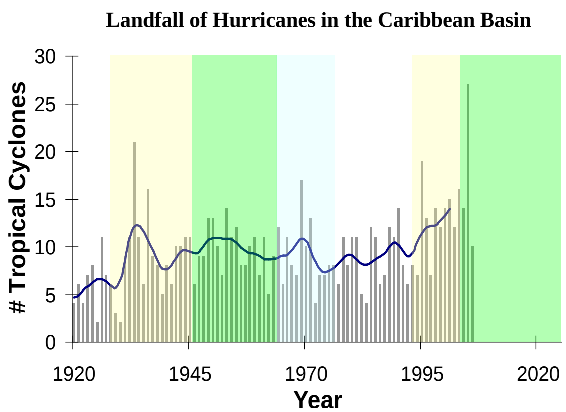
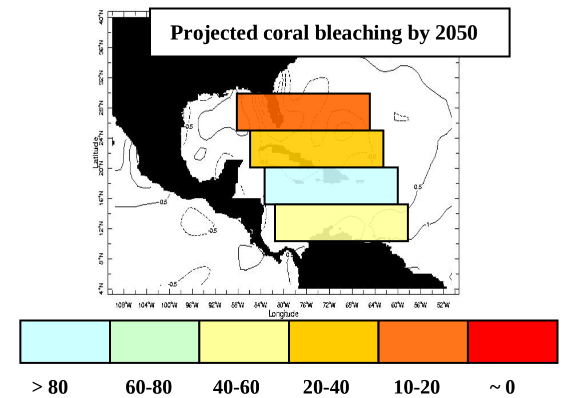
Latin America and Caribbean Region
Sustainable Development Working Paper 32

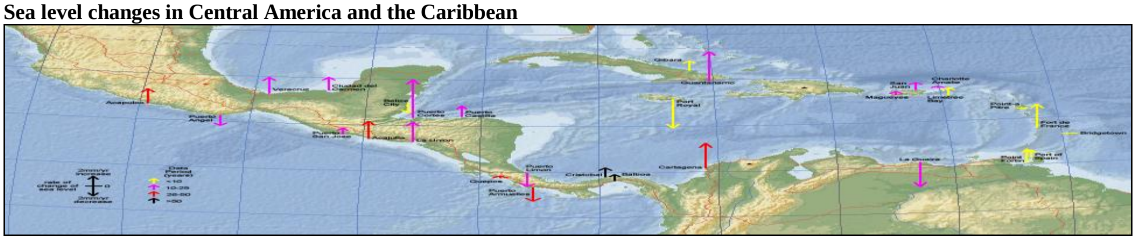
Assessing the Potential Consequences of Climate Destabilization in Latin America





Percent remaining from original coral cover at four different latitudes

Sea level changes in Central America and the Caribbean



June 2009

Edited by:
Walter Vergara

The World Bank
Latin America and the Caribbean Region
Sustainable Development Department (LCSSD)

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This report is based on data, information, and analysis of the results of work undertaken as part of the portfolio of adaptation activities in the Latin America Sustainable Development Department of the World Bank. The report has been made possible thanks to the contributions of many individuals and institutions, without whose support and hard work the results summarized here would not have been achieved. The authors wish to acknowledge the comments and contributions received from numerous colleagues both inside and outside of the institution, in particular Lawrence Buja from NCAR, John Nash, Sofia Bettencourt, Marea Hatziolos and Stefano Pagiola from the World Bank, Mark Lambrides from OAS, and Robert Buddenmeier, for agreeing to review an earlier version, or sections, of this report. Special thanks are due to Adriana Valencia, Janice Molina, Franka Braun and Chantal Toledo who assisted with the editing of the report.

Cover art credits:
Left panel: Evolution of tropical cyclones in the Caribbean Basin in “Potential Economic Impacts of Hurricanes in Central America and the Caribbean ca. 2020-2025”.
Right panel: Evolution of relative coral cover over time for one Latitude (Year 2050) in “The Consequences of Climate-induced Coral Loss in the Caribbean by 2050–2080”.
Bottom Panel: Sea Level Changes in Central America in “Land under Siege: Recent Variations in Sea Level through the Americas”.

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Contents

Foreword

Estimating the potential costs of climate destabilization is not a trivial matter. Potential climate impacts have multiple consequences, some of which can be monetized while others are beyond the reach of standard economic tools. A full assessment of the implications of climate impacts often cannot be completed because many of the consequences are only partly known.

This report summarizes data recently made available, through the portfolio of adaptation activities in the region, on some of the damages induced by climate destabilization. These include impacts from hurricane intensification, glacier retreat, and increased exposure to tropical vector diseases, coral bleaching, and composite costs of climate change in the particularly vulnerable Caribbean Basin.

Other costs are becoming evident but they still cannot be estimated. Most worrisome among these are the potential implications from Amazon dieback which, if realized, will drastically affect the water cycle in the region as well as environmental services essential to economic activity in the region, with wider global implications.

However, this is far from the whole story, which must also include the costs to other species. The region is host to unique ecosystems of global importance, including the Amazon rainforest, the coral reefs in the Caribbean, the high-mountain ecosystems of the Andes, and the vast coastal zones in the Gulf of Mexico. All of these habitats are seriously threatened by climate change. The region includes five of the world's ten most bio-diverse countries (Brazil, Colombia, Ecuador, Mexico, and Peru) and the world's single most biologically diverse area (the eastern slope of the Andes).

Although the full implications of these impacts are yet to be estimated, this report presents some of what is already known, with information derived from activities in the adaptation to climate change portfolio in the region. The report thus summarizes the value of damages induced by hurricane intensification, coral mortality, glacier retreat and warming of mountain ecosystems, increased incidence of tropical vector diseases, for specific areas of Latin America. The estimates range from tens of billion dollars as a result of increases in hurricane frequency and intensity in the Caribbean basin to a few million resulting from increased exposure to Malaria and Dengue in the Colombian piedmont. The estimates correspond to different analysis and while grossly consistent in terms of future climate assumptions, no effort was made to homogenize the timing of the projections.

The report refers to destabilization in the title as recognition, that the region is now facing impacts from major, destabilizing changes in its climate. The report does not include consideration of possible future adaptation actions, which may lower the impact and costs of climate destabilization in Latin America. The high costs potentially imposed by climate change underscore the importance of undertaking appropriate adaptation responses.

Climate Hotspots: Climate-Induced Ecosystem Damage in Latin America

Walter Vergara
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Introduction. This chapter serves as an introduction to the rest of this document. It introduces a typology of vulnerable ecosystems and a description of how these are being affected by climate impacts.

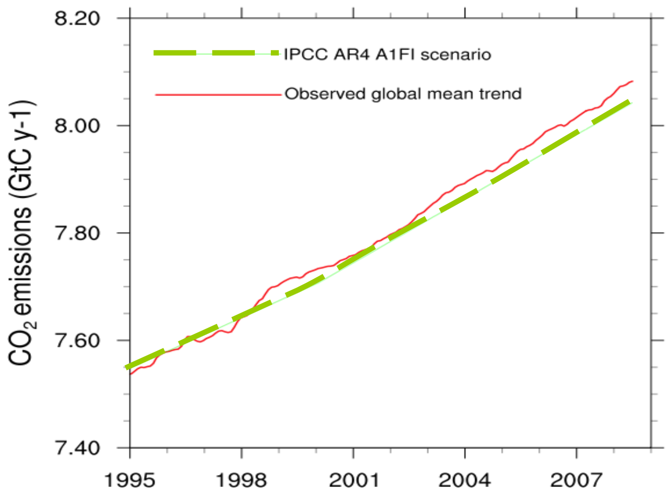
The global path of CO_2 already surpasses that anticipated under the worst-case SRES scenario (Figure 1). Thus, the current trend may result in a situation that exceeds the direst of anticipated consequences. Although there are uncertainties with regard to exact consequences, there is high confidence (IPCC 2007) that impacts from climate change, even under significantly more modest emission scenarios, will affect the functioning and integrity of key ecosystems worldwide. These impacts will add to the stress already resulting from local anthropogenic effects (Millennium Ecosystem Assessment 2007) and combined represent an unprecedented challenge to the global biosphere. While the impacts are being felt globally, some regions will be more affected than others.

In particular, the effects of climate change[1] will likely heavily impact Latin America and the Caribbean, where there remains a substantial, but intrinsically fragile, natural capital and where there are a number of climate-sensitive ecoregions. These climate-sensitive regions should be further characterized to reflect the relative vulnerability of dependent populations (not just humans) to climate impacts. The situation contrasts with a relatively modest volume of CO_2 emissions generated in the subcontinent.[2]

Before ensuing in a discussion on potential costs of climate impacts and required adaptation measures, there is a need to recognize that the best and probably cheapest approach to minimize the costs of adaptation is a forceful mitigation policy enacted, first of all, by the most energy-intensive societies. In setting up the proper framework for adaptation, dealing with adaptation costs without addressing mitigation is a losing proposition.

[1] In addition, climate change can affect climate variability, which modifies weather patterns in a very short time period (4–10 years). This of course can also have unexpected impacts on ecosystems and humans.
[2] With about 5% of the global share (1.4 billion tons in 2004) Latin America is a modest emitter of fossil CO2 emissions. LAC has 8% and 7 % of the global population and GDP respectively.

Figure 1. Comparison of current path of emissions with worst-case SRE (A1F) scenario 1995–June 2008



Source: Observed CO_2 values (through June 2008) taken from NOAA ESRL http://www.esrl.noaa.gov/gmd/ccgg/trends
IPCC values taken from IPCC-DDC. http://www.ipcc-data.org/ddc_co2.html

Addressing the irreversible loss of ecosystem services and biodiversity impacts is probably the single largest item in adaptation costs in Latin America and the Caribbean. As an example, cold-climate species (mountain tapirs, mountain anurans, high-altitude Andean flora and others) are likely to see their habitat in the Andes drastically reduced as temperature increases 3 to 4ºC during this century. Likewise, many coral species in the Caribbean may be bleached into oblivion during the same period. As horrific as this is, extinctions are just one of the symptoms of the loss of functioning ecosystems induced by climate change. Potential climate-induced reductions in the Amazon Basin (dieback of forests induced by climate change) would drastically impact the entire biosphere.

Destabilizing these ecosystems will have much wider implications for environmental services required by many species. All these impacts on agriculture, power and water supply, and infrastructure can also be traced back to impacts on nature. Therefore, this should be the starting point for an assessment of climate impacts, one that centers on the planet and not just on our use of it.

Moreover, the issue of relative vulnerability is critical at this point because it is being used, in combination with socioeconomic indicators, to make decisions that will affect the allocation of financial resources for adaptation. It is thus of more than scientific interest to assess the relative magnitude and consequences of climate impacts in Latin America and the capacity to respond. Vulnerability to climate impacts is thought to reflect both the potential impact and the capacity to respond. The capacity to respond, or adaptive capacity, in itself a subjective notion, is intended to reflect a measure of institutional and economic ability to manage the anticipated impacts. Compounded climate impacts arguably have important consequences in Latin America that will exceed the region's adaptive capacity.

Some of the impacts can be monetized (quantified in economic terms) and this report presents several examples of this quantification. However, a significant share of the impacts is felt by ecosystems and the damage inflicted is more difficult to evaluate. Although the economic services provided by these systems can be quantified, many of the effects are borne by numerous other species with little or no chance to adapt unassisted to quickly changing environmental conditions. We require the methodologies and tools to estimate such costs, but these need to be acknowledged upfront and efforts should be undertaken to develop the instruments that would allow us to properly consider the costs of adaptation for natural capital.

Climate Hotspots

To visualize these impacts on ecosystems, it is useful to discuss the notion of Climate Hotspots as those comprising ecosystems that are particularly affected by the physical consequences of climate change. Focusing on hotspots also helps in defining areas that require urgent attention or need to be highlighted to press for forceful climate action.

In this working definition, Climate Hotspots are defined by a combination of:

Immediacy. Impacts are already being felt or the effects are expected to take place in the near term;

Irreversibility. The changes experienced by the affected ecosystems cannot be reversed;

Magnitude. The impacts would render the affected ecosystem non-operational or the damage is so thorough that the ecosystem is no longer providing meaningful levels of its original environmental services, many of which are difficult to assess in financial terms;

Consequences. The changes would imply considerable losses of natural and eventually financial capital.

This definition can be applied to some of the system-wide impacts in evidence in the region. These include: a) the bleaching of coral reefs, leading to an anticipated total collapse of the coral biome in the Caribbean Basin; b) the warming and eventual disabling of mountain ecosystems in the Andes; c) the subsidence of vast stretches of wetlands and associated coastal systems in the Gulf of Mexico; and d) the risk of forest dieback in the Amazon Basin (see Table 1 below).

Table 1. Some Climate Hotspots in Latin America

Climate Hotspot	*Direct effect*	*Immediacy*	*Irreversibility*	*Magnitude of physical impacts*	*Economic consequence*
Coral Biome in the Caribbean	Bleaching and mass mortality of corals	Now	Once temperatures pass the threshold for thermal tolerance, corals will be gone.	Total collapse of ecosystem and wide-ranging extinction of associated species.	Impacts on fisheries, tourism, increased vulnerability of coastal areas.
Mountain ecosystems in the Andes	Warming	Now	The thermal momentum in mountain habitats will result in significant increases in temperature, leading to major uni-directional changes in mountain ecology.	Disappearance of glaciers, drying-up of mountain wetlands, extinction of cold-climate endemic species.	Impacts on water and power supply, displacement of current agriculture and changes in planting patterns (with varying degrees of impacts depending on location, sesonality, and ability to adapt).
Wetlands in the Gulf of Mexico	Subsidence and salination; increased exposure to extreme weather	This century	Irreversible sea level rises will submerge coastal wetlands, affecting their ecology.	Disappearance of coastal wetlands, displacement and extinction of local and migratory species.	Impacts on coastal infrastructure, fisheries and agriculture.
Amazon Basin	Forest dieback	This century	If rainfall decreases in the basin, biomass densities would also decrease.	Drastic change to the ecosystem, leading to potential savannah.	Impacts on global water circulation patterns, agriculture, water and power supply on a continental scale

Collapse of the coral biome in the Caribbean Basin

Coral reefs are home to more than 25% of all marine species, making them the most biologically diverse of marine ecosystems and an equivalent to rainforests in land ecosystems. Corals are also very sensitive to changes in environmental conditions. When stressed by rising temperatures, corals are expected to lose the ability to conduct photosynthesis, eventually leading to their bleaching and death. Increased carbon dioxide concentrations in the atmosphere also lead to more acidic seas, which impairs the ability of corals to assimilate carbonates. Corals also play very important roles for other species, providing the habitat for the spawning of many species and protection and mechanical support for other plants and animals.

The warming of the Caribbean Sea has led to many impacts but scarcely any equals the intensity with which it has affected the coral reefs in this region (Wilkinson and Souter 2008). Gradual and consistent increases in sea surface temperatures have yielded increasingly frequent bleaching events, the latest of which (2005) caused wide-scale bleaching throughout the region. As sea surface temperatures continue to increase, the ability of coral beds to withstand thermal shocks diminishes, leading to mass mortality.

In the wake of coral collapse, major impacts are anticipated, including severe loss of biodiversity, impacts on fisheries, tourism, and coastal protection. Although the latter three can be reasonably monetized, the loss of species and ecosystem integrity is more difficult to evaluate, yet it may represent the most important of these consequences. One-third of the more than 700 species of reef-building corals are already threatened with extinction. It is estimated that between 60 to 70 endemic species of corals in the Caribbean are also in danger (Carpenter et al. 2008). The costs of adapting corals to future environmental conditions in the Caribbean and protecting and recovering affected populations are likely to be very high, yet remain unassessed. The Bank is supporting efforts by the Caribbean Community Climate Change Center to develop a pilot for the recovery of coral populations affected by bleaching. This pilot could eventually provide some of the information required to make this assessment.

