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Caribbean beach changes and climate change adaptation

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Beach monitoring data are presented and show an average beach erosion trend of 0.5 m yr $^{-1}$ *in eight Caribbean islands over the period 1985–2000, with elevated rates in those islands impacted by a higher number of hurricanes. The data are based on 5 to 15 years of continuous monitoring, conducted at three-month intervals, at 113 beaches (200 profile sites) on eight islands, using standard methodology. The causes of the erosion are discussed and include anthropogenic factors, climate variability and projected climate change. Based on the Intergovernmental Panel on Climate Change projections for the Caribbean region, and the likely increase of anthropogenic stresses such as coastal development, it is likely that the beach erosion trend will continue and increase. Nonexclusive approaches to help beaches adapt to climate change include structural, planning or ecological measures. Two case studies illustrating climate change adaptation measures are discussed, one focuses on coastal planning measures in Anguilla and Nevis, and the second focuses on ecological measures, specifically the rehabilitation of a coastal forest in Puerto Rico. These case studies have not reached a stage where their effectiveness can be evaluated, however preliminary outcomes show that community-based climate change adaptation measures require careful planning such that the entire community is involved in a participatory manner and sufficient time is allocated for awareness-raising, information-sharing and discussion.*

Keywords: Anguilla, beach erosion, climate variability, coastal forests, hurricanes, Nevis, planning, Puerto Rico, sea level rise, tourism

Introduction

Climate change is one of the most critical issues facing the Caribbean region where rising sea levels, increasing mean temperatures and changes in rainfall and weather patterns, are already being experienced. The Caribbean region experienced on average a mean relative sea-level rise of 1 mm yr^{-1} during the 20th century, although there was extensive local variation (Intergovernmental Panel on Climate Change (IPCC), 2007a). The likely increasing severity and frequency of natural hazards related to climate change is also of serious concern to the Caribbean islands. During the last century there have been multi-decadal fluctuations in hurricane activity in the Atlantic Basin and Caribbean Sea with a marked increase in activity since 1995; although the record is insufficient to indicate whether these fluctuations are linked to climate change.

The natural resource base of the Caribbean islands is critical for the region's socio-economic development. Tourism is the major economic driver in the insular Caribbean (Rivera-Monroy et al., 2004), and for some islands it is the prime industry. The industry is primarily located close to the coast and is heavily dependent on the tropical climate and the presence of sandy beaches and scenic coastal areas with clean, clear seas free from pollution and abundant in marine life. In addition, most of the islands' major cities, towns and villages are located near the

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coast – the area most vulnerable to certain climate change impacts, e.g. sea level rise and increased storm severity.

Anthropogenic degradation of coastal and marine resources is a serious problem in the Caribbean (Richards and Bohnsack, 1990; Ogden, 1987). Activities such as beach sand mining, beachfront development, removal of mangroves, destruction of seagrass beds and coral reefs, and overfishing have become serious issues in almost every Caribbean island over the last several decades. Efforts are underway by governments, the public, regional organizations and others, to reduce the level of degradation, yet as human populations increase, the rate of anthropogenic change may rise above current levels. Furthermore, it is difficult to separate, in a systematic and quantitative manner, the natural changes from those due to man's actions in most of these ecosystems. Climate change will likely add a third level of change, yet it may be difficult or impossible to separate out this component as multiple stressors are acting in concert.

Human adaptations to climate change need to ensure ecosystems are more resilient and healthy not just for today but for the long term (Carter and Raps, 2008). A wide beach backed by a coastal forest and protected by a healthy coral reef can better withstand sea level rise and future high wave events than a narrow beach confined by concrete infrastructure on the landward side and a degraded, dying coral reef on the seaward side.

This paper discusses measured trends in beach systems on eight islands in the eastern Caribbean between 1985 and 2000. Causes of beach change include anthropogenic factors, climate variability, and climate change. Future trends are examined in light of climate change projections. Two work-in-progress case studies relating to different climate change adaptation strategies are described and discussed.

