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Chapter 5

SEA LEVEL CHANGE AS A FORCING FUNCTION OF ANCHIALINE CAVE ENVIRONMENTS READJUSTMENT IN THE HUMID TROPICS OF THE GULF OF MEXICO AND THE CARIBBEAN

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ABSTRACT

A rise of the sea level between 0.15 and 0.27 m would be expected in the Gulf of Mexico and the Caribbean by 2100. Previous work has suggested future submergence of mangroves in the wider Caribbean region based on historical and geological rates of peat accretion. Less attention has been devoted to the effect of changing sea level on specific aspects related with the stability of coastal karst ecosystems and specifically with cave environments. The expected sea level raise will produce a combination of the following effects over the coastal cave environments and its support system like: the disappearance of stable cave ecosystems including anchialine cave environments; the extinction, disappearance or at least in the best scenario a migration of aquatic cave populations to connected inland aquifers; major changes in groundwater chemical composition which in turn affects the mass fluxes in karst ecosystems sand the loss of connections to the surface and among caves producing some sort of genetic isolation or recolonization of

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reflooded caves by troglobites. Those effects will be particularly enhanced in the case of anchialine caves because of their particular hidrodynamics and biochemistry and are discussed in this contribution.

INTRODUCTION

One of the most complex effects of the climate change for the islands and small islands and the coastal zone of the karst regions of the Gulf of Mexico and the Caribbean is related with the ascending sea level. As a matter of fact, according to the last report of the International Panel for Climate Change (IPCC) the range of sea level increase for the last decade of the XXI century will be expected between 0.18 and 0.59 m above the average of the last 20 years of the XX century.

Main attention of researchers and governments has been focused upon the problem of the coastal flooding. This is indeed an actual problem because there´s a large population, tourist facilities and economics based on the coastal zone ecotones. It is common that despite the efforts of the scientific community to divulgate the information of the damages that are and will be associated in the next future with this particular effect no substantial engineering (structural) measures neither non-structural measures like improvement of the construction standards, environmental education, laws and regulationshave been implemented (Gill et al., 2004; Molerio et al., 2007, Molerio & Parise, 2009).

Karst coastal aquifers (Molerio et al., 2007) all over the world are important because of their potential to provide fresh water resources to coastal communities (Arfib et al., 2007). In the other hand, freshwater aquifers usually house communities of vertebrate and invertebrate faunas, largely characterized by their high levels of endemism and fragility (Humphreys, 2006; 2008).

Because of their proximity to the sea coastal aquifers are more likely affected by sea level rise. As sea level rises, increased ocean hydrostatic head will cause the saltwater interface to migrate inland, especially if the water table is held constant (Zygnerski & Langevin, 2007). Nevertheless, there are relatively few studies ofkarstcoastal aquifers, and they are often limited to the description of particular aquifers (e.g., Stringfield & Legrand 1971; Calvache & Pulido-Bosch, 1994; Howard & Mullings, 1996). Spechler (1994) proposed four mechanisms of intrusion of saltwater within aquifer systems in Florida:

- The movement of unflushed pockets of relict seawater within the aquifer system.
- Landward movement of the freshwater-saltwater interface.
- Regional upconing of saltwater below pumped wells, and
- The upward leakage of saltwater from deeper, saline water-bearing zones of the aquifer system through semiconfining units that are thin or are breached by joints, fractures, collapse features, or other structural anomalies.

A recent increase of chlorine content of freshwater in aquifers due to saltwater intrusion has been reported in Florida (Spechler, 2001; Zygnerski & Langevin, 2007). There are not available evaluations of the impact of sea level rise and the concomitant saltwater intrusion on stygofauna aquifers. Because aquifer ecosystems are frequently isolated (…) the persistence of the aquatic fauna will largely depends on the physiology of the species and the adaptation to higher saline environments. For example, Cuban cave dwelling fishes seems to be tolerant to variable degree of salinity (García-Machado, 2011).