The effects are immediate, major, and likely to be irreversible. The economic consequences for the countries in the region are severe. Clearly, the coral biome constitutes a Climate Hotspot even if the full value of the damage escapes quantification.

Rapid warming of high-mountain ecosystems in the Andes

Glaciers, mountain moorlands *(páramos*, neo-tropical high elevation wetlands*)* and cloud forests are experiencing abrupt climate change (Ruiz et al. 2008; Vergara et al. 2007). Analyses of ensemble products from global circulation models appear to indicate that the rate of warming may be faster at higher altitudes in the Andes (Bradley et al. 2006). Other analyses of field data confirm this trend. As discussed in the section on glaciers in this report, there is a well-documented major loss in ice cover in the Andes and substantial evidence that the associated glacier retreat is accelerating. Glacier retreat diminishes the mountains’ water regulation capacity, making it more expensive to supply water for human consumption, power generation, or agriculture, as well as for ecosystem integrity in associated basins. Impacts on economic activities can be monetized (see Vergara et al. 2007, and the chapter on glaciers in this report). However, the loss of integrity of high-mountain habitats is more difficult to evaluate. The combination of higher temperatures and altitudinal changes in dew points also affect high-altitude species with little room to move up.

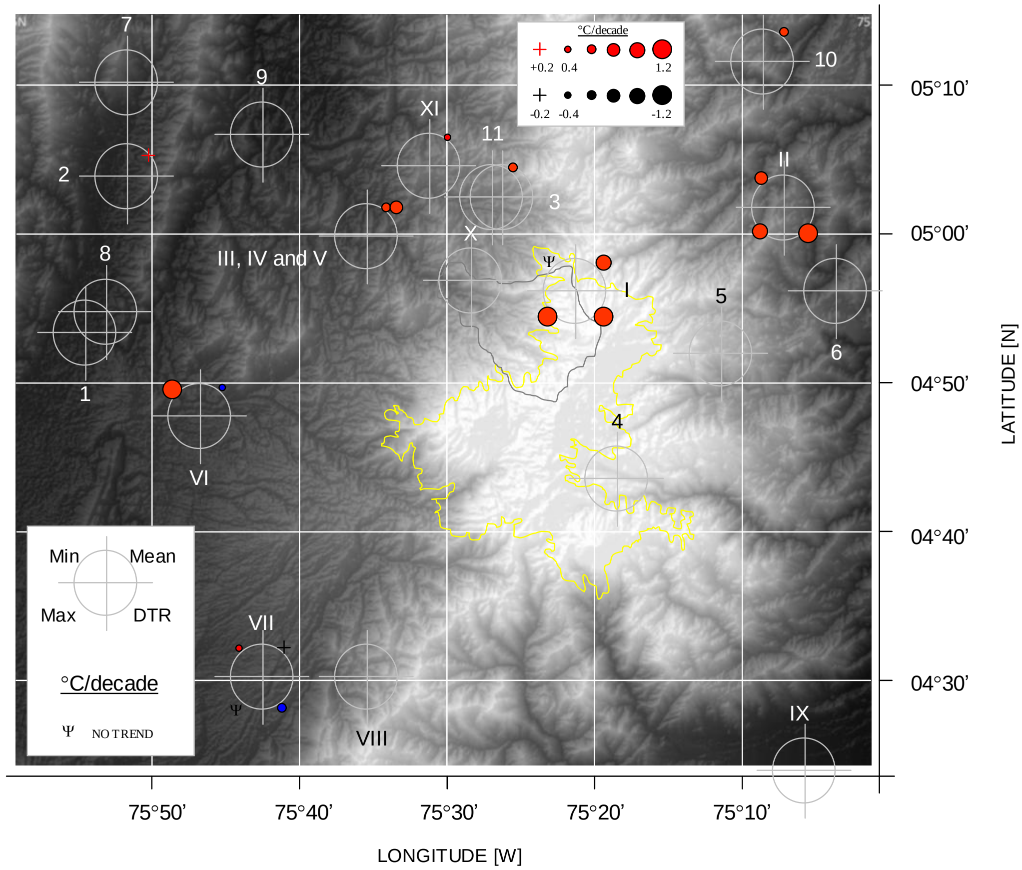
High-mountain ecosystems, including *páramos* and snowcapped terrain, are among the environments most sensitive to climate change. These ecosystems have unique endemic flora and provide numerous and valuable environmental goods and services. Although understanding of glacier retreat and its consequences has significantly increased, the consequences of climate change on the functioning of páramos and cloud forests require additional work.

Data recently made available (Ruíz et al. 2007) suggest that climate impacts have already altered the circulation patterns responsible for producing and moving water vapor to the region. These changes have probably contributed to the disappearance of high-altitude water bodies as well as to the increased occurrence of natural and human-induced mountain fires. It could also be behind some of the reductions in populations of mountain flora and fauna in the Andes. Thus, understanding the páramos' function and response to climate change remains a critical priority.

Likewise, an analysis of páramo dynamics, supported by the Bank, points to worrisome temperature trends (for example, see Ruiz et al. 2008, Figure 2). These seem to indicate positive anomalies on the order of 0.6ºC per decade, affecting the northern, more humid section of the Andes. Other work, undertaken by IDEAM in Colombia as part of the Integrated National Adaptation Plan (INAP), is assessing changes in the carbon sinks of these ecosystems, induced by warmer soil temperatures.

Changes in the altitudinal location of dew points, a consequence of warming of the troposphere, will also affect the relative formation of clouds and horizontal precipitation and eventually lead to disruption of cloud forests, which today in the Andes house an important fraction of global biodiversity. Rapid warming may also lead to an increase in the rate of desertification of mountain habitats. Combined, these impacts constitute a serious threat to water supply and critical habitats in the region. The changes are current (immediate) and cumulative, likely to be irreversible, and occur region-wide.

Figure 2. Observed temperature trends (observatory analysis) in the perimeter of the Los Nevados Natural Park in Colombia[3]



Source: Ruiz et al. 2008.

Loss of wetlands in the Gulf of Mexico

Wetlands provide many environmental services, including regulation of the hydrological regime; human settlement protection through flood control; protection of the coastal region; help in mitigating storm impacts; control of erosion; conservation and replenishing of coastal groundwater tables; reduction of pollutants; regulation and protection of water quality; retention of nutrients, sediments, and polluting agents; sustenance for human communities settled along the coast; and habitats for wildlife.

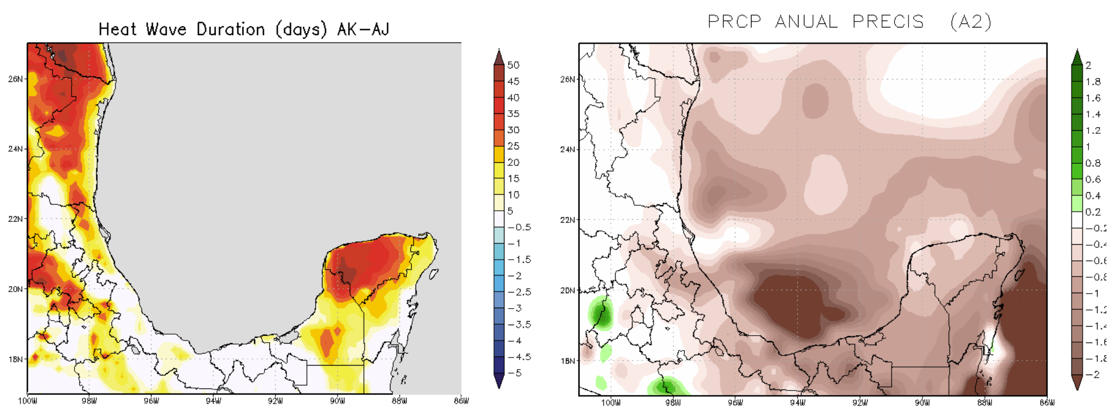
Wetlands in the Gulf of Mexico have been identified by Mexico's National Institute of Ecology (INE) as one of the ecosystems that are most critical and threatened by

[3] Observed trends (observatory analysis) in minimum (top left quadrant), mean (top right quadrant), maximum temperatures (bottom left quadrant) and mean diurnal temperature range (bottom right quadrant). Circles denote the location of weather stations; red dots depict increasing trends; black dots depict decreasing trends; yellow solid line delineates the perimeter of the Los Nevados Natural Park; grey solid line shows the Claro River's high altitude basin.

anticipated climate changes. Data published on projected forced hydro-climatic changes, as part of IPCC assessments (Milly et al. 2005) indicate that Mexico may experience significant decreases in runoffs, on the order of minus 10 to 20% nationally, and up to 40% over the Gulf Coast wetlands, as a result of global climate change. Mexico's third national communication (NC)[4] and other studies have documented ongoing changes in the wetlands of the Gulf and have raised urgent concerns about their integrity. Other studies have indicated that the wetlands in this region are particularly vulnerable to subsidence and saline intrusion, both forced by climate change.[5] These impacts would further aggravate the country's water budget and critically affect the integrity of coastal wetlands. The threat is worrisome because the Gulf of Mexico possesses one of the region's richest ecosystems (Caso et. al. 2004).

Located along the lower reach of the Gulf's main water tributaries, the Gulf wetlands are considered the country's most productive ecosystem (INE 2007). The Gulf of Mexico is home to more than 75% of all coastal wetlands in Mexico. Forty-five percent of all shrimp, 90% of the country's oysters, and no less than 40% of commercial fishing volume originate in these geo-forms. The mangrove surface calculated for the Gulf of Mexico totaled 545,000 ha in 2000 but is being lost at a rate of at least 1% annually since 1976 (with higher estimates of 2.5% per year; INE 2005). Global circulation models coincide in identifying the Gulf of Mexico as a coastal region highly vulnerable to climate-induced impacts.[6] Although other coastal areas will also be prone to similar impacts, the biological and economic value of the region justifies it as a Climate Hotspot.

Figure 3. Projected heat waves and precipitation changes in the Gulf of Mexico under Scenario A2



Source: Data developed by INE during preparation of Adaptation to Impacts in the Gulf of Mexico Wetlands

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[4] INE. 2007. Third National Communication to the UNFCCC.

[5] Note, however, that aside from climate change there are other important reasons why wetlands are deteriorating in the Gulf of Mexico (i.e., industrial purposes).

[6] Recent results of the work with the Earth Simulator, supported by the Bank as part of the preparatory work for Mexico: adaptation to climate impacts in the Gulf of Mexico and other modeling tools confirm the magnitude of the challenge.

Risk of Amazon dieback

The **Technical Summary of the Fourth Assessment Report of the UNFCC**, reflecting a consensus view, indicates a potential Amazon loss of between 20 and 80% as a result of climate impacts induced by a temperature increase in the basin of between 2.0 and 3.0ºC. The IPCC also indicates a likelihood of major biodiversity extinctions as a consequence. If this loss takes place, it would be **one of the most profound potential impacts of climate change in the twenty-first century and it would affect the ecosystem integrity of the large Amazon Basin.** Temperature increases and disruption in precipitation cycles would seriously hamper the workings of the Amazon as a forest ecosystem, reducing its capacity to retain carbon, increasing its soil temperature, and possibly forcing the Amazon through a gradual process of savannization. However, Amazon dieback will not only be a result of climate change but it would also contribute to it and accelerate global warming by the release of carbon dioxide into the atmosphere. Thus, the Amazon dieback is not a unidirectional impact of climate change but it can result in a vicious feedback loop that will also affect the hydrological cycle and that could trigger the process of desertification over other areas of Latin America.

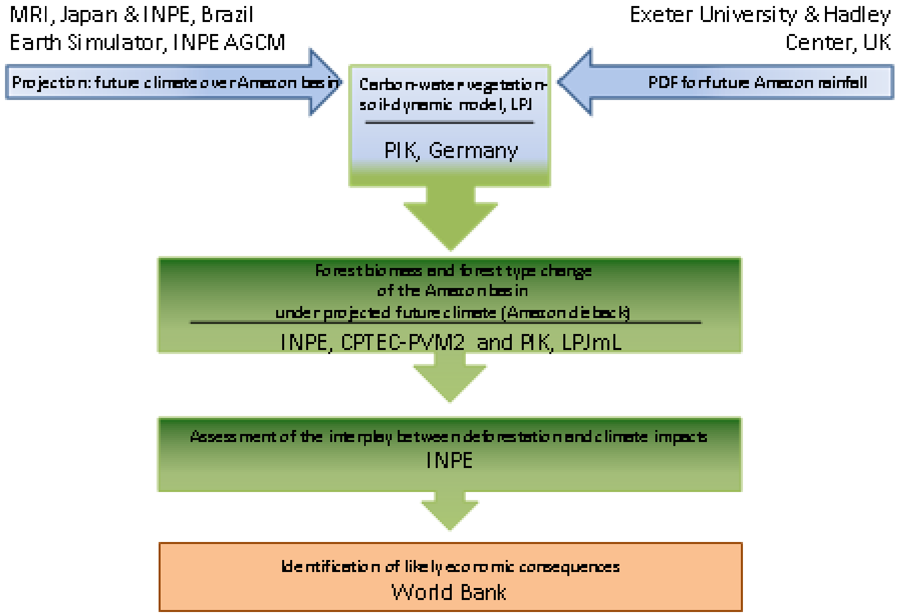
Although there is no agreement in the scientific community on the likelihood and pace of this savannization process, some models indicate a drastic reduction in biomass cover as a result of reductions in rainfall in the western Amazon (up to a 90% reduction by the end of the century; Cox 2008). These predictions were reinforced in 2005 when large sections of southwestern Amazonia experienced an intense drought (among the most severe of the last hundred years). The drought severely affected settlements along the river and its western and southwestern tributaries. The causes of the drought were clearly not related to El Niño,[7] but at the time of its occurrence there was an anomalously warm tropical North Atlantic, and a reduced intensity in northeast trade wind moisture transport into southern Amazonia during the peak summertime season was experienced. The weakened upward motion over this section of Amazonia resulted in reduced convective development and rainfall (Alves et al. 2008).

The Amazon rainforest plays a crucial role in the global climate system. It helps to drive atmospheric circulation in the tropics by absorbing energy and recycling about half of the rainfall that falls upon it. Furthermore, tropical rainforests are estimated to account for over 40% of global net primary productivity and the Amazon basin accounts for a significant fraction of this total (Melillo et al. 1993). Despite large-scale deforestation, it still seems likely that the region continues to act as a net sink for anthropogenic CO_2 emissions. Impacts derived from dieback include the reduction of moisture delivered to the Central and Northern Andes and effects on the functioning of the northern plains in Brazil and Argentina. However, the largest predicted decrease of precipitation in

[7] El Niño-Southern Oscillation (ENSO) is related to climate variability. According to NOAA, El Niño is an oscillation of the ocean-atmosphere system in the tropical Pacific having important consequences for weather around the globe. These consequences include increased rainfall across the southern tier of the US and in Peru, which has caused destructive flooding, and drought in the West Pacific, sometimes associated with devastating brush fires in Australia.

continental regions, outside of the tropics, as a result of reduction in biomass density in the Amazon is seen in North America (Avissar and Werth 2005).

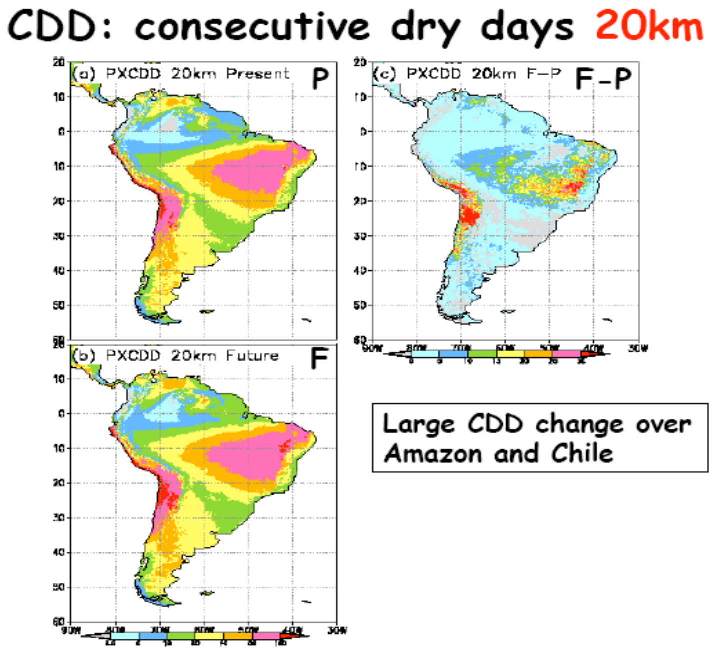
Figure 4. Schematic of the structure of the Bank-supported Risk Analysis of Amazon Dieback



Amazon dieback is a severe potential climate change impact in Latin America, yet its prospects are poorly understood. The resilience of the forest to the combined pressures of deforestation, land use changes, and human-induced fires, coupled with climate change, is therefore of great concern.