Beach changes in the Eastern Caribbean, 1985–2000

During the period 1985–2000 several islands in the Eastern Caribbean set up beach monitoring programmes within the framework of a project entitled Coast and Beach Stability in the Caribbean (COSALC) supported by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the University of Puerto Rico Sea Grant College Program (UPR-SGCP). The project was established on several islands during the early 1980s because of concerns about beach erosion and its impact on the tourism industry. The primary objective was to develop in-country capacity to address the serious problems resulting from beach erosion. Beach profiles were measured quarterly using a standardized methodology (Cambers, 2003; Cambers and Gray, 2005) and after major wave events such as tropical storms and hurricanes. Beaches selected for monitoring were representative of the different conditions existing on north, south, east and west facing coasts, and in addition had to fulfil one or more of the following criteria: (a) importance for tourists, (b) importance for island residents, (c) erosion or pollution perceived to be an issue, (d) pristine condition. Preliminary results for the ten-year period 1985–1995 were discussed (Cambers, 1997a), and results for the period 1985–2000 were compiled in a series of booklets designed for a general audience (UNESCO, 2003).

For the purposes of this paper, data from eight islands, where five or more years of consecutive monitoring information was available, have been compiled and analysed. These islands are all located in the eastern Caribbean and stretch from Anguilla in the north to Grenada in the south. Three of the islands: Anguilla, Antigua and Barbuda are predominantly flat, limestone islands, although the geology and topography of Antigua is more varied than the other two islands. The remaining five islands: Dominica, Grenada, Montserrat, Nevis and St. Kitts, are all mountainous, volcanic islands. In general, the five volcanic islands have narrower offshore shelves and less extensive coral reefs than the three limestone islands. Table 1 lists the characteristics of the monitoring programmes of the eight islands (listed in a north to south sequence) as well as the hurricanes that impacted particular islands during the period covered by the monitoring data.

Table 2 lists the mean annual rate of beach change for each island, the maximum range in the data, the percentage of beaches showing erosion and the number of hurricanes impacting the island during the monitoring period. The mean annual beach change rate represents the average yearly change in beach width as determined from the beach profiles. A negative beach change value represents a retreat rate or erosion rate, and a positive beach change value represents an accretion rate.

On lowland coasts where the land behind the beach is not developed, the beach will reposition

Table 1. Characteristics of the Beach Monitoring Record and Hurricane Events in Selected Caribbean Islands.

Island	Monitoring Period	Number of Beaches Monitored	Number of Profile Sites Monitored	Hurricanes Impacting the Island
Anguilla	1991–2000 (10 years)	15	35	H. Luis, 1995 H. Georges, 1998 H. Lenny, 1999
Barbuda	1995–1999 (5 years)	6	8	H. Georges, 1998 (Measurements started After H. Luis in 1995 and did not include H. Lenny in 1999)
Antigua	1992–1999 (8 years)	19	42	H. Luis, 1995 H. Georges, 1998 H. Lenny, 1999
St. Kitts	1991–2000 (10 years)	20	34	H. Luis, 1995 H. Georges, 1998 H. Lenny, 1999
Nevis	1988–2000 (13 years)	11	18	H. Hugo, 1989 H. Luis, 1995 H. Georges, 1998 H. Lenny, 1999
Montserrat	1990–1996 (7 years)	10	14	H. Luis, 1995
Dominica	1987–2000 (14 years)	20	26	H. Hugo, 1989 H. Luis, 1995 H. Georges, 1998 H. Lenny, 1999
Grenada	1985–1999 (15 years)	12	23	H. Lenny, 1999

Table 2. Beach Changes and Hurricane Frequency in Selected Caribbean Islands, 1985–2000.

Island	Mean Annual Beach Change Rate (m yr^{-1}); Number of Years of Measurement (N)	Maximum Range of Beach Change Rates (m yr^{-1})	Percentage of Beaches showing Erosion (%)	Number of Hurricanes Impacting the Island during Measurement Period
	Flatter, predominantly limestone islands			
Anguilla	−1.26; N = 10 yrs	−4.60 to + 1.38	93%	3
Barbuda	+ 0.39; N = 5 yrs	−4.20 to + 5.20	33%	1
Antigua	+ 0.02; N = 8 yrs	−2.00 to + 2.20	47%	3
	Mountainous, volcanic islands			
St. Kitts	−0.73; N = 10 yrs	−3.00 to + 1.10	70%	3
Nevis	−1.04; N = 13 yrs	−2.66 to + 2.00	64%	4
Montserrat	−0.23: N = 7 yrs	−2.60 to + 2.30	60%	1
Dominica	−0.95; N = 14 yrs	−2.90 to + 0.70	90%	4
Grenada	−0.30; N = 15 yrs	−3.10 to + 1.40	75%	1

Table 3. Climate Projections for the Insular Caribbean (IPCC, 2007b).