The most important karst aquifers of the Gulf of Mexico and the Caribbean are exposed to marine intrusion (Planos Gutiérrez, 2008). A rise of the sea level between 0.15 and 0.27 m would be translated in an estimated loss of 6 % of the territory and 14 % of coastal forest in Cuba by 2100 (Centella & Benzanilla, 2008). Previous work has suggested future submergence of mangroves in the wider Caribbean region based on historical and geological rates of peat accretion (Ellison & Stoddart, 1991; Parkinson et al., 1994).

Less attention has been devoted to the effect of changing sea level on specific aspects related with the stability of coastal karst ecosystems and specifically with cave environments (Molerio & Balado, 2012). In fact the expected sea level raise will produce a combination of the following effects over the coastal cave environments and its support system:

- The disappearance of stable cave ecosystems including anchialine cave environments.
- The extinction, disappearance or at least in the best scenario a migration of aquatic cave populations to connected inland aquifers
- Major changes in groundwater chemical composition which in turn affects the mass fluxes in karst ecosystems.
- The loss of connections to the surface and among caves producing some sort of genetic isolation or recolonization of reflooded caves by troglobites.

Those effects will be particularly enhanced in the case of anchialine caves because of their particular hidrodynamics and biochemistry. Special attention to the effects of sea water level increase on anchialine karst environments is given in this paper.

THE ANCHIALINE ENVIRONMENT CONCEPT

Respect to the definition of the term anchialine Ginés & Ginés (2007) points out that "the term anchihaline was introduced by the carcinologist Holthuis (1973) in the oddly spelled form *"anchialine" pools* (sic), in reference to water in hollows near the coast that are influenced by the present sea level. However, regarding the traditional usage in ecology and natural sciences of similar terms (like halocline, halite, euryhaline, halophile, etc.), we think it should be preferable to use the alternative spelling *anchihaline*, as suggested by Sket (1996). Unfortunately, many recent publications seem to have standardized the term anchialine, as accepted implicitly by Sket (2005) in his recently published definition*: "Anchihaline (or anchialine) habitats are water bodies in hollows along the sea coasts where the influence of the sea may be felt and which are inhabited by some subterranean species... Such a habitat may contain seawater, but it primarily has layers of different brackish salinities"*. The ecological concept of anchialine habitats has been discussed and refined by Stock et al., (1986), Sket (1996, 2004 & 2005), and Iliffe (2003)".