The Bank is supporting the assessment of the risk of Amazon dieback induced by climate impacts. The structure of the task, which includes the downloading of Earth Simulator data for end-of-century climate in the basin, the development of a probability development function for rainfall as a function of CO_2 concentration, and the assessment of biomass response to these changes through the application of the LPJ model and a consequence analysis, is depicted in Figure 4. Recent results from the application of the Earth Simulator are already available and some of the data indicate a projected reduction in rainfall during the dry season and an increase in consecutive dry days (Figure 5).

Figure 5. Anomaly in consecutive dry days (CDD) predicted through the Earth Simulator for end of century, Scenario A2



Source: Kitoh A.,2008.

Relative Vulnerability

Do all of these at-risk ecosystems make the region particularly more vulnerable than others? The wide geographical coverage and diverse character of these impacts seem to indicate so. The combination of large-scale loss of functioning ecosystems (home to a significant share of global biodiversity), the significant potential impacts on power and water supply, and the very likely increased costs in health and food make the region a priority in the climate change adaptation agenda. It is obvious that few other impacts may rival in costs the consequences of Amazon collapse, desertification of the Andes, and destruction of coral reefs. The lack of adaptation strategies, responses, and programs could make the costs of these impacts higher.

The magnitude of the population that could be affected and its ability to cope with the potential impacts is a question that currently cannot be answered with certainty. Subsequent sections of this report present cost data for very specific situations. An estimate of costs induced by the intensification of hurricanes in the Caribbean Basin is presented by Judith Curry and colleagues. The aggregated costs of climate impacts in the Caribbean are presented by Natsuko Toba, based on an earlier report by Erik Haites. An analysis of potential consequences of coral loss and the costs of glacier retreat, illustrated by impacts on the cost of water and of power supply in Peru, are presented in reports by Walter Vergara and colleagues, (the latter, expanding on an analysis published in 2007). The costs associated with increased exposure to tropical vector diseases in Colombia are estimated by Javier Blanco and Diana Hernández. The analysis, although limited by the scope and availability of data, paints an emerging picture of significant and growing economic consequences of climate impacts.

The report includes other impacts, including the analysis of the current status of the coral biome and the trends in sea level rise with its potential impacts on coastal infrastructure and ecosystems, despite the lack of associated monetization of such impacts.

There is a growing discussion on the need to allocate scarce adaptation resources in areas that are not only likely to receive the brunt of impacts but also for populations that lack the capacity to respond. Clearly, there is a significant advantage in implementing adaptation strategies and programs in these areas. However, provided that impacts are comparable for different regions, the following questions on how to allocate adaptation resources emerge: Should adaptation resources be allocated on the basis of lack of capacity to respond? Is it not better to invest resources at the start of large adaptation programs, in those areas that could use them more expeditiously and arguably with better results? Would it not also make financial sense to invest in protecting critical ecosystems already affected by climate impacts and whose collapse will literally impoverish the Earth? These are questions that require further dialogue and a timely response.

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Potential Economic Impacts of Hurricanes in Mexico, Central America, and the Caribbean ca. 2020–2025

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Introduction

This report builds upon our previous report, "Landfalling Tropical Cyclones in Central America and the Caribbean: Past and Future" (June 15, 2007). In this report the authors make specific projections of landfalling tropical cyclones for a five-year period ca. 2020–2025, accounting for the impacts of both natural variability and global warming on tropical cyclone frequency, intensity, and the cyclone tracks. Specific projections of the range of likely landfalling tropical cyclone characteristics are made for the following individual regions: Mexico, Central America and the Yucatan, Bahamas, Lesser Antilles, and Greater Antilles.

Methodology

In recent years, three different disaster risk analysis methodologies have been developed, each with slightly different objectives to consider the Disaster Deficit Index, Local Disaster Index, Prevalent Vulnerability Index, and Risk Management Index: the Disaster Risk Indexing Project (DRI), Hotspots, and the Americas Project. The DRI focuses on human vulnerability while Hotspots focuses on economic loss. On the other hand, the Americas Project focuses on possible economic losses, exposure and susceptibility, socioeconomic fragility and lack of resilience, and performance regarding risk management practices at the country level. The three indices share a common theory of disaster causality: exposure to hazard, the frequency or severity of the hazard, and the vulnerability of exposed elements.

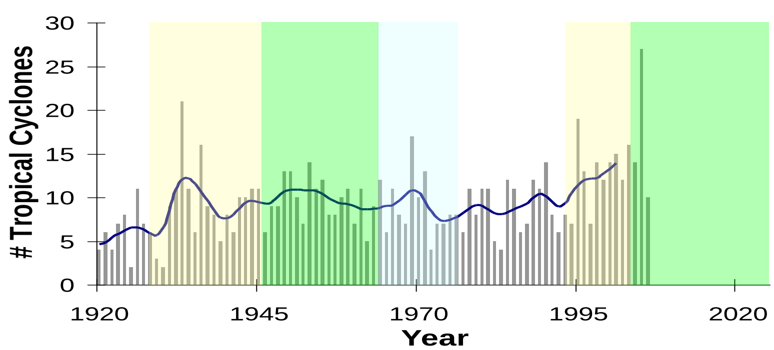
However, to our knowledge, none of these methodologies has been applied to future risk from tropical cyclones. The strategy adopted here is to use the available data and indices that have been calculated for the relevant countries and project forward the population and GNP. The calculated disaster indices, combined with projections of population and GNP, are used with damage estimates from past hurricanes and potential projections of future tropical cyclone activity to estimate the future risk. Since this strategy hinges on the availability of economic data, this methodology is only applied to countries where complete economic data are readily available: Antigua and Barbuda, Barbados, Bahamas, Belize, British Virgin Islands, Cuba, Dominica, Dominican Republic, Haiti, Grenada, Honduras, Jamaica, Mexico, Nicaragua, Puerto Rico, St Kitts and Nevis, St. Lucia and the Grenadines.

Estimate of landfall activity ca. 2020–2025

Decadal scale projections of future tropical cyclone (TC) activity must integrate in some way the climate model projections of externally forced century-scale climate change with what is known about natural modes of climate variability and their future changes. By 2025, the tropical sea surface temperature (SST) is forecasted to increase by 0.6°C due to external forcing by greenhouse gases. Predictability of the natural modes of climate variability arises from the general predictability and persistence of multidecadal modes such as the Atlantic Multidecadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO). The AMO is expected to remain in the warm phase, the PDO is expected to be in the negative phase (with greater frequency of La Niña), and the North Atlantic Oscillation (NAO) is expected to continue in the negative phase before shifting to a more predominantly positive phase during the 2020–2025 period.

Figure 1 shows the time series of total North Atlantic tropical cyclones since 1920. The yellow shading indicates the warm phase of the AMO and the blue shading indicates the cool phase of the PDO (associated with greater frequency of La Niña), with green indicating the overlap. It is seen that the total number of tropical cyclones is elevated in the yellow and green regions. Conditions of warm AMO and cool PDO (green) are expected to persist until 2025.

Figure 1. Time series of total North Atlantic tropical cyclones (the line represents a 9-year Hamming filter). Yellow shading indicates the warm phase of the AMO, blue indicates the cool phase of the PDO, and green indicates their overlap.



The global warming signal in the tropical cyclone count is difficult to discern due to the convolution of the decadal climate signals with the global warming and the issue of undercounting in the earlier part of the data record. To provide an upper bound on the plausible increase of tropical cyclone frequency for a 0.6°C SST increase, we take two approaches. The first approach compares the two yellow periods in Figure 2 (1928–1945 and 1994–2002), finding a scaled increase of 6.4 TCs for an equivalent 0.6°C temperature increase. This approach effectively eliminates the signal of the decadal scale natural variability, but is hampered by likely undercounting in the earlier part of the record. The second approach is to compare the 1968–1977 period (encompassing a minima in the SST) with the last 10 years (1997–2006), encompassing the warmest part of the temperature record and resulting in a scaled increase of 5.4 TCs for an equivalent 0.6°C SST increase. This approach has the advantage that the tropical cyclone count is presumed to be accurate during this period (the satellite era), while the disadvantage is that comparing these two periods introduces a bias from the AMO that may be more complex than the increase in SST. High-resolution climate model simulations produce a scaled annual increase in the number of tropical cyclones for a 0.6°C SST increase to range from 0–1. Thus, we bound the projected increase in North Atlantic TC frequency to be 0 to 5.

Figure 2. Time series of total North Atlantic tropical cyclones (blue) and sea surface temperature in the main development region (red) (lines represent a 9-year Hamming filter). Yellow shading indicates the warm phase of the AMO, blue indicates the cool phase of the PDO, and green indicates their overlap.

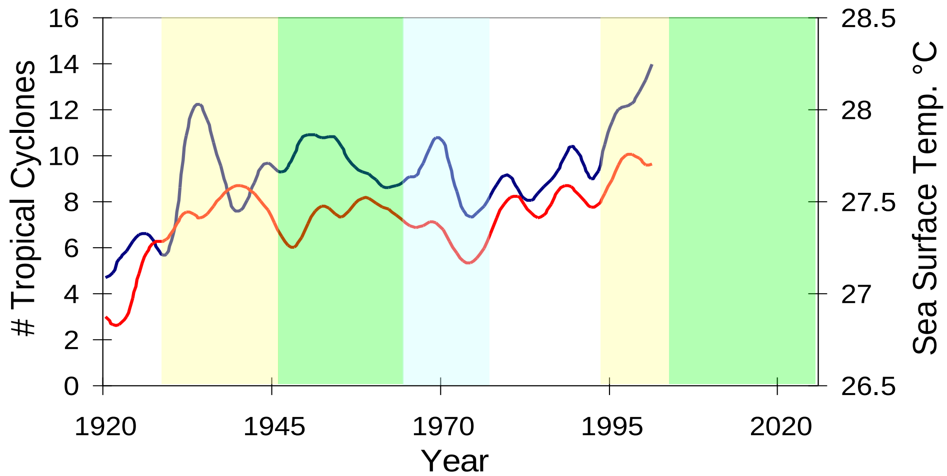
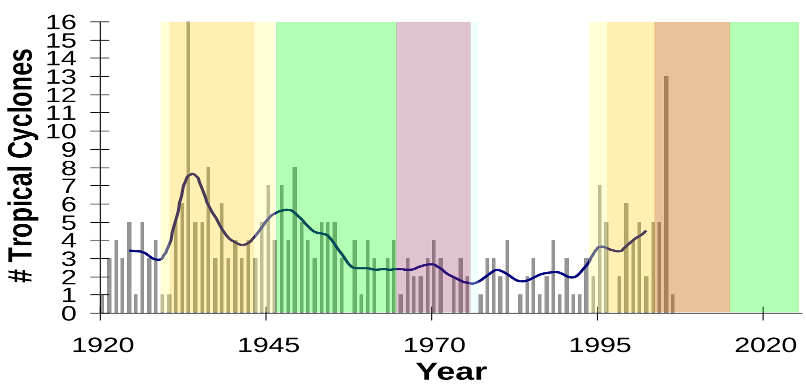


Figure 3 shows total Caribbean and Central American landfalls. The color scheme is the same, with the addition of the North Atlantic Oscillation (NAO), the negative phase of which is represented in red and combines with the other colors to produce orange, purple, and brown. Of particular interest is the brown period that began in 2003 and is expected to continue for a few more years, before the NAO becomes predominantly positive. The negative phase of the NAO is seen to contribute to increased landfalls, particularly during the warm phase of the AMO. The period with the greatest average number of annual landfalls is from 1930 to 1942, during the warm phase of the AMO with conditions of negative NAO.

Figure 3. Time series of North Atlantic tropical cyclones striking the Caribbean or Central America (the line represents a 9-year Hamming filter). Yellow shading indicates the warm phase of the AMO, blue indicates the cool phase of the PDO, and green indicates their overlap. The negative phase of the NAO is indicated in red, with overlapping colors of orange, purple, and brown.



We seek to estimate the frequency of Central American and Caribbean landfalls for a five-year period ca. 2020–2025 in the following five zones: Mexico, Central America and the Yucatan, Bahamas, Lesser Antilles, and Greater Antilles.

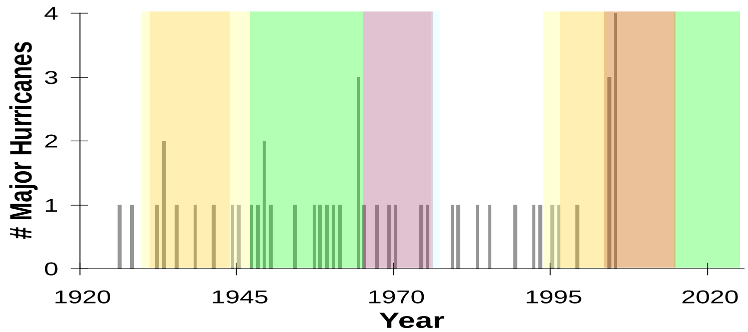
This is accomplished in two steps: by projecting the ratio of total Caribbean and Central American landfalls (TL) to North Atlantic TCs (TC), and then by distributing the landfalls among the five different regions. We consider a range of projected TC, accounting for range of 0 increase to an increase of 5 tropical cyclones. We assume that the ratio TL/TC for 2020–2025 is the same for the 1995–2006 period, accounting for the lowering of the ratio associated with the eastward extension of the tropical warm pool. The distribution of landfalls in the five different regions is determined by considering the distributions in two periods: 1946–1964 (green), which is the closest representation for natural variability, and the most recent active period (1995–2006), which reflects the influence of global warming. A comparison of the different distributions for these two periods (Table 1) indicates that the main shifts occur in Central America/Yucatan and the Greater Antilles. In Table 1, the 2020–2025 projection is determined by averaging the percentage of landfalls over the two periods. The two rightmost columns in Table 1 reflect the projected average number of landfalling tropical cyclones in each of the five regions for the 2020–2025 period (based upon equal weighting of the landfall distributions for the two periods), bounded by a low estimate (based upon a zero increase in total TC count) and a high estimate of an increase of 5 TCs.