Climate Parameter	Predicted Change
Air temperature	Increase of 0.94–4.18°C by 2099
Global sea level	Rise of 0.18–0.59 m by 2099
Carbon dioxide	Reduction in pH of the oceans by 0.14–0.35 units by 2099
Hurricanes	More intense with larger peak wind speeds and heavier precipitation
Precipitation	−49.3% to +28.9% - the range of projections is still large and the direction of change is not clear

itself further inland over time as erosion takes place. However, where the land behind the beach is developed with infrastructure, then the beach will not be able to retreat inland, and in these cases it is likely that beaches will get narrower and eventually over time they will disappear, unless other measures such as the placement of groynes, offshore breakwaters and beach nourishment are undertaken.

Averaging the data from all eight islands shows an overall erosion trend with a retreat rate of 0.5 m yr^{-1} with elevated rates in those islands impacted by a higher number of hurricanes (with the exception of Antigua). This figure (0.5 m yr^{-1}) represents the average change for all measured beaches, including those showing no change or accretion. However, among the three flatter limestone islands, there was considerable variation, with Anguilla showing a high retreat rate, while Barbuda showed accretion and Antigua showed little overall change. The five volcanic islands showed a more consistent erosion trend with between 64 and 90% of the measured beaches exhibiting erosion with an average retreat rate of 0.65 m yr^{-1}. It is also evident from Table 2 that increased retreat rates were recorded in those volcanic islands impacted by a higher number of hurricanes, particularly St. Kitts, Nevis and Dominica.

This paper discusses beach changes averaged over time and space, however, beaches change rapidly on a daily basis, and there is often variation within a beach with one section eroding and another section accreting. Thus from management and scientific perspectives, it is also important to study and understand individual beaches in terms of their geological, oceanographic, biological, anthropogenic and structural (sea defences) characteristics.

Climate change projections and beach responses

Climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and is observed over long time periods (multi-decadal). There is now unequivocal evidence that the earth's climate is changing as a result of human activities, principally increased carbon dioxide emissions since the Industrial Revolution in the 1700s (IPCC, 2007a). Climate change is distinct from climate variability which is attributable to natural causes such as the El Niño/La Niña oscillation.

Table 3 shows the climate predictions for the insular Caribbean (IPCC, 2007b). Where there is no specific Caribbean projection for a climate parameter, the global value is used.

The most significant impact of climate change for beach systems is an accelerated rate of sea level rise. Stronger hurricanes will also generate more extreme wave events. The Bruun Rule (Bruun, 1962) predicts that as sea level rises, sand is eroded from the upper beach and deposited on the offshore bottom so as to maintain an equilibrium profile. This results in beach retreat so that for every 1 cm of sea level rise, the beach retreats inland 1 m. While the Bruun Rule is not an exact prediction of the rate of retreat, and while data on sea level changes in the Caribbean is still very sparse, climate change projections indicate that a heightened rate of sea level rise and stronger hurricanes will cause beaches to retreat inland at a faster rate than is already occurring.

Climate change adaptation measures

Moving from direct scientific measurements of beach changes to climate change adaptation measures is a difficult step particularly in a multi-causal context such as beach erosion. Measures to help beaches adapt to climate change may be of a structural, planning or ecological nature and selection of appropriate measures will depend on the specific characteristics of the beach in question. Two case studies that are each a work-in-progress are described here, one focusing on planning measures and one on ecological measures. However, neither of the case studies is at a stage where their effectiveness can be scientifically evaluated.

Climate change adaptation – planning case study: development setbacks in Anguilla and Nevis

Between 26 August and 16 September 1995, one tropical storm (Iris) and two hurricanes (Luis and Marilyn) directly impacted the islands of the eastern Caribbean. While these islands had experienced several hurricanes in the previous two decades (Hurricanes David and Frederick in 1979, Allen in 1980, Klaus in 1984, and Hugo in 1989), of the two islands discussed in this case study, only Nevis had been significantly impacted (by Hurricane Hugo in 1989).