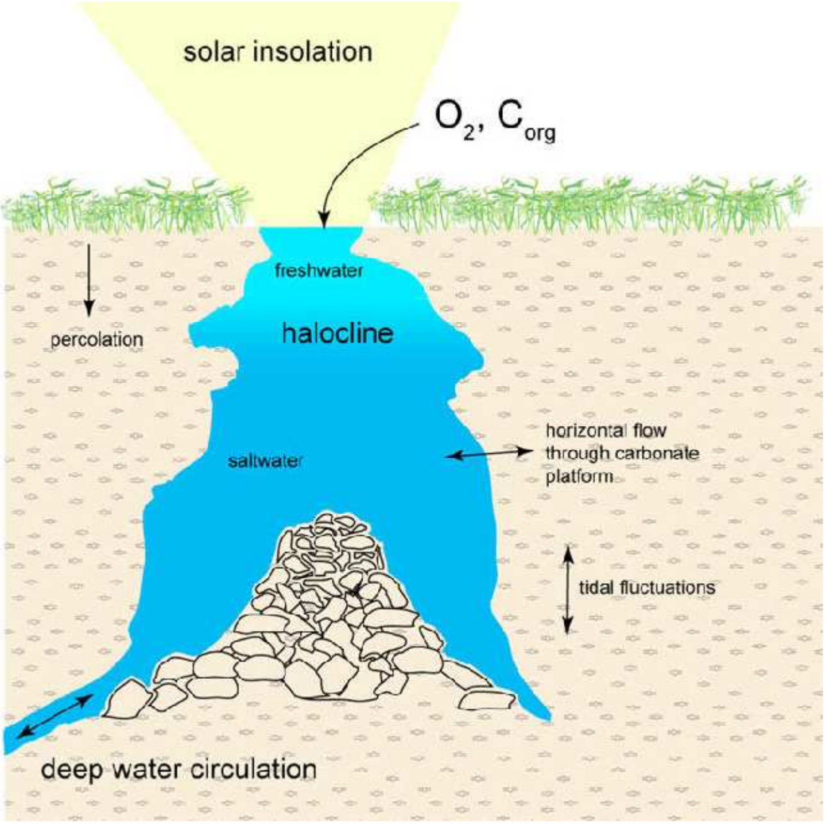

Figure 1. Characteristicsinkhole-type Bahamianinland blue hole. (After Gonzalez et al., 2011).

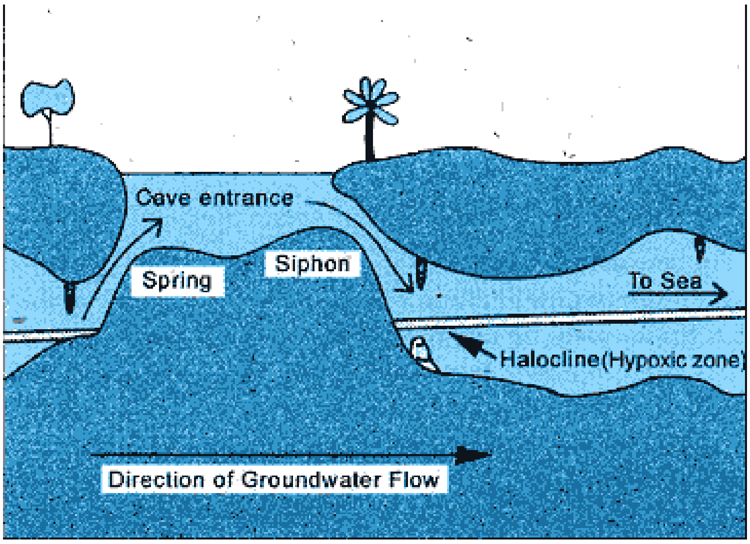

Figure 2. Cross section of a typical anchialine cave (after Pohlman et al., 1997)
http://www.globalunderwaterexplorers.org/files/page_images/research/environment/009_b.gif

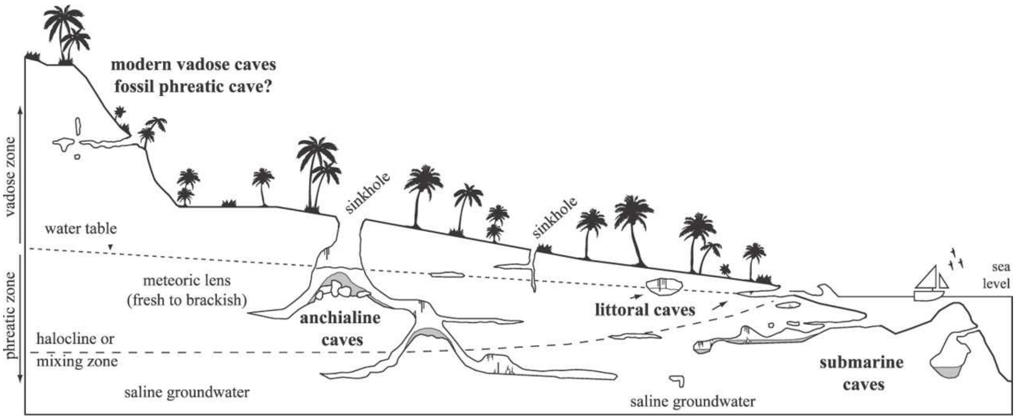

Figure 3. Structure of cave coastal and marine ecological niches (after Van Hengstum & Scott, 2011).

Gonzalez et al., (2011) has defined anchialine caves as those caves that characteristically contain vertically stratified fresh and salt water under tidal influence. As they have pointed out, vertical stratification results from salinity gradients and the absence of strong currents and windorwave-induced mixing.