Table 1. Projection of changes in landfalling tropical cyclones for defined zones in the Central America/Caribbean Basin, in context of the landfall distributions during 1946–1964 and 1995–2006

	1946-1964	**1995-2006**	**2020-2025 landfall %**	**2020-2025 Low**	**2020-2025 High**
Total N. Atlantic TCs	9.74	14.42	-	14.42	19.42
Total CA/Carib. Landfalls	3.84	4.58	36%	5.19	6.69
Mexico Landfalls	0.74	0.92	20%	1.04	1.34
CA/Yucatan Landfalls	0.68	1.17	22%	1.14	1.47
G. Antilles Landfalls	1.58	1.08	33%	1.71	2.21
L. Antilles Landfalls	1.00	1.25	26%	1.35	1.74
Bahamas Landfalls	0.74	0.83	19%	0.99	1.27

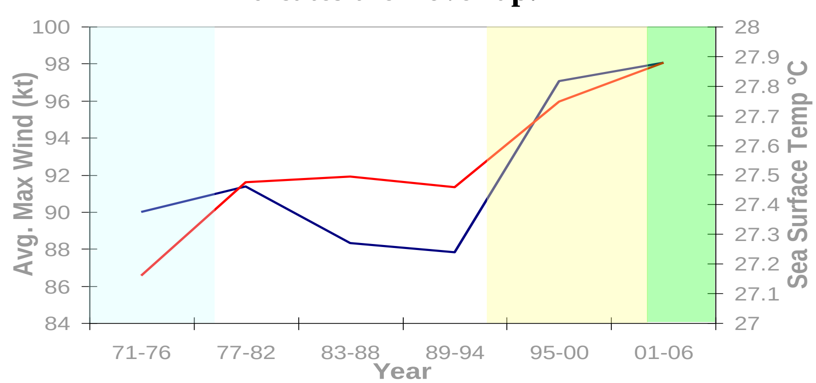
Landfalling major hurricanes in the region are also influenced by the modes of natural variability. Figure 4 shows that although the region typically fluctuates between zero to one major hurricane landfall per year, spikes in these values occur when under the influence of a warm AMO, a cool PDO, and/or a negative NAO. It is also probable that the marked increase in recent years of major hurricane landfalls in the region is influenced by the increasing SSTs being forced by an increase in greenhouse gases. In the last four years, including 2007, two or more landfalls have occurred in three out of the four seasons. The lack of marked variability prior to recent years makes precise projections difficult, but it does appear that the combination of natural and anthropogenic forcing mechanisms will lead to multiple landfalls by major hurricanes in the region for a typical year in the 2020–2025 period.

Figure 4: Time series of major hurricanes striking the Caribbean or Central America. Yellow shading indicates the warm phase of the AMO, blue indicates the cool phase of the PDO, and green indicates their overlap. The negative phase of the NAO is indicated in red, with overlapping colors of orange, purple, and brown.



The increase in landfalling major hurricanes is indicative of a broader increase in average tropical cyclone wind speeds as sea surface temperature increases, as well as a shift in the intensity distribution toward a greater number of Category 4 and 5 hurricanes. Figure 5 shows the change in North Atlantic hurricane intensity for the period since 1971 (unfortunately the quality of the prior data is highly uncertain), along with the sea surface temperature. The data are averaged into six-year increments to reduce the impact of the year-to-year variability associated with ENSO. Linear regression analysis indicates trend of 6.75% intensity increase associated with a 0.6°C SST increase. Due to some uncertainty in the data prior to 1983 (most likely a low bias), the true increase is likely to be somewhat lower. Figure 5 shows that the large increase in intensity is associated with the onset of the warm phase of the AMO ca. 1995. Thus, it is likely that both natural variability (primarily the AMO) and global warming are contributing to the intensity increase. A projection of the likely intensity increase ca. 2020–2025 requires a separation of the AMO signal from the global warming signal, which is not possible given the short length of the reliable dataset.

Figure 5. Time series of maximum hurricane intensity (blue) and sea surface temperature (red), averaged in six-year windows. Yellow shading indicates the warm phase of the AMO, blue indicates the cool phase of the PDO, and green indicates their overlap.



An analysis (Webster et al. 2005) of the global tropical cyclone intensity data (of uncertain quality) since 1970 indicates an average increase in intensity of 6% for a 0.6^{o}C SST. High-resolution climate models indicate a 2% intensity increase when scaled for a 0.6^{o}C SST increase, and potential intensity theory yields an increase of 2.7% (Emanuel) and 5.3% (Holland). Considering these results in the context of the North Atlantic intensity data, we bound the average intensity increase in the North Atlantic associated with 0.6^{o}C global warming by 2–5%. This translates to a 6–16% increase in wind damage (which goes up as the cube of the wind speed increases) and a 15–40% increase in total damage (which goes up as the 7th power of wind speed increases, according to estimates from catastrophe modelers based on historical U.S. damage data). For the Central American/Caribbean region, we use an intermediate value of the 5th power of the intensity to estimate damage (where a 2–5% intensity increase corresponds to a 10–26% damage increase), although we recognize that this damage power may vary regionally based upon the type of damage (wind, flooding, storm surge) and the nature of the assets and economy in the region.

Based upon this analysis, four different scenarios are delineated for the characteristics of regional landfalling tropical cyclones ca. 2020–2025, in terms of numbers and intensities:

A1: no North Atlantic (NATL)[8] frequency increase, 2% intensity increase;
A2: no NATL frequency increase, 5% intensity increase;
B1: 35% NATL frequency increase, 2% intensity increase; and
B2: 35% NATL frequency increase, 5% intensity increase.

Table 2 in turn shows total damage increase estimates for 2020–2025 for each scenario as well as an average of the four scenarios, scaled relative to the average values for the 2001–2006 period. These factors are used in the next section in the projection of damages for the 2020–2025 period. The landfall A scenario corresponds to the “2020–2025 Low” column in Table 1, and the landfall B scenario corresponds to the “2020–2025 High” column.

Table 2. Projected values for the four scenarios and scenario average of percentage frequency and average intensity increase of regional landfalling tropical cyclones, relative to average values for the 1995-2006 period

	A1 #/Damage	A2 #/Damage	B1 #/Damage	B2 #/Damage	Average #/Damage
Mexico	1.13/1.10	1.13/1.26	1.46/1.10	1.46/1.26	1.30/1.18
C. America & Yucatan	0.97/1.10	0.97/1.26	1.26/1.10	1.26/1.26	1.12/1.18
Greater Antilles	1.58/1.10	1.58/1.26	2.05/1.10	2.05/1.26	1.82/1.18
Lesser Antilles	1.08/1.10	1.08/1.26	1.39/1.10	1.39/1.26	1.24/1.18
Bahamas	1.19/1.10	1.19/1.26	1.53/1.10	1.53/1.26	1.36/1.18

[8] NATL refers to basin-wide totals.

Historical hurricane losses

Data on historical hurricane losses during the 1979–2006 period were obtained primarily from the U.S. National Hurricane Center reports, and also from Wikipedia and additional references therein. Some storms during the period considered are not included in the damage statistics due to the unavailability of data. It is possible that insurance agencies, particularly MunichRe, have better hurricane loss data but these do not seem to be readily accessible. We have established a meaningful contact with MunichRe from which we may be able to obtain better information to improve this report once the agency considers the analysis presented in this report.

To understand the damage that might accrue from future hurricanes, we consider the damage and loss of life caused by previous hurricanes. Here we adopt the normalized loss approach following Pielke et al. (2000). The normalized loss dataset accounts for inflation/deflation, wealth, and population. Accounting for inflation/deflation is necessary because the value of a currency varies over time. Increases in wealth and population mean that more people and more property are located in exposed areas and thus more can be lost. The damage for each hurricane normalized to 2007 dollars was determined using the following equation (after Pielke et al. 2000):

$$\textit{Normalized Loss} = \textit{Reported Damage} * I * W * P$$

The variables are defined as follows for a normalization to 2007 values:

- *Reported Damage* – In 2007 U.S. dollar amounts.
- *I* – An inflation factor determined by dividing the U.S. GDP Deflator in 2007 with the U.S. GDP Deflator in the year of hurricane landfall.
- *W* – A wealth factor determined by dividing the GDP per capita for a country in 2007 by the GDP per capita in the year of hurricane landfall.
- *P* – A population factor determined by dividing the 2007 population of a country by the population in the year of hurricane landfall.

To minimize the impacts of the assumptions made in the normalization, we consider hurricanes only from the last 30 years. Unfortunately, a number of very damaging hurricanes occurred during the previous warm period of the AMO (1926–1966) that could not be included in this analysis due to the incomplete economic data. Because of the relatively small physical size of the Caribbean islands, we assume that the entire country is exposed. Due to Mexico’s large size, we consider damage statistics separately for six states (grouped under “Gulf Coast”) that are influenced by Atlantic hurricanes, including Campeche, Quintana Roo, Tabasco, Tamaulipas, Veracruz, and Yucatan. The Central American countries considered here are vulnerable not only near the coasts, but also inland due to flooding and landslides.

We focus on two different damage metrics:

- Maximum Considered Events (MCE): for each country, the single tropical cyclone that caused the most damage and loss of life.
- Cumulative Loss (CL): for each country, the accumulated damage from tropical cyclones over a 20-year period.

Table 3 presents the Maximum Considered Event (MCE) for each country during the 1979–2006 period, which was the period for which credible damage data were available. Of the twenty countries considered here, a total of eight were hit directly by a major hurricane (Category 3 or greater). The single storm that caused the greatest amount of damage was Hurricane Mitch (1998), which was the MCE for a total of five countries (note: at the time of landfall, Hurricane Mitch was a tropical storm). Normalized damage for the MCEs exceeded US$1B for nine of the countries and lives lost per 100,000 inhabitants exceeded 10 people for a total of seven countries.

During the 1950–1978 period the following major hurricanes struck the region, for which we do not have adequate damage data:

- 1971 Hurricane Edith: struck Nicaragua and Honduras
- 1967 Hurricane Beulah: struck Mexico and the Yucatan
- 1960 Hurricane Donna: struck the Lesser Antilles and Bahamas
- 1955 Hurricane Janet: struck the Yucatan and Belize.

Thus, the MCEs in Table 3 are for a 30-year period and this population of storms is not representative of the 50-year MCE.

The losses from smaller but more frequent events can be substantial, particularly for the most vulnerable countries. Data for the past 20 years are used to determine Cumulative Losses (CL) for each country. Three countries (Bahamas, Cuba, Puerto Rico) had more than 10 strikes during the period, while six countries (Belize, Dominica, Guatemala, Honduras, and St. Kitts/Nevis) had three or fewer strikes. A total of twelve countries had normalized damage exceeding $1B in 2007-equivalent dollars. The cumulative number of lives lost exceeded 1,000 for four countries: Dominican Republic, Haiti, Honduras, and Nicaragua.

Table 3. Maximum Considered Event for each country during the 1979–2006 period. [9]

Country	Storm	Normalized Damage 2007 US$M	Lives Lost per 100,000 Pop.
Mexico			
Gulf Coast[10]	2005 Wilma (5)	10,078	0.3
C. America			
	2000 Keith (4)	362	8.4
Belize	2001 Iris (4)	102	21.0
Costa Rica	1998 Mitch ((TS))	149	0.2
El Salvador	1998 Mitch ((TS))	370	4.2
Guatemala	1998 Mitch (TS)	1,159	0.6
Honduras	1998 Mitch (1)	5,180	118.9
Nicaragua	1988 Mitch (TS)	2,940	77.0
Greater Antilles			
Cuba	2001 Michelle (4)	2,589	0.04
Dominican Rep.	1979 David (5)	7,247	34.1
Haiti	2005 Dennis ((2))	1,431	0.6
Jamaica	1988 Gilbert (3)	4,213	2.1
Puerto Rico	1989 Hugo (3)	5,505	0.4
Lesser Antilles			
Antigua & Barbuda	1995 Luis ((4))	1,369	4.2
Barbados	1980 Allen(3)	11	0
British Virgin Is.	1989 Hugo (4)	607	37.6
Dominica	1995 Luis ((4))	71	1.5
Grenada	2004 Ivan ((3))	920	36.3
St. Kitts & Nevis	1998 Georges (3)	645	11.9
St. Lucia	2004 Ivan ((3))	9	0
St. Vincent & Gren.	2004 Ivan ((3))	46	0
Bahamas	2004 Frances (4)	671	0.3

[9] The year and name of the storm are provided, and the intensity of the storm is indicated parenthetically by category number according to the Saffir-Simpson scale (a double parenthesis indicates that the storm did not directly hit the country). The estimated normalized damage is given in millions of 2007-equivalent U.S. dollars. The lives lost in the storm are expressed by 100,000 individuals. The year and name of the storm are provided, and the intensity of the storm is indicated parenthetically by category number according to the Saffir-Simpson scale (a double parenthesis indicates that the storm did not directly hit the country). The estimated normalized damage is given in millions of 2007-equivalent U.S. dollars. The lives lost in the storm are expressed by 100,000 individuals.

[10] Includes Campeche, Quintana Roo, Tabasco, Tamaulipas, Veracruz, and Yucatan.

Table 4. Cumulative Losses for each country during the 1979-2006 period.
The estimated normalized damage is given in millions of 2007-equivalent U.S. dollars.
The lives lost in the storm are expressed by 100,000 individuals.

Country	Total Cyclones	Damage (2007 US$ M)	Avg. Damage % of GDP	Total Lives Lost	Avg .Lives Lost per 100,000 pop.
Mexico					
Gulf Coast	16	47,315	5.29	380	2.4
C. America					
Belize	3	469	11.71	69	9.8
Costa Rica	4	168	0.37	42	0.3
El Salvador	2	370	2.00	253	2.2
Guatemala	1	1,159	3.86	68	0.6
Honduras	3	5,196	32.69	7,042	39.8
Nicaragua	6	5,176	25.29	3,957	16.2
Greater Antilles					
Cuba	14	8,042	2.35	38	0.03
Dominican Rep.	7	9,439	5.30	2,418	5.6
Haiti	7	2,495	22.87	4,721	8.5
Jamaica	7	4,675	12.17	72	0.4
Puerto Rico	12	11,365	0.94	48	0.1
Lesser Antilles					
Antigua & Barbuda	6	1,753	55.53	4	2.9
Barbados	5	11	0.09	1	0.4
British Virgin Is.	6	607	179.34	6	37.6
Dominica	3	71	21.46	1	1.4
Grenada	4	1,040	105.37	40	12.4
St. Kitts & Nevis	3	1,436	110.05	6	7.2
St. Lucia	5	14	0.52	22	5.8
St. Vincent & Gren.	4	64	6.96	5	1.4
Bahamas	11	2,648	7.60	6	0.4

A comparison of Tables 3 and 4 shows that the cumulative loss was dominated by a number of storms rather than a single event for the following countries: Bahamas, Cuba, Puerto Rico, St. Kitts and Nevis, and St. Lucia.

Vulnerability indices

Each country has different economic and social characteristics, which combine to determine the country's vulnerability to natural hazards. Arguably the most sophisticated measure of vulnerability was established in a program of the Inter-American Development Bank and applied to a number of countries in Latin America (Cardona et al. 2004). The Prevalent Vulnerability Index (PVI) assesses inherent socioeconomic vulnerability, and the Risk Management Index (RMI) is an indicator of disaster risk management performance. These indices have been analyzed for twelve countries in Latin America, but only five of these countries overlap with the countries analyzed in this study: Dominican Republic, Jamaica, Guatemala, El Salvador, and Costa Rica. Due to the limited availability of Cardona's risk indices for the countries considered in this analysis, these indices are not used further in the quantitative analysis of damage from tropical cyclones.

To interpret the vulnerability for all 20 of the countries considered here, we examine the Human Development Index (HDI). Values of HDI greater than 0.8 indicate high human development, while values between 0.5 and 0.8 indicate medium human development and values below 0.5 indicate low human development. A total of six countries in the region are classified as high (Antigua and Barbuda, Bahamas, Barbados, Costa Rica, Cuba, St. Kitts and Nevis), while only Haiti is classified as low development. Most of the countries are classified as medium development.

Table 5. Values of the Human Development Index (HDI) for each country or region (2002 values)

Country/ Region	HDI	Country/ Region	HDI	Country/ Region	HDI
Antigua and Barbuda	0.800	El Salvador	0.72	St. Lucia	0.777
Bahamas	0.815	Grenada	0.745	St. Vincent and the Grenadines	0.751
Barbados	0.888	Haiti	0.463	Campeche (Mexico)	0.819
Belize	0.737	Honduras	0.672	Quintana Roo (Mexico)	0.824
Costa Rica	0.834	Jamaica	0.764	Tabasco (Mexico)	0.768
Cuba	0.809	Nicaragua	0.667	Tamaulipas (Mexico)	0.811
Dominica	0.743	Puerto Rico	0.942 (1998)	Veracruz (Mexico)	0.742
Dominican Republic	0.738	St. Kitts and Nevis	0.844	Yucatan (Mexico)	0.778

The vulnerability of the countries to hurricane losses when sorted by HDI is given in Figures 5–6, considering the lives lost per 100,000 inhabitants and the normalized damage per GDP, both for the Maximum Considered Events (MCE) and Cumulative Losses (CL). A general observation is that less developed countries are proportionally more affected by weather hazards, although there is only one country (Haiti) with a low development ranking. With the exception of high development countries for lives lost in the MCE, countries of all development rankings are impacted substantially by hurricanes (both MCE and CL).

