H6	26.66	0.0041	0.0520
H5	26.88	0.0119	0.0580
H4	26.97	0.0074	0.0002
H3	27.54	0.0058	0.0250
H1 (Floor)	27.51	0.0033	0.0340

Table 2. Summary statistics for Crescent Top Cave temperatures.

and ceiling of the cave.

Crescent Top Cave

Temperature observations from the horizontal transect indicate Crescent Top Cave was cool near the entrance and warm at the back (Figure 6, Table 2). In addition, the variance of temperatures decreases moving from the entrance to the back (Table 2). Since the data collection period for Crescent Top Cave followed the data collection period for Garden Cave, a general warming temperature can be observed in the exterior temperatures and temperatures from the horizontal transect (Figure 6). This warming trend represents the modification of the cool, dry continental air mass which moved over the island after passage of the trough. It should be noted that two intense thunderstorms affected the northern part of San Salvador during the Crescent Top Cave data collection period (January 3 and 5, 1998). These storms caused a quick drop in exterior air temperatures. However, these short term temperature variations were not evident in the temperature data collected within Crescent Top Cave (Figure 6 & 7).

Temperature observations from the vertical transect in Crescent Top Cave represent a very different vertical thermal environment as compared to Garden Cave. Temperatures are warmer on the floor of the cave and decrease moving up towards the ceiling. In addition to this temperature gradient the vertical profile can be separated into two components; tidal and nontidal. In the nontidal component, the air temperatures display a warming trend after passage of the trough and no variability at the ceiling of the cave (Figure 7). The tidal component displays warmer conditions near the bottom of the tidal pool, and cooler conditions above the pool. In addition to this temperature gradient, there was a cyclical pattern in the temperatures (Figure 8). The cyclical pattern shows a rise and fall in temperatures twice a day. This rise and fall in temperatures correspond with the tidal chart from Nassau, Bahamas. The rise in temperatures corresponds with high tide and the decrease in temperatures corresponds with low tide. The authors believe the tidal water sits in Crescent Pond, near Crescent Top Cave, absorbing incoming solar radiation and increasing water temperature. As the tide begins to rise, this water flows into Crescent Top Cave raising the temperature of the tidal pool and the air column directly above it through conduction. Once this warmer water is inside the cave, heat is absorbed by the rock surrounding water and the water and air temperature decreases creating a repeated cyclical temperature pattern.

CONCLUSIONS

The purpose of this study was to determine the utility of the three-zone cave climate model for tropical cave systems and assess the potential for the occurrence of condensation-corrosion. Data collected for this study indicate that even though there was a dampening of the exterior climate influence moving toward the back of the cave, the three-zone model was not appropriate. A two-zone model may be more appropriate because the deep cave zone, or zone of constant climate conditions, does not exist in Garden or Crescent Top Cave. The temperatures in the back of the cave show variance and potential influence from exterior climate conditions. The reason for the absence of the deep cave zone was the physical dimensions of the caves themselves. It has long been recognized the shape and form of a cave is the major control on its microclimate (Geiger, 1965). The majority of caves observed in previous analysis of cave climate were phreatically developed and are much more extensive in depth and length. The relatively young flank margin cave systems of tropical islands are small by comparison. Thus, these caves do not allow for a zone so deep under the earth's surface that climate is constant and unaffected by exterior conditions.

In regard to condensation-corrosion, one of the first requirements for the development of convection inside a cave is an atmospherically unstable environment. An atmospherically unstable environment is created by warm, less dense air underneath cooler, denser air (Barry & Chorley, 1992). This allows for air to rise and cool and then subside, continually perpetuating convection. In condensation-corrosion, air rises by convection, cools to the dew point, condenses on the cave ceiling, and dissolves limestone rock, creating a depression feature (a bellhole in Bahamian caves) (Dublansky & Dublansky, 1998; Tarhule-Lips & Ford, 1998). Bellholes are present in both Garden Cave and Crescent Top Cave, and the vertical temperature transects used for observation in this study were placed from the cave floor to the top of bellholes. Only in Crescent Top Cave was the

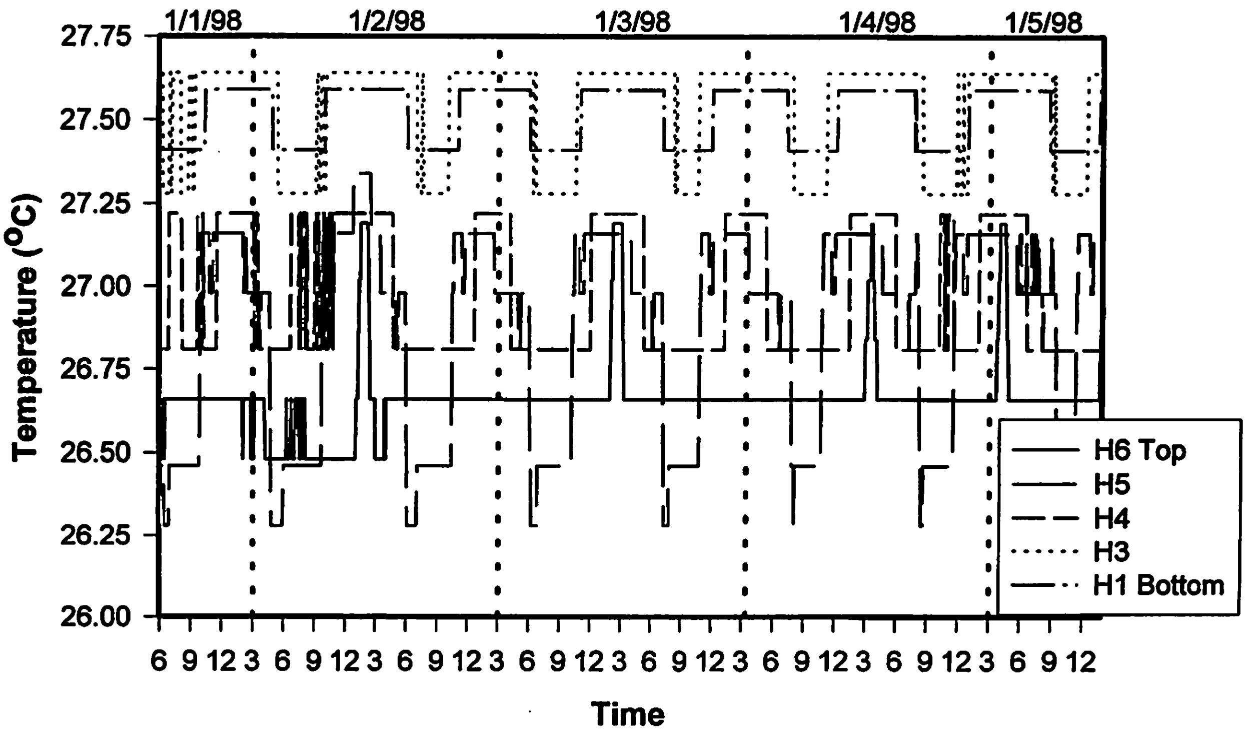

Figure 8. Crescent Top Cave, Bahamas: vertical transect temperature observations, tidal component

atmosphere unstable (warm at floor, cool at ceiling). Thus, from these limited observations it appears the existence of tidal water creates an unstable cave climate. Such tidal caves may be the tropical equivalent to thermal caves where many ceiling dissolution features are associated with condensation-corrosion.

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