Variability ingeological, hydrological, and chemical characteristics such as passage configuration, tidal cycles, and salinity stratification has yielded a great diversity ofanchialine cave systems globally. Figures 1, 2 and 3 shows different anchialine environments present in coastal karsts.

During the 2nd International Symposium on "Anchialine Ecosystems" held in Cavtat, Croatia in Octuber 2-6, 2012, the need to re-define the term "Anchialine Ecosystems" was highlighted, so that over the round-table discussion new (working) definition was proposed. Therefore an anchialines ecosystem is: *"A type of subterranean estuary containing a stratified water body, that may or may not be in direct contact with the atmosphere, and is capable of supporting a characteristic biota"*(http://www.anchialine.com/).

Main characteristics of epigenetic (eogenetic) anchialine caves are (Bozanic, 1993;Iliffe & Bishop, 2007; Iliffe, 1992; Jaume & Boxhall, 2000; KWI, IMEDEA, EAM, 2009; Sarbu & Kane, 1995; Sarbu et al., 1994; Sawicki, 2003):

- A typical highly stratified water masses, with surface layers of fresh or brackish water, separated by a thermo-, chemo-cline from underlying fully marine, low dissolved waters due to the particular structure of the flow domain and the consequent geochemical hydrodynamics.
- The development of an anchialine regime relies on sea water intrusion into coastal aquifers.
- Little or no photosynthetic oxygen production and restricted vertical mixing.
- Tidally influenced layers of fresh or brackish and marine waters separated by a halocline.
- Water chemistry profiles showing little resemblance to ocean conditions but with dominating Cl and Na ions.
- Food webs in anchialine caves may be based partially or wholly on indigenous bacterial primary production.

- Little or no photosynthetic oxygen production and restricted vertical mixing two factors contributing to anoxic or microoxic conditions and biogeochemical cycling that differs strongly from that taking place in marine environments
- Anchialine cave contain a rich and diverse, endemic, stygobitic fauna. These habitats serve as refuges to "living fossil" organisms, e.g., members of the crustacean class Remipedia, and to animals closely related to deep sea species.
- A singular carbon cycle with specific relations among the biocomponents of the ecosystem (Figure 4).

THE CAVE ENVIRONMENT

Karst itself is a singular ecosystem characterized by its low resilience and high vulnerability and fragility. Caves, in particular constitute the most sensitive ecological niche where the absence of light, almost complete silence and the stable properties of the cave atmosphere are the most important features that allows the strong interaction between the physical and biological levels.

At the physical level, microclimate, mass fluxes and substratum are the main characteristics to account. The biological level of caves is surprisingly diverse. Even when life abundance is not the most important characteristic of caves, it is remarkable the biodiversity –including endemism- that with different adaptive levels could be found in the cave environment.

As stated by Poulson & White (1969) the cave environment is usuallythought of as being separated into a twilight zone near the entrance, a middle zone of complete darkness and variable temperature, and a zone of complete darkness and constant temperature in caves form above the deep interior. The twilight zone has the largest and most diverse fauna; the deep middle zone has several very common species which may commute to the surface. This zonation is strongly related with the conditions of radiation, illumination, temperature, humidity, mass fluxes and the mass transfer carried out by animals living underground but that obtain their food in surface, sometimes far from the cave. CO_2 and O_2 concentrations underground contribute to the processes of decomposition and oxidation of the organic matter (Molerio & Condis, 2012).

EFFECTS OF CHANGES IN SALINITY AND CHEMICAL COMPOSITION

A remarkable side-effect of the ascending sea level is the inland penetration of saline waters. The inland advance of sea water intrusion will exert more pressure to the scarce fresh water resources of small and very small islands as well as of the continental coastal areas. The displacement of populations from coastal zones to inner areas at higher latitudes and elevations and the abandonment of fresh water sources are the commonly immediate expected consequences of sea level change.