Figure 6. Bar charts for the Maximum Considered Events showing a) the lives lost per 100,000 inhabitants and b) damage per GDP, averaged by the three HDI categories (high, medium, low development)

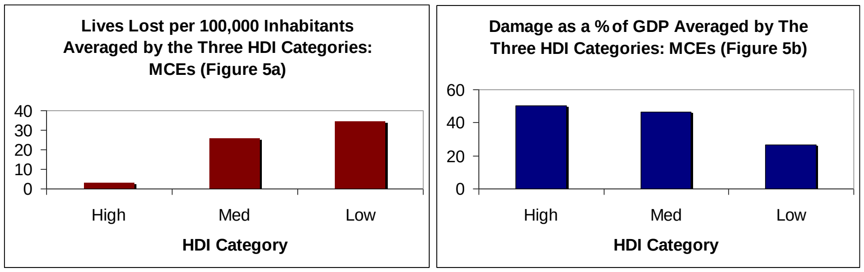
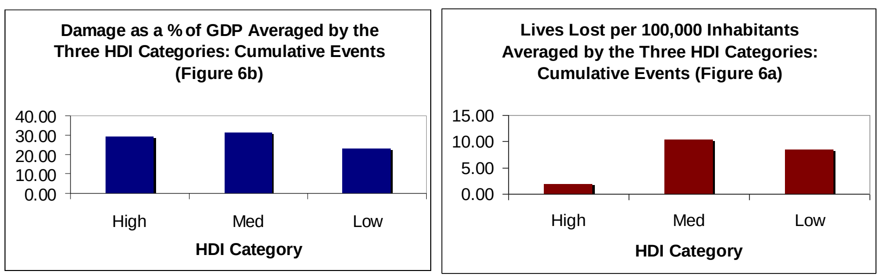


Figure 7. Bar charts for the Cumulative Losses showing a) the lives lost per 100,000 inhabitants and b) damage per GDP, averaged by the three HDI categories (high, medium, low development)



Loss from Hurricanes ca. 2020–2025

Estimations of the potential future loss from hurricanes require that the projections be made not only for hurricane activity but also for population and GDP. Population and GDP projections were obtained from the United Nations Statistical Division. An additional source for GDP projections was also used (see reference list), and the GDP value used here was an average of the two values.

Both the increased population and GDP are normalized by the 2007 values. The Economic Loss Potential (ELP) is determined as the product of the normalized values of population and GDP. Table 6 provides projections for the increased population and GDP for each country, with the countries sorted by the HDI. All of the countries are projected to have at least a 23% increase in Economic Loss Potential. The countries with the greatest increase in Economic Loss Potential are Nicaragua, Belize, and the Dominican Republic, countries with medium human development and presumably high levels of socioeconomic vulnerability.

Table 6. Projections of population and GDP increase for 2020 plus Economic Loss Potential, normalized by 2007 values

Country	HDI	Pop	GDP	ELP	Country	HDI	Pop	GDP	ELP
Mexico					Haiti	0.463	1.22	1.01	1.23
Gulf Coast	0.792	1.14	1.30	1.49	Jamaica	0.764	1.12	1.11	1.24
C. America & Yucatan					Puerto Rico	0.942	1.11	1.35	1.50
Belize	0.737	1.21	1.38	1.67	**Lesser Antilles**				
Costa Rica	0.834	1.24	1.12	1.39	Antigua & Barbuda	0.800	1.16	1.15	1.33
El Salvador	0.720	1.19	1.12	1.33	Barbados	0.888	1.05	1.28	1.34
Guatemala	0.649	1.27	1.05	1.33	Dominica	0.743	1.01	1.18	1.19
Honduras	0.672	1.28	0.98	1.25	Grenada	0.745	1.11	1.25	1.39
Nicaragua	0.667	1.32	1.41	1.86	St. Kitts & Nevis	0.844	1.07	1.36	1.46
Greater Antilles					St. Lucia	0.777	1.12	1.39	1.56
Cuba	0.809	1.02	1.32	1.35	St. Vincent & Gren.	0.751	1.06	1.45	1.54
Dominican Republic	0.738	1.18	1.40	1.65	**Bahamas**	0.815	1.17	1.07	1.25

The projected damage ca. 2020–2025 from hurricanes is determined by multiplying the 2007 values of MCE and CL/4 by the normalized values of ELP and a factor that accounts for the scenarios of hurricane activity during the 2020–2025 period. The factors for the change in hurricane activity are determined using the data in Table 2. The factor for the MCE is related only to the increase in average wind speed; here we use the 5th power of the wind speed to estimate the damage, so the factor for a 5% increase in average intensity is 1.26. For the CL, the factor is determined by multiplying the fractional increase in landfall frequency (# in Table 2) by the factor for the increase in average intensity.

Table 7. Multipliers for increases in hurricane activity ca. 2020–2025 (relative to 2007) for MCE and CL under 4 scenarios for the 5 different regions

	A1 MCE/CL	A2 MCE/CL	B1 MCE/CL	B2 MCE/CL
Mexico	1.10/1.24	1.26/1.42	1.10/1.60	1.26/1.84
C. America & Yucatan	1.10/1.07	1.26/1.22	1.10/1.39	1.26/1.58
Greater Antilles	1.10/1.74	1.26/1.99	1.10/2.26	1.26/2.58
Lesser Antilles	1.10/1.19	1.26/1.36	1.10/1.53	1.26/1.75
Bahamas	1.10/1.31	1.26/1.50	1.10/1.68	1.26/1.93

Table 8 and 9 give projected damage for the 2020–2025 period in millions of 2007 U.S. dollars for the scenario average and four different scenarios, respectively. The greatest projected losses are for Puerto Rico, the Dominican Republic, and the Gulf Coast of Mexico. The high projected losses in these two countries arise from the high expected landfall incidence in the Greater Antilles and the high values of the Economic Loss Potential, driven primarily by relatively large projected increases in the GDP.[11]

Table 8. Projected damage ca. 2020–2025 in millions of 2007 U.S. dollars, for the scenario average. Values in parenthesis for each region are the projected hurricane risk factors from Table 7.

		Scenario Average	
Country	**ELP**	**MCE**	**CL**
Mexico		(1.18)	(1.53)
Gulf Coast	1.49	15542	91298
C. America		(1.18)	(1.32)
Belize	1.67	714	257
Costa Rica	1.39	245	77
El Salvador	1.33	581	162
Guatemala	1.33	1819	507
Honduras	1.25	7641	2135
Nicaragua	1.86	6453	3165
Greater Antilles		(1.18)	(2.14)
Cuba	1.35	4125	5815
Dominican Rep.	1.65	14110	8342
Haiti	1.23	2077	1644
Jamaica	1.24	6165	3105
Puerto Rico	1.50	9744	9131
Lesser Antilles		(1.18)	(1.46)
Antigua & Barbuda	1.33	2149	850
Barbados	1.34	18	6
Dominica	1.19	100	31
Grenada	1.39	1509	527
St. Kitts & Nevis	1.46	1112	764
St. Lucia	1.56	17	9
St. Vincent & Grenadines	1.54	84	36
Bahamas		(1.18)	(1.61)
Bahamas	1.25	990	1272

[11] Note again that, given the lack of alternate data sources, there is a level of uncertainty in the data.

Table 9. Projected damage ca. 2020–2025 in millions of 2007 U.S. dollars, for the 4 different scenarios. Values in parenthesis for each region are the projected hurricane risk factors from Table 7.

			A1		A2		B1		B2	
Country	**HDI**	**ELP**	**MCE**	**CL**	**MCE**	**CL**	**MCE**	**CL**	**MCE**	**CL**
Mexico			(1.10)	(1.24)	(1.26)	(1.42)	(1.10)	(1.60)	(1.26)	(1.84)
Gulf Coast	0.792	1.49	15316	79665	15767	79665	15316	102930	15767	102930
C. America			(1.10)	(1.07)	(1.26)	(1.22)	(1.10)	(1.39)	(1.26)	(1.58)
Belize	0.737	1.67	665	209	762	239	665	272	762	309
Costa Rica	0.834	1.39	228	63	261	71	228	81	261	92
El Salvador	0.720	1.33	541	132	620	150	541	171	620	194
Guatemala	0.649	1.33	1696	412	1942	470	1696	535	1942	609
Honduras	0.672	1.25	7123	1737	8159	1981	7123	2257	8159	2566
Nicaragua	0.667	1.86	6015	2575	6890	2936	6015	3345	6890	3803
Greater Antilles			(1.10)	(1.74)	(1.26)	(1.99)	(1.10)	(2.26)	(1.26)	(2.58)
Cuba	0.809	1.35	3845	4723	4404	5401	3845	6134	4404	7003
Dominican Rep.	0.738	1.65	13153	6775	15067	7748	13153	8799	15067	10046
Haiti	0.463	1.23	1936	1335	2218	1527	1936	1734	2218	1979
Jamaica	0.764	1.24	5747	2522	6582	2884	5747	3275	6582	3739
Puerto Rico	0.942	1.50	9083	7416	10405	8481	9083	9632	10405	10996
Lesser Antilles			(1.10)	(1.19)	(1.26)	(1.36)	(1.10)	(1.53)	(1.26)	(1.75)
Antigua & Barbuda	0.800	1.33	2003	694	2294	793	2003	892	2294	1020
Barbados	0.888	1.34	16	4	19	5	16	6	19	7
Dominica	0.743	1.19	93	25	107	29	93	33	107	37
Grenada	0.745	1.39	1407	430	1611	492	1407	554	1611	632
St. Kitts&Nevis	0.844	1.46	1036	624	1187	713	1036	802	1187	917
St. Lucia	0.777	1.56	15	7	18	8	15	9	18	10
St. Vincent & Grenadines	0.751	1.54	78	29	89	33	78	37	89	43
Bahamas			(1.10)	(1.31)	(1.26)	(1.50)	(1.10)	(1.68)	(1.26)	(1.93)
Bahamas	0.815	1.25	923	985	1057	1241	923	1263	1056	1597

Note: HDI =Human Development Index. MCE=Maximum Considered Events, represents the surge event or sudden loss risk. CL=Cumulative Loss, represents the total loss risk. ELP= Economic Loss Potential. Note that ELP is the product of the normalized values of population and GDP; which is used rather than GDP to more properly reflect the true loss potential, which is greater than just GDP.

Future work

This report has described a methodology for projecting future damage from tropical cyclones in the Central America/Caribbean region, and has presented some preliminary estimates. The report concludes that cumulative loss in Mexico's Gulf ranges between 79 and 102 billion dollars, for the 2020-2025 period. For Cuba the corresponding loss range is 4.7 to 7.0 billion dollars. There are however two remaining key issues: the methodology and the data. A summary of the outstanding issues with the methodology presented is given below.

- Research is continuing to understand the historical data record so as to better separate the influences of natural variability and global warming particularly with regard to landfall location.
- The Monte Carlo model of hurricane tracks based on Bayesian statistics can be used to generate synthetic datasets of future landfall distributions, which also include increases in hurricane size and duration (in addition to increases in frequency and intensity).
- Assessment of the return time for the maximum considered event.
- The economic data on historical hurricane damage[12] are not complete, and it is hoped that a more thorough investigation of a variety of sources and possible access to insurance databases would improve the completeness and accuracy of these data.
- The method for normalizing historical damage (accounting for changes in population, GDP, and inflation) needs further examination and possible improvement.
- Investigation of the relationship between damage and hurricane intensity is needed for each country.
- Improved GDP projections are desired, and are undoubtedly available from World Bank sources.
- Improved intrinsic socioeconomic vulnerability indices (such as those proposed by Cardona) are desired for all of the countries.

Making full use of this type of analysis for a cost/benefit analysis of proposed adaptation strategies requires that the methodology be extended to include a more complete macroeconomic analysis; similarly, it requires a thorough assessment of the local geographic vulnerabilities. Understanding the full potential impact of global warming on losses from hurricanes requires a more complete economic and fiscal loss analysis. Assessment of the local physical vulnerability from hurricanes requires assessments for each country of the nature of local geographic vulnerabilities to storm surge, landslides, flooding, and winds. A country-by-country analysis of all these combined factors is needed.

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Potential Economic Impacts of Climate Change in the Caribbean Community

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Abstract. The purpose of this report is to assess the potential economic impact of climate change on the countries of the Carribean Community (CARICOM) countries. It develops estimates of potential economic impacts due to climate change in the absence of adaptation actions. The estimated total annual impacts of potential climate change on CARICOM countries ca. 2080[13] are US$11.2 billion. For all 20 CARICOM the total Gross Domestic Product (GDP) for 2007 (in 2007 US$ prices) is US$99.3 billion. That is, the estimated total annual impacts are about 11.3% of all 20 CARICOM countries' total annual GDP in 2007.

Introduction.

In this chapter, the author aims to assess the potential magnitude of possible impacts of climate change on communities in the CARICOM countries and to quantify how much such impacts compare to the GDP of 2007.

Methodology and Data limitations. The methodology used for the analysis is similar to the one used in the 2002 World Bank report by Haites (World Bank 2007), which assessed the impact of various variables (such as tourism, hurricane damage, and loss of land) oc climatic conditions of the future. Compared to the 2002 Bank report that examined only 12 countries of CARICOM countries, this paper investigates all members and associated members of CARICOM. All the secondary data used in the current paper are adjusted in the assessment process in US$ 2007 prices and 2007 values for non monetary data such as population. The analysis is conducted, to assess the estimated impacts of climate in ca. 2080 as if such potential impacts of climate change were experienced in 2007. That is, the economic impacts are expressed as impacts on the current (2007) economy (e.g. populations and prices of 2007) even though climate change impacts may not be fully experienced for some decades. This is standard practice in the literature (World Bank 2002).

Due to limited time and resources, all data used for this study are derived from secondary data found in the 2002 World Bank report by Haites (World Bank 2007), Intergovernmental Panel on Climate Change (IPCC)'s Assessment Reports and documents in the internet. This lack of data resulted in limitations to conduct more rigorous economic valuations.

Despite the extremely limited data, data inconsistency and time constraints, this study made all possible efforts to make at least very preliminary estimates to illustrate the potential magnitude of the impact of climate change on CARICOM countries to inform

[13] This reference in time is used to be consistent with the IPCC scenario.

policy makers. As it is always the case of this kind of studies, the results are very sensitive to the data, assumption and methodologies, which originated from mostly heterogeneous secondary sources. With these caveats, the results are correct and true to the data available, assumptions and methodologies.

Despite best efforts to keep the assessment as consistent as possible (such as choosing or adjusting the data to the A1B scenario of the Special Report on Emissions Scenarios (SRES) of the IPCC Third Assessment Report (TAR) (SRES A1B) in terms of population numbers and other values), the estimates are based on secondary data from various sources with mostly heterogeneous methodologies and data characteristics. Thus, more comprehensive analyses with consistent methodologies and data sources would yield more reliable estimates. The data for all CARICOM estimations is available upon request.

Scenario. The climate change scenario is followed by the one in the IPCC Fourth Assessment Report (FAR) Working Group Report, Chapter 11–Regional Climate Projections for the Caribbean (Christiansen et al. 2007), which is the most recent assessment, and the median values[14] are taken for this study (Table 1). Accordingly, annual costs of climate change impacts around 2080 are assessed in US$ prices and situations in 2007. Since the projections of the FAR are based on the A1B scenario of the Special Report on Emissions Scenarios (SRES) of IPCC TAR, all data are adjusted to the A1B scenario as much as possible (e.g., ratios of values among B1, A1B, and A2 scenarios are approximately B1: A1B: A2 = 0.69: 1: 1.17, noted in the IPCC FAR Working Group Report, Chapter 11–Regional Climate Projections). When data projections for the year 2080 were not available, earlier data were used for the assessment, which may lead to some conservative estimates.