Anguilla, a small island in the north-eastern Caribbean, was in the direct path of Hurricane Luis, a Category-4 hurricane, that impacted the island from 4 to 6 September, 1995. Following surveys of the hurricane's impact in Anguilla, it quickly became apparent that most of the severe damage was in the coastal area where the port facilities, hotels, tourism villas, condominiums, restaurants and bars were located. As a result, the Government resolved to put in place measures to protect their coastlines, economies and personal livelihoods. Assistance was obtained from the then British Development Division in the Caribbean and UPR-SGCP.

One of the components of the assistance programme was to design new guidelines for coastal development setbacks, so that new development would be situated a "safe" distance from the active beach zone. Most of the Caribbean islands have coastal development setback guidelines included in their planning laws, these range from 15 m from high water mark in the British Virgin Islands to 30 m from high water mark in Barbados (Cambers, 1997b).

A coastal development setback may be defined as a prescribed distance to a coastal feature, such as the line of permanent vegetation, within which, all or certain types of development are prohibited. Such setbacks provide buffer zones so the beach has the space to erode or accrete, and maintain its protective function during high wave events, without the need for expensive sea defence structures. They also allow for improved vistas and access along the beach, and provide privacy for coastal property owners and beach users alike.

In the expectation that the frequency and intensity of hurricanes would likely increase in the Caribbean, and knowing that sea level rise was already a factor in the region, a protocol for coastal development setbacks was designed that included adaptation to these two aspects of climate change (Cambers, 1997b). Recognizing that there was considerable variation from one beach to another, coastal development setbacks were calculated for each individual beach thereby providing greater setbacks on eroding beaches and smaller setbacks on stable or accreting beaches.

A methodology was developed based on the assumption that historical erosion rates would continue, to increase as a result of increased frequency and intensity of hurricanes and accelerated sea level rise. Development setback distances were determined for each beach based on (1) historical coastline changes; (2) projected changes likely to result from a major hurricane; (3) coastline retreat resulting from sea level rise in the next 30 years; and (4) specific geographical and planning factors. (The period of 30 years was selected since it represented the average economic life of a building or structure). The following formula was developed:

$$\text{Coastal Development Setback distance} = (a + b + c) * d$$

Where the setback is measured from the line of permanent vegetation (the tree line or equivalent) and

- a is the projected change (m) in coastline position over the next 30 years based on historical changes determined from beach monitoring data or aerial photograph comparison;
- b is the projected change in coastline position (m) likely to result from a major hurricane (based on field measurements after the most recent major hurricane);
- c is the predicted coastline retreat (m) by 2030 resulting from sea level rise (based on the Bruun Rule);
- d represents other factors of an ecological, planning and social consideration (essentially qualitative, but too important to be omitted and requiring local knowledge) specifically:

- Wave exposure and coastline shape (beaches experiencing high wave energy or having convex-shaped beach forms are likely to be more vulnerable to change)

- Existence of low accretionary features such as sand spits, sand bars and tombolos (observations have shown these have become increasingly vulnerable with successive hurricanes e.g. Scotts Head in Dominica (Cambers 1997a))
- Changes in offshore features (e.g. a once healthy coral reef has been degraded)
- Anthropogenic factors that historically impacted a beach (e.g. sand mining and offshore dredging)
- Planning considerations (e.g. national park designations)

If none of these factors are relevant to a particular beach, d remains equal to 1; if one factor is applicable, $d = 1.3$; if 2 factors are applicable, $d = 1.6$; if 3 or more factors apply $d = 2$. No development is permitted seaward of the vegetation line with the obvious exception of docking facilities such as jetties.

Using this methodology, coastal development setback distances were calculated for each beach in Anguilla. For ease of application, the beaches were grouped with setback distances as follows: 18 m, 30 m, 45 m, and 92 m. Twenty of the 25 beaches in Anguilla were listed in the 30 m from the vegetation line category. This represented an increase over the previously used guideline of 30 m from the high water mark. These new guidelines have been used since 1996 by the Department of Physical Planning when considering applications for coastal development. In some cases the recommended setback distances listed in the guidelines have been applied exactly as recommended but for the majority of proposals, the Department has found it necessary to customize, on a site-by-site basis, the setback distances outlined in the guidelines. In 2007 work started on drafting a policy for the protection of coastal lands using the modified setback distances that have been customized and applied over the past 12 years. Additionally, the policy will also specifically address the coastal "hotspots" on the island, where there has been an increase in coastal development and redevelopment of existing hotels (Cambers et al., 2008).