Salt water encroachment will also be particularly important in the change of the physical and chemical properties of the ecological niches particularly in karst areas as are the most coastal continental and insular areas of the Gulf of Mexico and the Caribbean.In the case of the anchialine environments the impacts will be expressed as:

- Substantial changes in the chemical composition (major components) of waters.
- Modifications in the carbon and nutrient cycles.
- An elevation and eventual disappearance of the local halocline, the fresh-salt water interface and the upper fresh water lenses.
- A readjustment of the coastal zone cave environments due to the new configuration of the coasts.

Because of the little resilience of most karst systems and particularly of the cave environments is difficult to anticipate the quality and intensity of the above summarized impacts (negative/positive/neutral). But according to the known behavior of some anchialine systems some of them could be summarized following the general behavioral properties of cave environments summarized by Poulson & White, (1969):

- Connections to the surface of the present systems will turn rare in some instances whilst others new will be created.
- Little cave colonization of the new flooded passages should be expected unless conduits arewell integrated allowing adequate movement between caves.
- Changes in nutrients input will also make colonization difficult, but the constant physical conditions are conducive to survival.
- Chances for genetic isolation of troglobites will be lost because it should be expected an important cave colonization by troglophile and extinction of the intervening surface populations before a troglophile becomes troglobitic.

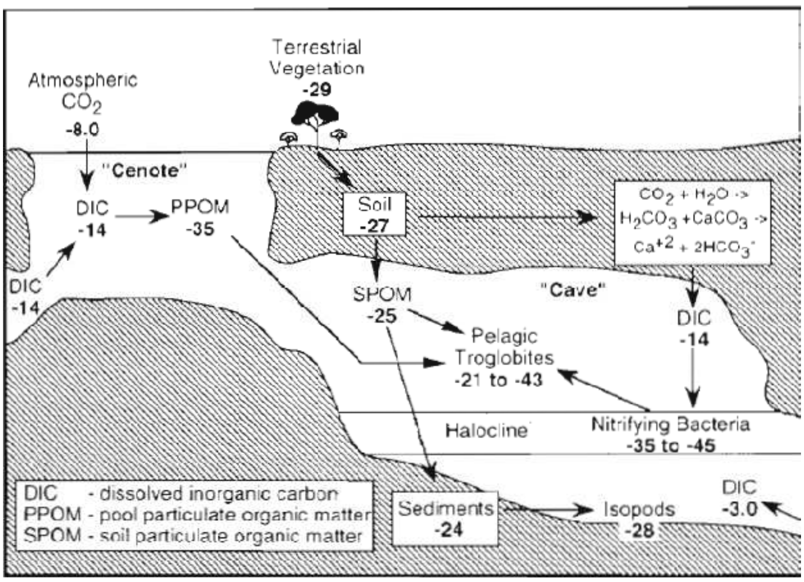

Figure 4.Model for carbon cycllng into and within the anchialine ecosystem. The pelagic troglobites consist of all crustaceans and fish living in the water column of the cave (after Pohlman et al., 1997).

MODELING SPECIES DISTRIBUTION AS A RESPONSE TO CLIMATE CHANE. GEOGRAPHIC RANGE REDUCTION AND EXTINCTION RISK

It is a central premise in biogeography that climate exerts a main control over the natural distribution of species (Pearson and Dawson 2003). Because it is enough evidence of global climatic change ongoing toward warmer conditions (IPCC 2001; IPCC 2007; USGCRP, 2009), it is of special concern to determine the impact of increasingly temperatures over the Earth surface on biodiversity. In the past two decades a number of investigations have combined models of future climate change and "bioclimate envelope" of species (Carey 1996; Bakkenes et al., 2002; Berry et al., 2002; Pearson et al., 2002; Franklin 1995; Mack 1996; Guisan and Zimmermann, 2000; Thuiller et al., 2005; Araújo et al., 2006, Araújo & Luoto 2007) to predict the future redistribution of species and extinctions. Such bioclimate envelope modeling are frequently based in two environmental predictor variables: temperature and precipitation.