[14] IPPC median values and data are used in order to maintain consistency because these values are widely cited and/or applied by other people and organizations.

Table 1. Climate Change Scenario of IPCC FAR Working Group I for the Caribbean (median values)[15]

Temperature response, annual (Celsius)	2 (low: 1.4 and high: 3.2)
Precipitation, annual (%)	-12 (low: -39 and high:11)
Sea level rise (meter)	0.35 (low: 0.23 and high:0.47)

Source: Christiansen et al. 2007.

Assessment process.
A large literature on the impacts of climate change exists, although most of it is inconsistent in terms of data and methodologies, as well as less quantitative. This paper avoids repeating a review of this literature. Instead, this section elucidates the process of available data and variables. Recent documents entitled "Valuing the Environment in Small Islands–An Environmental Economics Toolkit" (van Beukering et al. 2007), the Stern Review on the Economics of Climate Change in 2006 (Stern 2006), and the "Fourth Assessment Report (FAR)" of IPCC in 2007, among others, may be referred to for a very preliminary introduction to the valuation of climate change impacts. The economic impacts are expressed as impacts on the current (2007) economy even though the climate change will not reach its full potential for some decades. This is standard practice in the literature (Haites 2002). Due to the lack of data, time and resources, this assessment is a gross estimate under partial equilibrium model (e.g., values of tourism and fishery include operation and maintenance costs. Employment that may be created by the reconstruction of infrastructure is not included in the estimates.). This will avoid adding additional layers of complications, possibilities of errors and uncertainties in assumptions and estimation.

Climate Disasters

Damages from floods, droughts, and windstorms. Total and agricultural damage (decreases in crops and livestock production) from floods, droughts, and windstorms due to climate-related disasters during 2000–2005 in the Caribbean are estimated based on the data from an input report on Latin America and the Caribbean (Nagy et al. 2006) to the Stern Review on the Economics of Climate Change in 2006 (Stern 2006). With the assumption of a 27% increase in hurricane and related activities during 2080, the total annual flood damage cost for the entire Caribbean Region is estimated at US$363.1 million. Of this, the cost of agricultural damage is estimated at US$1.7 million and the cost of total annual drought damage is estimated at US$3.7 million[16]. On the other hand,

[15] Sensitivity analyses are conducted by applying the lowest and the highest scenarios of Table 1 above, i.e., lowest (+1.4 Celsius) and highest (+3.2 Celsius) temperature changes, the lowest (+0.23 meters) and highest (+0.47 meters) sea level changes, and the lowest (-39%) and highest (11%) precipitation changes, projected by IPPC FAR. These results are the estimated annual impacts of the lowest estimate or about US$7.2 billion (7.3% of all 20 CARICOM countries' total annual GDP) and the highest estimate or about US$18.0 billion (18.0 % of all 20 CARICOM countries' total annual GDP).

[16] Note that of the US$3.7 million annual drought costs, US$0.5 million are related to agricultural damage.

the total annual windstorm damage is estimated at US$2,612 million (US$1.9 million of which are related to agricultural damage), all ca. 2080 in 2007 US$ prices.

Human costs from floods. Impacts of increased floods on humans are estimated as a loss of GDP per capita, based on a report on human health impacts of climate change by the World Health Organization (WHO) (McMichael 2003). The report estimated the impacts as Disability Adjusted Life Year (DALY) in 2003 and increased risk of deaths from floods due to climate change for Latin America and the Caribbean Region in 2030 (the estimated risk increases 2.81 times in 2030 relative to 2003). By (i) adjusting the population number to the Caribbean Region, (ii) applying the increased risk of death to DALY, and (iii) assuming the increased risk in 2030 for 2080, the estimated cost of impacts of floods on humans due to climate change as GDP is US$0.8 million for the Caribbean Region per year ca. 2080 (in 2007 US$ prices).

Tourist expenditure loss. Tourist expenditure loss due to an annual increase in hurricanes is estimated by applying a 27% hurricane increase. The 2002 World Bank report by Haites on impacts of climate change on CARICOM countries notes that in 1995 Hurricanes Luis and Marilyn devastated coastal areas, causing severe damage to hotel and other tourism properties, leading to a 17% decrease in the number of tourist arrivals, and adversely affecting employment and foreign exchange. Adapting this data, the tourist expenditure is assumed to decrease by 17% due to hurricanes. With the assumption of a 27% increase in annual hurricanes, the tourist expenditure loss due to hurricanes is assumed to increase by a further 27% (i.e., because hurricane-induced tourist expenditure loss without climate change is 0.17, a further 27% reduction means 0.17 times 0.27 equals 0.046 or a 4.6% increase to 21.6% = 17% + 4.59%). The additional loss due to the increased number of hurricanes totals US$446.9 ca. 2080 in 2007 US$ prices for CARICOM countries.[17]

Employment loss. The hurricane-induced loss of employees in the hotel industry is also assumed to increase further by 27%. The average number of employees per room was obtained from the Caribbean Tourist Organization. The annual loss of employment due to increased hurricanes (in 2007 US$ prices) was found to be US$58 million.[18]

Government loss. Government losses due to increased hurricanes are estimated to increase by 27%. A recent World Bank report entitled "Results of Preparation Work on the Design of a Caribbean Catastrophe Risk Insurance Facility Background Document" (World Bank 2007) estimated the annual average government loss from hurricanes to include: damage to government buildings, reduction of annual tax revenue due to the loss of commercial facilities, business interruption, loss of import and tourism taxes, damage

[17].In exchange for these tourist expenditures, tourists need to be provided with food, lodging, and a variety of services, all of which require effort and resources to produce. Using loss of tourist expenditures thus may overstates the costs. However, due to lack of data, we could not track down these resources costs further to estimate the value added.

[18] There may be an increase in employment generated by the need to clean up, repair, and reconstruct after a hurricane, which may be considered as a benefit as employment creation.

to infrastructure, and government relief expenditures.[19] The annual government loss due to increased hurricane activity is US$81.3 million ca. 2080 in 2007 US$ prices for 18 CARICOM countries.

Gross Domestic Product loss due to climate change-related disasters. According to Nagy et al. (2006), the Caribbean region's cumulative losses of climate-related disasters for 1970–1999 represent 43% of the region's GDP. The number of climate-related disasters per year between the periods of 1970–1999 and 2000–2005 increased 2.4 times; however, only 19% of this latter period was costed. The annual average cost of climate-related disasters during 2000–2005 was estimated based on this information. The annual GDP loss due to climate change-related disasters ca. 2080 is estimated to be US$4,939.8 million in 2007 US$ prices.

Sea Level Rise Impacts

Loss of land. The 2002 World Bank report on impacts of climate change on CARICOM countries (World Bank 2002) estimated that a 0.13 meter rise in sea level and a 2°C increase in temperature from 1999–2080 will lead to an average 3% loss of land in CARICOM countries. Because this study assumes the same 2°C increase between 1980–1999 and 2080–2099, adjusting the 0.13 meter rise in sea level assumed in the 2002 Bank report to this study's assumption of a 0.35 meter rise in sea level rise led to an 8% land loss due to sea level rise for this study. This loss would occur gradually, year after year. By 2080, a cumulative 8% of the land areas of each of the countries would be lost. To estimate the value of this loss in terms comparable to the annual estimates of loss used in other estimates, there is a need a measure of the flow of value that this area would have generated in 2080 had it not been lost to sea level rise. The midpoint of the estimates of land value derived in the 2002 World Bank report are used (which estimated the value of land as being between US$0.4 million and US$1 million per hectare) [20] , or US$0.7 million per hectare. This is converted to 2007 dollars, giving US$0.89 million per ha, and then convert it to a flow of value by using a capital recovery factor of 0.065 (assuming a 30 year time horizon and a 5% real interest rate), giving a value of US$0.05 million per hectare per year. Based on the land area of thee 20 CARICOM countries, the annual cost of loss of land due to sea level rise in 2080 is thus about US$20.2 million. Similar assumptions and approaches are used for the following costs due to the sea level rise below.

Hotel room replacement cost. Following the same assumption as loss of land, 8% of hotel rooms are assumed to be replaced due to sea level rise. The 2002 Bank report on impacts of climate change in CARICOM countries estimated that the average cost per room of a new hotel is US$80,000 for the low scenario and US$100,000 for the high scenario. It also assumed a 5% real interest rate with a 30-year term. Adapting the low scenario estimate of US$80,000 and a 5% real interest rate with a 30-year term, the

[19] Although some of the listed costs are transfer, dissagregated data are not available.
[20] The market price for vacant land inland from the coast unused or used for agriculture or forestry in Tobago, St. Lucia, Grenada, and Barbados.

annual hotel room replacement cost is US$46 million ca. 2080 in 2007 US$ prices per year in CARICOM countries.

Loss of electricity infrastructure. Following the assumption in the estimation of land loss, it is assumed that 8% of the electricity infrastructure would be lost due to sea level rise. This loss of electricity infrastructure is estimated by an 8% loss of annual total expenses (operational and capital) of electricity services. The result for eight CARICOM countries is US$33.1 million ca. 2080 in 2007 US$ prices per year.

Alternatively, much higher results can be found if other assumptions and data are used to estimate the loss in electricity infrastructure. That is, using data obtained from a World Bank infrastructure study report for the Caribbean Region (Jha ed. 2005) and assuming an increased cost of reconnecting 8% of the population due to land loss, much higher cost estimates are found. Assuming 30 years of plant life and network connection and a 5% real interest rate, the total for nine CARICOM countries is US$380.1 million per year ca. 2080 in 2007 US$ prices.

Loss of telephone line infrastructure. Following the assumption of an 8% land loss due to sea level rise, 8% of the telephone mainlines are assumed to be lost due to sea level rise. Thus, an investment need for 8% of mainline connections is estimated with the data obtained from two Bank reports (Jha ed. et al. 2005; Fay and Yepes 2003), which estimated an investment cost of US$400 for mainline connections per household. Assuming a 5% real interest rate and a 30-year life of mainline connections, the annual total for 15 CARICOM countries is US$3.9 million ca. 2080 in 2007 US$ prices.

Loss of water connection infrastructure. Following the assumption of an 8% land loss due to sea level rise, an investment requirement of 8% of water connections due to sea level rise is estimated with data obtained from two World Bank reports (Jha ed. et al. 2005; Fay and Yepes 2003). The estimated investment cost is US$400 for water connection per household. Assuming a 5% real interest rate and a 30-year life of water connections, the annual total for 13 CARICOM countries is US$6.7 million ca. 2080 in 2007 US$ prices.

Loss of sanitation infrastructure. Following the assumption of an 8% land loss due to sea level rise, 8% of sanitation service connections to households are assumed to be lost due to sea level rise. Two World Bank reports (Jha ed. et al. 2005; Fay and Yepes 2003) estimated that the investment cost is US$700 for sanitation connection per household. Assuming a 5% real interest rate and a 30-year life of sanitation connections, the annual total for 13 CARICOM countries is US$8.9 million ca. 2080 in 2007 US$ prices.

Loss of road infrastructure. Following the assumption of an 8% land loss due to sea level rise, 8% of the road network is assumed to be lost due to sea level rise. According to Jha ed. et al. (2005) and Fay and Yepes (2003), the investment cost is US$410,000 per kilometer of paved two-lane road. Assuming a 5% real interest rate and a 30-year life of roads, the annual total for five CARICOM countries is US$76.1 million ca. 2080 in 2007 US$ prices.

Loss of rail infrastructure. Following the assumption of an 8% land loss due to sea level rise, 8% of railroads are assumed to be lost due to sea level rise. Jha ed. et al. (2005) and Fay and Yepes (2003) estimated the investment cost to be US$900,000 per kilometer of rail, including associated rolling stock. Assuming a 5% real interest rate and a 30-year life of railroads, the annual total is US$2.6 million ca. 2080 in 2007 US$ prices.

Temperature Rise

Loss of tourist expenditures. The 2002 World Bank report by Haites on impacts of climate change on CARICOM countries notes that a 2ºC increase in temperature will make Caribbean tourism less attractive by 15–20%. Using an average of 17.5%, the contribution of tourist expenditures to GDP is assumed to decline by 17.5%. This gives an annual total of GDP loss from tourist expenditures of US$4,027.3 million ca. 2080 in 2007 US$ prices. [21]

Loss of fish exports. According to Nagy et al. (2006), 29% of coral reefs in the Caribbean are vulnerable to climate change. Based on these data, a 29% fish production reduction is assumed. Financial values of total fish production in CARICOM countries are unavailable, but export values are estimated from the fishery export share of the GDP for 12 available CARICOM countries. The result of annual losses of fish exports due to a 29% decrease in fish production totals US$93.8 million ca. 2080 in 2007 US$ prices.[22]

Loss of coral reefs. Nagy et al. (2006) noted that about 12% of the world's coral reefs exist in the Caribbean and that during 2015-2060 and thereafter, wetland and coral reefs losses would very likely be important due to the progressive and accumulated effects of human direct intervention and impact, storm surges, and warming under slightly increasing sea level rise in the Atlantic coast in Mexico and Central America and Caribbean. The world's total coral reefs are estimated to be 284,300 km^2 long. The 2002 World Bank report on impacts of climate change in CARICOM countries notes that the annual value of coral reefs for Fiji and Kiribati has been estimated at US$145 to US$290 per hectare. Using the average of this estimated value and assuming a 29% loss of coral reefs due to warming and other climate change related pressures, the annual value of coral reef loss is estimated as US$941.6 million ca. 2080 in 2007 US$ prices.[23]

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[21] As the impacts of coral reef estimated earlier includes tourism, there may be some overalp in valuation. However, to mitigate this double counting, an conservative estimate was made uding an average value.

[22] The export value is a gross value of fish, not a net (e.g., operation costs), thus overestimating the values. World Resource Instiute estimates 25% of gross revenue as non-labor operating costs, for evaluating coral reef-associated fisheries impact for Tobago, St Lucia and Belize (http://www.wri.org/project/valuation-caribbean-reefs). On the other hands, data on local consumption of fish means underestimating the total values of fishery.

[23] Loss of coral reef includes value of sussistence fisheries and commercial coastal fisheries, which may includes fish exports valued ealier.

Loss of tourists' sea-related entertainment expenditures. The value of the loss of tourists' sea-related entertainment expenditure is estimated based on the above coral reef and estimates by Mimura et al. (2007) of a 38% beach loss in Bonaire and Netherlands Antilles with a range ±24% at 0.5 m sea level rise and a reduction of up to 35% in turtle nesting habitats. . Assuming that at least 30% of entertainment expenditures are spent on sea-related activities, and 30% of these sea-related entertainment expenditures will be lost with the loss of beaches and coral reefs due to climate change, the estimated costs of the annual loss of tourists' sea-related entertainment expenditures in CARICOM countries is US$88.1 million ca. 2080 in 2007 US$ prices.

General Climate Change Impacts

Agricultural loss. Following a report by the International Institute for Applied Systems Analysis (IIISA 2002), an increase of 7.1% of land with severe environmental constraints for rain fed crop production is assumed to be the loss of agricultural GDP loss and export loss. The annual totals for agricultural GDP loss are US$220.5 million in 2007 US$ prices for 14 CARICOM countries and US$74.4 million ca. 2080 in 2007 US$ prices due to agricultural export loss for 13 CARICOM countries.

Jones et al. (2003) estimated the potential loss of maize production in 2055 compared to 2000 due to climate change in Guyana (26.1% loss) and Belize (25.2% loss) and it is assumed that this loss will be the same for 2080 for this study. The resulting annual loss of maize production is US$2.3 million for Belize and US$0.2 million ca. 2080 in 2007 US$ prices.