The island of Nevis, part of the Federation of St. Kitts and Nevis, was also impacted by the hurricanes of 1995 and almost every building on the west coast of the island within 30 m of the beach was badly damaged or destroyed. The same methodology was used to calculate setback distances for each beach in Nevis in 1998 and these have been used as a guide by the Department of Physical Planning. However, difficulties have been encountered. In some cases the guidelines conflict with federal law, namely the National Conservation and Environmental Protection Act of 1987. The guidelines were not included in legislation. Developments built prior to 1998 inside the setback distance now require protection and there are no standards in place, therefore improperly built coastal protection infrastructure is becoming a problem. These issues are further discussed in Cambers et al., 2008. To begin to address some of these problems, the 1998 setbacks have been included in the Draft Building Regulations – 2nd Schedule (2007).

Climate change adaptation - ecological case study: coastal forest in Puerto Rico

Similar problems relating to coastal degradation, beach erosion and escalating coastal development exist in Puerto Rico in the Greater Antilles (Bush et al., 1995). Sea level changes have been measured here since 1955 (Mercado, 2007), see Table 4. Rates of beach change are not as well documented as in the smaller islands discussed in this paper, however, there is widespread visual evidence of beach erosion.

A condominium community in Rincón on the northwestern coast of Puerto Rico was concerned about the vulnerability of their community and the nearby beach. The condominium was constructed between 2000–2002 behind a sandy beach with beachrock outcrops. The site had been used for sand

Table 4. Changes in Rate of Sea Level Rise, Puerto Rico, 1955–2006.

Parquera (Southwest Puerto Rico)		San Juan (North Puerto Rico)	
Measurement Period	Sea Level Rise (mm yr^{-1})	Measurement Period	Sea Level Rise (mm yr^{-1})
1955–1989	1.7	1962–1989	1.6
1990–2006	2.4	1990–2006	2.5

extraction in the 1980s and 1990s and was also a turtle nesting beach. Behind the beach there is a low ridge or semi-artificial sand dune, which is vegetated with palms (*Cocus nucifera*), sea grape (*Coccoloba unifier*) and West Indian almond (*Terminalia catappa*) as well as low shrubs, grasses and vines. This vegetation belt is about 10 m wide and about 1–2 trees deep. Landward of the coastal trees there is a gently sloping grassy area, 30 m wide, separating the condominiums from the beach. Beach width varies seasonally, during winter swells (November through to March) waves often reach the coastal trees; while during the summer season the beach (measured from the trees to high water mark) varies between 10–20 m wide. The exposure of beachrock on this beach is an indicator of long term beach erosion (Cambers, 1998). Therefore, in the absence of any regular monitoring of this beach, it can still be assumed that the beach is undergoing long term erosion.

Residents from this condominium were represented at a Climate Change Round Table discussion, organized by the University of Puerto Rico, in May 2007. They determined that there is a need to strengthen the resilience of the beach system so that it can better withstand the likely impacts of climate change, namely accelerated sea level rise and more intense hurricanes. To do this they plan to widen the existing narrow belt of coastal trees by planting further trees, specifically the deep-rooting seagrape (*Coccoloba uvifera)* and almond trees (*Terminalia catappa*). Trees will be planted on the landward side of the existing ones and care for the tree seedlings during their early growth stages will be an important component of the project. Roots and stems tend to trap fine sand and soil particles, forming an erosion-resistant layer once the plants are well established (US Army Corps of Engineers, 1981). Mature coastal trees are resistant to salt spray, flooding and burial by sand (Williams et al., 1999). It is projected that a well-established coastal forest will help to hold the sand in place, and may help to slow down the rate of beach erosion, although the forest will not permanently stop the erosion. The trees will also enhance the area's biodiversity by providing additional habitat for birds and animals.

The interested residents are working to promote the project amongst all the condominium owners and the developers of the condominium before it can be implemented. While there has been some interest there has also been some opposition by individuals who perceive the thicker forest will reduce their view of the sea and may also impede their access to the beach.