Additionally there are two main modeling strategies frequently used: (1) correlative models (which considered that the best indicator of a species` climatic requirements is its current distribution; e.g: Huntley et al., 1995; Peterson et al., 2001; Bakkenes et al., 2002; Pearson et al., 2002)and (2) mechanistic models (based on relationship between climate parameters and physiologically species response; e.g: Woodward 1987; Prentice et al., 1992; Haxeltineand Prentice 1996; Sykes et al., 1996). The output of the bioclimateenvelope modeling are often given graphically and the reliability of the predicted distributions depends largely on the information available, ecological constraints of species in study, scales, and modeling strategies employed (Pearson & Dawson, 2003). In spite of limitations of bioclimate envelope modeling of species distribution, it has been proved to be useful in selection of natural reserves for threatened species (Araújo et al., 2004; Hannah et al., 2007) and for management and planning in general (Dale & Rauscher,1994; Guisan & Thuiller, 2005; Kueppers et al., 2005; Mulholland et al., 1997).

Expected species` responses to critical climate change are (Graham & Grimm, 1990; Collingham et al., 1996; Holt, 1990):

- movement
- adaptation
- extirpation

If species are sufficiently mobile, they may found new geographic locations that meet their ecological requirements (environmental and biotic conditions within which they are able to maintain populations). If species are capable of rapid evolutionary change, or have a wide range of physiological tolerances, adjustment to changing conditions andlandscapes may be possible. Failing both: mobilityand adaptability, extirpation is the likely result (Holt, 1990; Melillo et al., 1995). Species with reduced geographic distribution and highly adapted to stable environmental conditions will reduce their range under climate change scenario. Such induced range contractions increase a species` risk of extinction: species that are already restricted are likely to be pushed into more restricted areas, of less favorable habitat. In turn, this will fragment and isolate populations, make dispersal and recolonization events rare and result in metapopulation dynamics (Isaac, 2009).

These isolated populations will be highly susceptible to stochastic events, such as hurricanes and wildfires, which are predicted to become increasingly common in tropical regions of the globe as the climate changes (Nicholls & Alexander, 2007). Thomas et al., (2004) predicted that 11% of terrestrial species (plants and animals) included in their study are expected to become extinct in 2050, using a minimum expected climate change scenario and considering dispersal ability for all the species.

When maximum expected climate change and no dispersal ability was considered, the predicted percentage of species extinction rise to 58%. Because of the scale, broad assumptions and uncertainties, Thomas et al., (2004) prevented the use of such results as precise predictions.

SEA LEVEL RISE AND LOWLAND, AQUIFERS AND ISLAND ECOSYSTEMS VULNERABILITY IN TROPICAL REGIONS

Although it has been paid considerable attention to impact of global climate warming on biodiversity in the past two decades, the scientific concern about consequences of the sea level rise is relatively recent (e.g: McKee et al., 2007; Menon et al., 2010; Bellard et al., 2013). The sea level rise is considered a direct consequence of the climatic change ongoing (Nicholls & Cazenave, 2010) that could potentially alter the ecosystem dynamics in lowlands, wetlands, estuaries, coastal zones or even submerge an entire island. Marine intrusion is a global phenomenon, but is most prominent in Southeast Asia and nearby islands, eastern North America, northeastern South America, and western Alaska (Menon et al., 2010).

Some conservative estimates of the sea level rise are on the order of 0,5 to 1,0 meters for the next century (Carter et al., 2007). Global mean rates of eustatics ea level rise, currently estimated at 1.5–2.0 mm year^{-1}, are predicted to increase with global warming to 3-5 mm year^{-1} (McKee et al., 2007). Locally, the effects of sea level rise could be increased or diminished due to geological uplift/subsidence (IPCC, 2007). It is relative sea level change that drives impacts and is of concern to coastal managers (Nichols & Klein, 2005; Harvey, 2006).