Water stress on safe water access. Nagy et al. (2006) estimated the number of people without access to safe drinking water with and without climate change impacts in 2025 under HadCM3 and Coupled Global Climate Model (CGCM) 2A2 scenarios. The estimated cost of investing in water supply systems (per capita) was found to be US$157. Using the difference of the number of people without safe drinking water with and without climate changes and assuming the same number of people for 2080, the increased costs of investments in water supply systems due to increased water stress from climate change is estimated for the countries whose data on the population's access to safe water are available. An annualized cost of water supply systems is estimated at US$10.7 per capita, assuming 30 years of life of water supply systems and a 5% real interest rate. The annual total is US$104 million for eleven countries ca. 2080 in 2007 US$ prices.

Human health cost. The World Health Organization (WHO) report on human health impacts from climate change (McMichael 2003) estimated the increased risk of deaths from malaria due to climate change for Latin America and the Caribbean Region in 2030. The estimated risk increases 1.14 times in 2030 relative to 2003. By (i) adjusting the population number to the Caribbean Region, (ii) applying the increased risk of death to DALY, and (iii) assuming the increased risk in 2030 for 2080, the estimated costs of malaria impacts on humans due to climate change as GDP is US$2,596 for the Caribbean Region per year ca. 2080 in 2007 US$ prices.

The 2002 World Bank report on impacts of climate change on CARICOM countries estimated the increase cost of health due to climate change as US$0.36 per capita per year, including acute respiratory infections, acute diarrheal diseases, viral hepatitis, chicken pox, and meningococcal meningitis, under the assumption of a 2ºC increase in temperature from 1999–2080. Because this study assumes the same 2ºC increase between 1980–1999 and 2080–2099, the resulting total cost (with the application of annual health costs of US$0.36 per capita for the CARICOM countries) is US$7 million per year ca. 2080 in 2007 US$ prices.

Conclusion

The estimated total annual impacts of potential climate change on CARICOM countries ca. 2080 are US$11.2 billion. For all 20 CARICOM countries, the total Gross Domestic Product (GDP) (in 2007 US$ prices) is US$99.3 billion. Therefore, the estimated total annual impacts are about 11.3% of all 20 CARICOM countries' total annual GDP. Not surprisingly, climate change related disaster loss had the largest impacts. Per country basis, Bermuda had the largest impacts due to the large loss of tourism. However, these observations cannot be assertive due to the limited and inconsistent data availability.

Although this study is based on the use of secondary data, it still provides an indication of the magnitude of climate change damages to CARICOM countries, which is useful for decision makers in addressing climate change impacts.

Table 3 below shows the annual economic impacts of climate change in CARICOM countries circa 2080 (in million 2007 US$). Note that the lower impact estimates are used when there are various approaches or data sources to estimate the impacts, which is the case for loss of electricity infrastructure due to sea level rise and the cost of deaths from hurricane-related disasters. To avoid double counting, each county's total cost does not include the costs that are only available as a regional total. Empty cells represent that no data were available to produce the estimate for that country.

Table 3. Annual Economic impacts of Climate Change in CARICOM countries circa 2080 (in million 2007 US$) [24]

	Pre-subtotal	*Subtotal*	*Total*
Total GDP loss due to Climate Change related disasters:			4,939.9
Tourist expenditure		447.0	
Employment loss		58.1	
Government loss due to hurricane		81.3	
Flood damage		363.2	
of which agricultural damage	1.7		
Drought damage		3.8	
of which agricultural damage	0.5		
Wind storm damage		2,612.2	
of which agricultural damage	1.9		
Loss of labor productivity (GDP/capita) due to increased hurricanes related disaster (wind storm, flood and slides)		0.1	
Floods DALY (GDP/ capita)		0.8	
Sea level rise			
Loss of land			20.2
Hotel room replacement cost			46.1
Housing replacement			567.0
Electricity Infrastructure Loss			33.1
Telephone line infrastructure Loss investment need			3.9
Water connection infrastructure loss investment			6.7
Sanitation connection infrastructure loss investment needs			9.0
Road infrastructure loss investment needs			76.1
Rail infrastructure loss investment needs			2.7
Temperature rise			
Loss of tourists expenditure			4,027.4
Loss of fish export (rising temperatures, hurricanes, and sea level)			93.8
Loss of coral reefs (rising temperatures, hurricanes, and sea level)			941.6
Loss of sea related tourism entertainment expenditures			88.2
General Climate changes			
Agricultural loss			220.5
Loss of Maize production		2.7	
Agricultural Export loss		74.4	
Water Stress: Cost of additional water supply			104.0
Health			
Malaria DALY (GDP/capita)			0.003
Other diseases costs			7.1
Total	**Grand total**		**11,187.3**
	% of GDP		11.26%

[24] Caribbean community included member 15 member countries and 5 associate member countries, totaling 20 countries. Some data are not available for some countries and thus such costs are not estimated in those countries for a specific item. Therefore, the total estimates may be regarded as conservative. For more detail, see annex 1.

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Acronyms

AMO	Atlantic Multidecadal Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
CGCM	Coupled Global Climate Model
CRED	The Centre for Research on the Epidemiology of Disasters
DALY	Disability Adjusted Life Year
EM-DAT	Emergency Disasters Database
ENSO	El Niño-Southern Oscillation
FAR	Fourth Assessment Report
GCM	General Circulation Model
GDP	Gross Domestic Products
HadCM3	Hadley Centre Coupled Model, version 3
IPCC	Intergovernmental Panel on Climate Change
MMD	Multi-Model Data Set (at PCMDI)
NAH	North Atlantic Subtropical High
NAO	North Atlantic Oscillation
PCMDI	Program for Climate Model Diagnosis and Intercomparison
SERS	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
TAR	Third Assessment Report
WHO	World Health Organization

The Potential Consequences of Climate-induced Coral Loss in the Caribbean by 2050–2080

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Introduction

In this article the authors study the impact of a future warmer climate on coral reefs and present an assessment of the associated economic losses. Using the Coral Mortality and Bleaching Output (COMBO) model to simulate coral behavior to increases in sea surface temperature, it is concluded that all corals might disappear in the Caribbean Basin within 50 years. The authors estimate both direct and indirect associated losses, as well as non-use values of the coral biome and their intrinsic value as unique genetic information depositors.

Background.
Coral reefs support more than 25% of all marine species, making them the most biologically diverse of marine ecosystems and an equivalent, in terms of biomass productivity, to rainforests on land ecosystems. Corals have been around for over 200 million years and have evolved over time to adjust to relatively stable environmental conditions in tropical seas, defined through a narrow range of temperatures, salinity, and pH. Because of their stable environment, most corals are also very sensitive to changes in environmental parameters, and when stressed by rising temperatures, corals can lose their symbiotic arrangements to conduct photosynthesis. Loss of the photosynthetic ability leads to their bleaching, and may eventually cause death. Increased carbon dioxide concentrations in the atmosphere also lead to more acidic seas, which impair the ability of corals to assimilate carbonates. Corals also play very important roles for other species, providing the habitat for spawning of many life forms and protection and mechanical support for other plants and animals.

Gradual and consistent increases in sea surface temperatures have yielded increasingly frequent bleaching events (1993, 1998, 2005), the latest of which caused wide-scale bleaching throughout the Caribbean Region. The extended coral mortality caused during these events is only partially recovered over time, provided that no subsequent bleaching takes place. More than one bleaching event over a short timeframe can be devastating. Under conditions anticipated by the Intergovernmental Panel for Climate Change (IPCC), temperatures in the Caribbean during the current century may reach threshold values that would lead to a collapse of the coral biome (Christensen et al. 2007).

In the wake of coral collapse, major impacts on fisheries, tourism, and coastal protection are anticipated, as well as severe loss of biodiversity, species extinction and impacts on ecosystem integrity. Appropriate monetization of these impacts is not easy. Among these, the loss of species and ecosystem integrity is much more difficult to evaluate, yet may represent the most important. One-third of the more than 700 species of reef-building corals worldwide are already threatened with extinction (Carpenter et al. 2008). It is estimated that between 60 to 70 endemic species of corals in the Caribbean are also in danger: Extinction risks are increasing due to more frequent bleaching events experienced in recent years and expected in the future. The cost of reducing vulnerability of corals to bleaching and accelerating recovery of affected populations are likely to be very high but they remain unassessed.

Modeling climate-induced coral bleaching in the Caribbean

Although much has been learned from recent bleaching events in the Caribbean, there is still a great deal of uncertainty as to the specific responses, at a specific coral reef level, to a warmer future. For conservation and preservation planning purposes, it is particularly important to appraise the timing and intensity of coral mortality under currently projected scenarios of climate change in the Caribbean. To assess the prospects of coral bleaching and mortality in the region, the Coral Mortality and Bleaching Output (COMBO) model was used. COMBO models the response of coral growth to changes in sea surface temperature (SST), atmospheric CO_2 concentrations, and high-temperature-related bleaching events. The model has been described in detail elsewhere (Buddemeier et al. 2008). In brief, COMBO is able to estimate the growth and mortality of the coral over time based on future climate predictions and on the probability and effects of short-timed, high-temperature-related bleaching events taking place in the area.

Climate scenarios. The COMBO model uses data from the MAGICC/SENGEN global climate model for the CO_2 and future temperature scenarios. Three different scenarios have been considered for the simulations. The A1B "business as usual" scenario has been employed with different criteria: First, with a conservative 2ºC climate sensitivity to a doubling of preindustrial CO_2 levels (280 ppm; traditionally, 3ºC are chosen). Second, considering a more extreme 4.5ºC sensitivity. Finally, a comparison of the A1FI scenario (carbon-intensive path) with 3ºC temperature sensitivity has been made.[25]

The model assumes that at the beginning of the assessment, there is a relatively stable coral community where the rate of growth equals the rate of death.[26] The simulations performed assume that, when SST is high enough to induce bleaching, it actually takes place only 30% of the time. Furthermore, when it happens, only a 20% coral mortality is triggered. These values are cautious compared to other studies in which major bleaching-associated mortality was found (McClanahan 2004).

The model considers that both the steady rise of SST and high-temperature events affect the coral growth and death. Three user-selected threshold temperatures have been chosen;

[25] A number of assumptions have to be made to run COMBO. Within each different scenario run, we have tried to be conservative in our choice of parameters. The model assumes that there is a relationship of coral growth and death with temperature, and a third-order polynomial equation is used to describe that relationship. The equation implemented in COMBO has been deduced from multiple controlled temperature experiments. However, these experiments were conducted for Hawaiian corals, and there may be some differences with Caribbean biomes.

[26] On a colony-receding scenario, with mortality rate higher than growth, our results would be even more extreme.

these represent the heating doses needed for three subsequent bleaching events to take place. The probabilities of these events taking place are then calculated by the model, based on the predicted climate conditions. These temperatures have been set to be successively higher than one degree above the three-month average maximum temperature over the 2000–2004 period. This is a very cautious threshold (McWilliams et al. 2005). Through the choice of these temperatures, the thermal history of corals and their ability to adapt is implicitly being considered: the higher the thermal history, the higher the threshold temperatures should be to represent real potential damage to the corals.[27]

Results of the simulations. Hypothetical coral capacity to adapt to thermal stress and therefore reduce the mortality rate with temperature rise (Castillo and Helmuth 2004) is not included in the model, and growth equations do not correspond directly to Caribbean corals, even though a similar response is expected. For these reasons, our results should be taken as an indication of the coral response, not as absolute values.

In order to include in the simulations the thermal history of the specific area, the Caribbean Basin has been split into four different bands (Figure 1). On each band, local historical temperature data has been included in the model, and coral response to variations of SST related to that historical record has been studied. The evolution of relative coral cover over time for the four different locations in the Caribbean, and for the three selected scenarios, can be seen in Table 1.

Considering an initial 100% coral cover in the baseline year, the table shows the relative evolution of the coral mass over time at the four different locations. Although the natural tendency of corals is to grow and build reefs, results suggest that the climate change-induced increase in SST generates a negative environment for corals to subsist. Moreover, intense high-temperature anomalies give rise to brisk bleaching events leading to massive death, thus explaining the rapid lost of coral mass over subsequent decades for all three scenarios. The calculated percentages are relative and must be applied to the actual initial cover, which is normally much less than 100% of historical values. Thus, the relative values reported are higher than the actual absolute cover values would be.

Table 1. Evolution of relative coral cover in the Caribbean as modeled through COMBO (2000-2090)

Year	North			Mid-North			Mid-South			South		
	A1B 2º	A1FI 3º	A1B 4.5º	A1B 2º	A1FI 3º	A1B 4.5º	A1B 2º	A1FI 3º	A1B 4.5º	A1B 2º	A1FI 3º	A1B 4.5º
2000	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
2010	101.9	103.0	103.2	101.3	100.9	102.2	100.4	100.6	100.7	100.3	100.5	100.5
2020	108.9	113.3	115.3	105.8	103.3	109.6	101.7	102.3	102.4	101.2	101.5	101.5

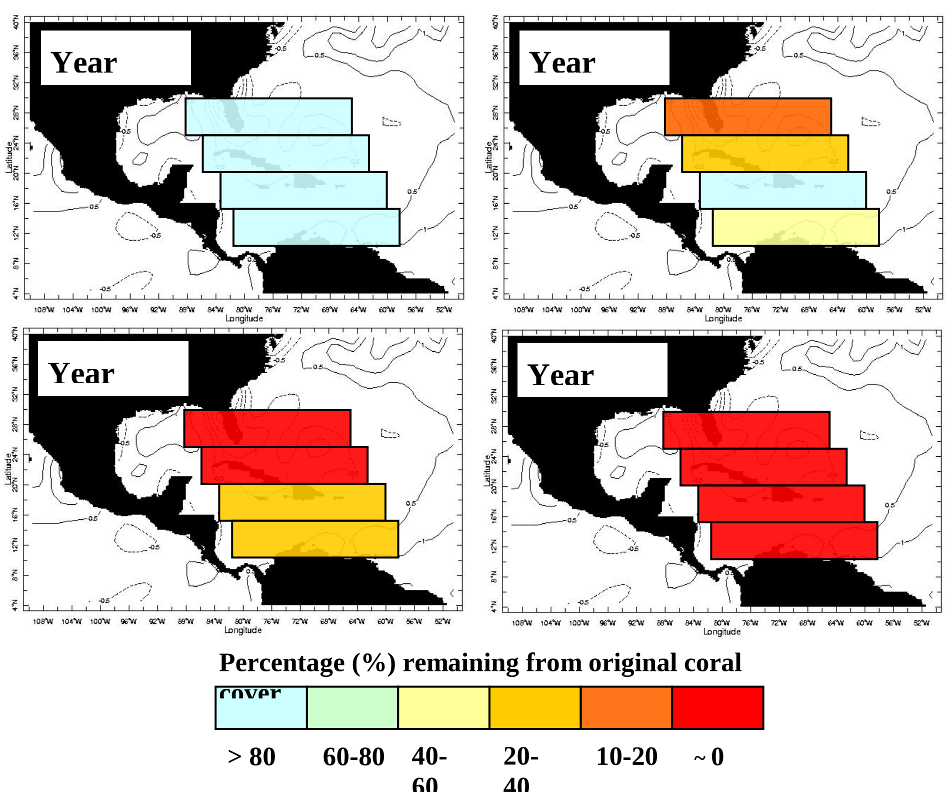
[27] Moreover, with COMBO it is possible to study the response of corals to rising concentrations of CO_2 in the ocean, which lead to less availability of CO_3^{2-}, the main ion used by corals to build their exoskeleton and grow (Kleypas et al., 1999). However, these effects, which would further magnify the negative effects of climate change because they prevent coral growth, have not been taken into account due to lack of specific information on the response of Caribbean corals.