Discussion

Beaches are among the most dynamic and fast changing environmental systems. In addition they display variation in form and shape thereby making any attempt at generalization as has been done in this paper, very difficult. While all the beaches on an island's west coast may be exposed to the same high energy wave event, their responses will be different depending on their particular geography, recent and historical changes, sediment characteristics, the presence and health of related marine ecosystems (e.g. coral reefs, sea grass beds), the level of development and infrastructure, use levels, and the presence of sea defense structures.

The erosion trend seen in six of the eight islands discussed in this paper over the period 1985–2000 has been related to anthropogenic factors, climate variability and climate change. Anthropogenic factors have been discussed in general and their further elaboration would require detailed examination of specific beaches and their characteristics. Anthropogenic factors have played a significant role in the changes recorded at most (minimum 75%) of the measured beaches, and with coastal development on the rise, their impact is likely to continue and expand in the future.

The effects of climate variability on beach changes are manifest through the number of winter swell events affecting a particular island; the frequency and intensity of tropical storms and hurricanes passing near the island in a particular year; and the number of high intensity rainfall events and their impact on the transport of sediment to the coast. The multi-decadal variation in hurricane frequency and intensity in the Atlantic Basin has been discussed in the literature (Emanuel, 2005) and the El Niño/La Niña cycle also serves to influence hurricane activity in the Atlantic Basin, with reduced activity during El Niño years (IPCC, 2007b).

Climate change, especially sea level rise has undoubtedly been a causative factor contributing to the average erosion trend between 1985 and 2000. However, in the context of beach erosion, where at any one particular beach there are likely to be several causative factors, it is difficult to quantitatively attribute the contribution of climate change and climate variability to the overall change. The Caribbean experienced on average a mean sea level rise of 1 mm yr^{-1} during the 20^{th} century (IPCC, 2007b); a total of 0.1 m. However, there was considerable regional variation due to large scale oceanographic phenomena such as El Niño, and volcanic and tectonic crustal movements of the Caribbean Basin rim, which affect the level of the land on which the tide gauges are located. On the west coast of Trinidad, for example, sea level is rising at a rate of 1 mm yr^{-1} in the north and 4 mm yr^{-1} in the south, the difference being a response to tectonic movements (Miller, 2005). Global sea level rose at a more rapid rate from 1993–2003 than during 1961–2003 and this is consistent with the sum of observed contributions from thermal expansion and loss of land ice (IPCC, 2007a). The projection is that the rate of sea level rise will continue to increase.

It is likely that the relative importance of these three causes (anthropogenic factors, climate variability and climate change) may only be determined at the scale of the specific beach, and even then it is uncertain whether the stresses can be separated quantitatively. Beach erosion is expected to continue and most likely increase, as anthropogenic stresses and climate change have an increasing impact.

Against this background the two case studies have important implications, since both showed that despite the level of knowledge about beach changes, climate variability and climate change, there exists a reluctance to implement climate change adaptation measures. The revised guidelines for setback distances were designed in Anguilla in 1996 and in Nevis in 1998, and although the respective physical planning agencies began to use the guidelines immediately, there was considerable resistance from other government institutions and on the part of the public, especially developers. In each island it was almost ten years later before necessity drove the incorporation of the guidelines into policies and building regulations. This delay may have been due to several factors, including insufficient attention to information-sharing among different stakeholder groups, resistance to change, a perception of strengthened government planning control, and a reduction in direct hurricane impact to these two islands since 1999.

The same pattern is emerging in Puerto Rico, where some residents of a condominium group are enthusiastic and ready to take adaptive action immediately, but it is essential that they take the time for discussion and information-sharing so that the majority of the community can understand and endorse the proposed action. Coastal forests are generally not valued in the Caribbean islands, and for the most part they have been destroyed or replaced with ornamental trees and non-native species. A view of the sea is a major selling point for coastal real estate and one that is much valued both from financial and aesthetic perspectives. Even though measures were included in the design of the case study to accommodate continued and improved access to the beach and to ensure that sea vistas were not diminished, many of the condominium owners remain unconvinced.

Conclusions

In conclusion, it appears that community-based climate change adaptation measures, as discussed in this paper, require careful planning such that the entire community is involved in a participatory manner, and in particular that sufficient time is allocated for awareness-raising, information-sharing and discussion.

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