Mainly studies in salinity impact over wetlands biodiversity are not directly related with marine intrusion, but reduction of the charge of freshwater via precipitations or river discharge. Changes in freshwater inputs to the coastal wetland affect community structure and function (Sklar & Browder, 1998) through fluctuations in the salt balance up and down the estuary. Some studies have eventually support the threats to existing flora and fauna in relation to salinity in wetlands; nevertheless, the increase of salinity is always related to a reduced flushing (Nielsen & Hillman, 2000; Clunie et al., 2002). McEvoyand Goonan (2003) have postulated that wetlands near the coasts (saline wetlands) are characterized by its resilience to salinity changes, due to adaptability of the biota. Nielsen et al., (2003) found a considerable reduction of taxa (aquatic plants and zooplankton) when salinities of water where between 1000 and 5000 mg·L^{-1}. In the other hand rotifers and microcrustaceans normally occurring in freshwater has been recorded in moderate saline waters. Although biological communities present in wetland are more or less adapted to the normal annual cycle of salinity, the impact of marine intrusion (salinities of seawater ≈ 35000 mg·L^{-1}) in such environments must be critical to biota survival.

Mangrove forests are considered complex marine-terrestrial ecosystems in the tropics. They provide habitat and feeding grounds to fish species, reptiles, amphibians, mammals, birds, crustaceans and other invertebrates (…). Mangroves and other tidal, saline wetlands such as salt marshes also have the capacity to sequester carbon into soil faster than in terrestrial ecosystems (Chmura et al., 2003).They also constitute an effective barrier against marine intrusion and erosion (Dahdouh-Guebas et al., 2005; Danielsen et al., 2005).

The influence of mangrove over the coral reef fish diversity has been highlighted by a report of the WWF Foundation (WWF, 2004). Mangrove trees are adapted to the salinity of the seawater, but specific events leading to hypersalinity (dry seasons and intense evaporation) can lead to destruction of the vegetation (Diop et al., 1997). As far as mangroves are concerned, the impact of sea-level rise depends on the environmental setting (Hogarth, 2007). In an estuary, mangrove trees often show a pattern of species zonation up and down the river, largely dependent on a salinity gradient, which is the outcome of the interplay of river and tidal flows (Hogarth, 2007).

A rise in sea level would have the effect of shifting thezonation pattern in an upriver direction (offset by any increase in local rainfall which might increase the river flow). Upshore/downshore zonation patterns might also move, in a landward direction. Trees on the seaward fringe would be inhibited by extended submergence times, while those on the landward margins might be able to extend, provided suitable habitat was available (Pernetta, 1993). Nevertheless, mangrove systems have the potential to build vertically via soil accretion by root growth and entrapment sediments and organic material (McKee et al., 2007). If rates of vertically buildings were higher than submerges rates, mangrove systems could persist despite the current sea level rise.

FINAL REMARKS

1. The expected sea level raise will produce a combination of the following effects over the coastal cave environments and its support system:
   a. The disappearance of stable cave ecosystems including anchialine cave environments.
   b. The extinction, disappearance or at least in the best scenario a shift inland of aquatic cave populations.
   c. Major changes in groundwater chemical composition which in turn affects the mass fluxes in karst ecosystems.
   d. The loss of connections to the surface and among caves producing some sort of genetic isolation or recolonization of reflooded caves by troglobites.
2. Salt water encroachment will also be particularly important in the change of the physical and chemical properties of the ecological niches particularly in karst areas as are the most coastal continental and insular areas of the Gulf of Mexico and the Caribbean. In the case of the anchialine environments the impacts will be expressed as:
   a. Substantial changes in the chemical composition (major components) of waters.
   b. Modifications in the carbon and nutrient cycles.

   c. An elevation and eventual disappearance of the local halocline, the fresh-salt water interface and the upper fresh water lenses.
   d. A readjustment of the coastal zone cave environments due to the new configuration of the coasts.
3. If species are sufficiently mobile, they may found new geographic locations that meet their ecological requirements (environmental and biotic conditions within which they are able to maintain populations). If species are capable of rapid evolutionary change, or have a wide range of physiological tolerances, adjustment to changing conditions and landscapes may be possible.
4. A rise in sea level would have the effect of shifting the zonation pattern in an upriver direction (offset by any increase in local rainfall which might increase the river flow). Upshore/downshore zonation patterns might also move, in a landward direction.

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