2030	126.0	131.7	95.6	115.7	107.1	115.0	103.7	104.3	104.2	102.2	102.3	101.8
2040	80.1	35.2	3.2	123.8	38.5	4.1	105.3	84.0	34.2	81.8	80.3	37.5
2050	13.8	0.0	0.0	30.3	0.0	0.0	84.1	3.2	0.1	63.5	5.0	0.2
2060	0.2	0.0	0.0	0.4	0.0	0.0	21.6	0.0	0.0	20.2	0.0	0.0
2070	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.7	0.0	0.0
2080	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2090	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

The A1B scenario with a 2ºC temperature sensitivity suggests that, if the suppositions made under this simulation were to become reality, the effects of both warm seas and severe high-temperature episodes could likely lead to the mortality of all corals in the area between 2060 and 2070. The A1FI scenario, carbon intense with a 3ºC temperature sensitivity, predicts complete disappearance of all corals by the 2060s. Finally, scenario A1B with a 4.5ºC sensitivity suggests that complete mortality could happen as soon as 2050. Both North and Mid-North bands appear likely to suffer the impacts sooner than Mid-South and South bands.

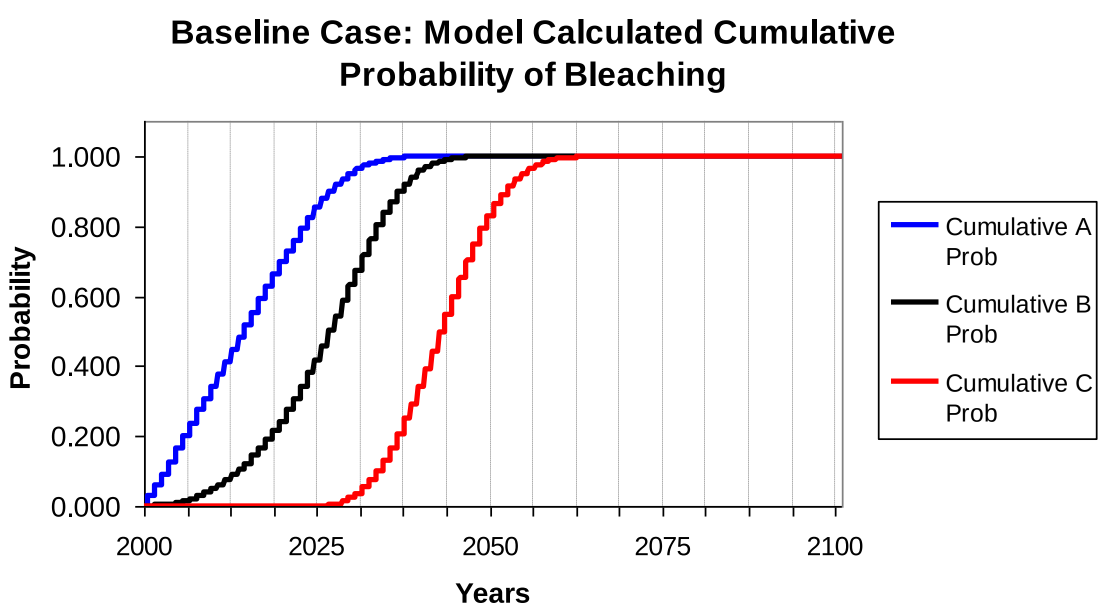
Under all simulations performed, the COMBO model suggests a total collapse of the coral cover within the 21st century. However, a hypothetical capacity of corals to adapt to warmer temperatures is not fully contemplated by the model.

Figure 1. Evolution of relative coral covers over time for the four different latitudes under the A1B scenario with 2ºC temperature sensitivity. Subjacent map obtained from www.portal.iri.columbia.edu



Given the future temperature pattern predicted by COMBO, it is possible to calculate the estimated cumulative probability that a severe bleaching event may occur. Taking the conservative scenario A1B with a 2ºC sensitivity as an example, Figure 2 shows a blue curve with the accumulated probability per year of having a single bleaching event. Black and red curves illustrate the accumulated probability per year of having two and three bleaching events. For the example provided in the figure, corresponding to the North band of the Caribbean, there is a 100% probability that three bleaching events will have occurred by year 2060. This proves to be devastating for corals, as observed in the coral cover graphs.

Figure 2. Probability of bleaching for the North Band



Estimation of the damage of coral loss.

What are the consequences of the collapse of the coral reef biome in the Caribbean? The Total Economic Value Theory (VET)[28], as discussed by Spurgeon (2003), considers that all benefits given by any species are received by human beings. This however would not

[28] The paper does not strictly follow the VET that differentiates between direct use values, indirect use values and non-use or passive use values. In this framework, direct use values are determined by the contribution an environmental asset makes to current production or consumption (i.e. its market value) whereas indirect use value includes the benefits derived from functional services that the environment provides to support current production and consumption (such as coral reefs providing biological support to near-shore fisheries), Finally, the non-use or passive use value represents the value of the asset derived merely from its existence, and not from its use. For purposes of analysis and calculation the framework proposed for this paper deviates slightly from this approach as it i) distinguishes between economic and biological values (Iecon and Ibio) of the lost services formerly provided by coral reefs as opposed to direct and indirect use losses, ii) defines the non-use value as "willingness to pay" for conservation of an environmental asset, and iii) includes an instrinsic use value that represents the value of a specie to humankind (that is difficult to measure or express in economic terms)..

consider benefits accrued by other species. In this analysis we estimate (i) the direct economic losses associated with coral degradation reflected in lost economic returns (e.g. fisheries, tourism activity, coastal protection); (ii) losses that would only indirectly result in losses to humans (loss of ecosystem integrity caused by coral collapse); (iii) the losses of non-use value (all these considered by Spurgeon 2003), plus (iv) loss of intrinsic value. This component does not follow traditional economic theory, but we have made an effort to document it with examples. The four terms are reflected in equation (1).

L (value of corals lost) = Lecon + Lbio + Lnon-use + Lintrinsic *(1),* where:

(i) Lecon refers to the value of the lost services of direct use to the human species. In order to have a rough estimate of the direct value of lost economic services, the costs of coastal protection, tourism, fisheries, and pharmaceutical value are considered. The first three items were derived from Reefs at Risk in the Caribbean (Burke and Maidens 2004) and the Economics of Worldwide Coral Reef Degradation (Cesar et al. 2003). A value of pharmaceutical use was derived from Spurgeon (2003). Table 2 presents the estimated annual impacts of the direct losses incurred in a scenario of 50% and 90% coral reef mortality, corresponding roughly to what would be expected by 2040 and 2060, respectively, under scenario A1B.

Table 2. Value of annual losses of economic services of coral reefs (Lecon), in 2008 US$ million

	50% Corals in Caribbean are lost		90% Corals in Caribbean are lost	
	Low estimates	High estimates	Low estimates	High estimates
Coastal protection	438	1,376	788	2,476
Tourism	541	1,313	973	2,363
Fisheries	195	319	351	574
Pharmaceutical uses	3,651	3,651	6,571	6,571
Total	4,824	6,659	8,674	11,985

These estimates are very sensitive to the data and assumptions[29], because valuation is affected by many variables in specific circumstances and uncertainties. Therefore, these estimates should be taken as examples, for which careful interpretation is necessary and should not be generalized.

(ii) Lbio refers to the value of the lost services that while of no direct use to the human species, contribute to the welfare of the global ecosystem. This item would ideally include the value of services that corals provide to other species and their contribution to the integrity of the marine ecosystem now and in the future. Examples are the symbiotic arrangements that corals provide for many species, the structural and physical service represented by the corals for other marine life and as coastal habitats, the nutrients produced by corals of use by other species, and other services, many of which are not

[29] For a detailed description of data sources and assumptions on which these estimates are based, please refer to Annex 2.

fully known to us. Many of these values of coral reefs result in goods and services that are not tradable in markets and are unpriced. Given the importance of assessing the relative economic worth of these goods or services using non-market valuation techniques, economics has developed a range of valuation techniques for assessing the economic value of biodiversity and ecosystems.[30]

Costanza et al. (1997) and other economists have alluded to the concept that the web of life provides an overall integrity to the global biosphere on which all species depend, even if we do not see a direct economic value. They consider that the services directly and indirectly provided by natural ecosystems are essential to maintain human activity and the integrity of the Earth and thus should be credited accordingly.

Alternatively, one can credit all of the services provided by other species that depend on or benefit from corals which, in the end, are of economic value to us. Thus, for example, one would account for the income generated by the tourism industry at turtle nesting sites for species that forage in coral reefs, and the increase in productivity of habitats adjacent to coral reefs as a result of this connectivity which ultimately result in the sustenance of species that may be of human use, or the value of land ecosystems that are enabled by the structural support and refuge provided by coral reefs. The list may be endless, limited only by lack of information on the linkages between ecosystems. This approach would be limited by failure to properly identify all of these linkages, evaluate them, and avoid double counting of costs already included in the direct use value.

(iii) Lnon-use (Option and non-use value). This reflects the economic cost of species loss. This could also be assessed through the proxy of the willingness to pay to maintain the species for reasons that exclude its direct or indirect economic value (such as fishery income, tourism income, etc.). Gustavson et al. (2000) estimated the value of conserving 25% of the biodiversity in reefs located in Jamaica and Curaçao. Although this willingness to pay is for conserving only 25% of coral reef biodiversity, this estimate has been used. Each family in the Caribbean and each tourist family were assumed to pay about US$2.4 to US$4.9 per year in 2008 US$ prices. Using those figures, a low estimate for 50% loss of corals is 14 US$ million in 2008 prices, and a high estimate is 19 US$m. For a 90% loss of corals, the low estimate is 24 US$m, whereas the high is 35US$m.(differences are based on areas, i.e., Jamaica or Curaçao, and local residents or tourists, which are reflected in the lowest and highest values). However, these estimates also have limitations in capturing the true value of coral biodiversity, just like other valuation approaches. Other economic agents willing to contribute to biodiversity conservation (governments, donors, philanthropic foundations, environmental NGOs, general public) were not consulted, making this willingness to pay exercise a lower bound estimate.

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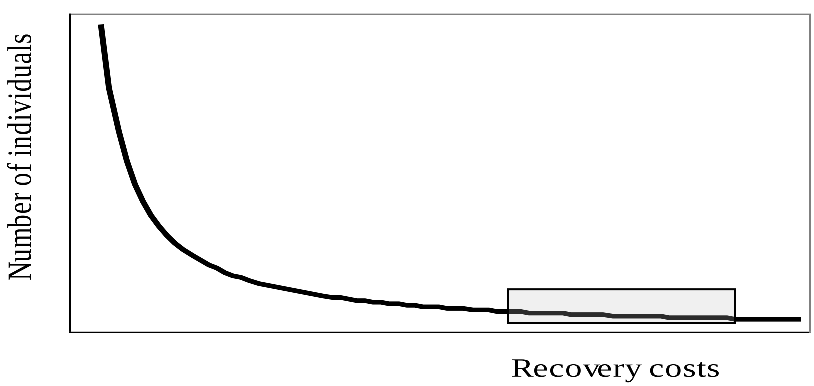
[30] Among these, a recent review by DEFRA (2007). Other discussions on valuation techniques and limitations include, for example, Spurgeon (2003), Spash (2000; 2002), Spash and Vatn (2006), Cesar (2000), Gustavson et al. (2000), Kosz (1998), Hanley et al., (1995), Pagiola et al. (2005), and Veisten et al. (2006).

(iv) Lintrinsic (Intrinsic value of lost coral). This loss relates to the intrinsic value of corals as depositors of unique genetic information. Again, there is no consensus on how best to assess their value from an economic perspective. There are even some economists such as Solow (1993) who find that "Sustainability does not require that any particular species of fish or any particular tract of forest be preserved." This view may be different from those of biologists and other types of economists. In contrast, there is an economic argument called lexicographic preference, where decision makers are unwilling to accept any trade-offs for the loss of a good or service (Gustavson et al. 2000; Veisten et al. 2006). In such a case, we may assume: (i) the possible existence of (modified) lexicographic preferences of a certain population that is better informed about the value of genetic information and the unique value of coral species, and that may have a greater willingness to pay (Hanley et al. 1995); and (ii) a high marginal value of recovering the very last individuals of a unique species. The last remaining coral individuals would command a much higher intrinsic value that reflects the accumulated loss of most of the species (e.g., willingness to recover the very last population of the specific species could be very high).[31]

Figure 3 illustrates the willingness-to-rescue concept, where the costs are represented by the value invested in the recovery of species that have at some point been at the brink of extinction. As the number of individuals or members of a given charismatic species shrink, the resources invested in the recovery efforts are expected to be higher. A certain degree of subjectivity is however expected in the building of the curve, depending on factors such as the charismatic power of the species, possible emblematic characteristics and others.

Figure 3. Increasing costs to save a species from extinction as the remaining number of individuals decreases



The shaded area indicates the threshold at which recue efforts are triggered.

Two examples where the number of remaining individuals of the entire species was so low that enormous amounts of money had to be invested to try to save them, are those of

[31] However, these estimates are based on hypotheses or conditions that merit further research, such as income constraints, association with rights and responsibilities, responses to uncertainty, satisfying behavior, political economy, and other factors (Spash, 2000; 2002; Spash and Vatn, 2006).

the California condor and the golden lion tamarin of Brazil. In 1982, with a dwindling population of only 22 condors (Walters et al. 2008), the State of California and the U.S. Federal Government embarked on an ambitious and costly effort to save the species. After 40 years, tens of millions of dollars have been invested and the condor has been brought from the brink of extinction; although its future is by no means secured, the total population has increased to 300 individuals.

Likewise, there were no more than about 500 to 1,000 remaining golden lion tamarins (small primates), most of them living in their shrinking natural habitat in Brazil's Atlantic Forest, when the ex situ/zoo conservation breeding program began in 1970. The total costs of the recovery program are not known, but a conservative estimate, which does not include the costs of maintaining their natural habitat,[32] has surpassed US$7.2 million (in historical value) since 1983 (Kleinman et al. 1991; Rimbaldi, personal communication 2008).

Our review of the consequences of coral loss in the Caribbean highlights the lack of economic tools for appraisal, and the existence of only partial assessments of the corals' value. Thus, there is a need for improvement of scientific knowledge about complicated direct and indirect linkages of coral reefs with other species, the integrity of ecosystems and the economic evaluation of coral reefs. In particular, valuations of indirect and non-use values at this point in time are beyond the scope of adequate quantification by traditional economic tools, but they remain significant. This is partly due to current limited scientific knowledge in this regard to support such valuations.

Direct coral loss, as shown above, can have significant economic impacts. It is however an estimate limited to direct economic services provided by corals. As discussed, there are many other valuable functions of coral reefs, and some cannot be appreciated in purely economic terms. The extinction of coral species would imply losses to be felt by countless other species as well as the disappearance of a unique biologic resource, unique DNA code. Thus, valuing the loss of corals under a traditional economic assessment might miss most of the value of corals and thus undermine the urgent case for mitigation of greenhouse gas emissions and conservation of the coral biome in the Caribbean.

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[32] At the time (early 1970s), it was said that there were only 100 to 200 left; based on our current understanding of available remaining habitat 40 years ago, this must be an underestimate.

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The Potential Consequences of Rapid Glacier Retreat in the Northern Andes

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Introduction. In the Andes, runoff from glaciated basins is an important element of the regional water budget and is essential to the integrity of mountain ecosystems. Many Andean valleys are relatively dry and depend on glacier runoff to maintain extensive mountain biomes. Specifically, glaciers play an important role in freshwater regulation in associated watersheds, assuring year-round water flows for agriculture, potable water, power generation, and ecosystem integrity. Glaciers store water as ice and snow during the ”rainy” season, then gradually release it during drier periods. In a steady state equilibrium, the buildup of water compensates losses. However, glaciers are rarely in equilibrium but rather fluctuate with climate variations. During the current period of accelerated glacier retreat, the amount of water released exceeds any accumulation. As a result, water users downstream experience an extra flow that is not sustainable in the long run.

Thus, glacier retreat places in doubt the sustainability of current patterns of water use and ultimately the viability of the economies and ecologies of glaciated basins and may also have wider impacts on the entire Andes region. The current paper estimates the economic costs faced when net runoffs from glaciers are significantly reduced or stop all together. The changes induced by tropical glacier retreat constitute an early case of the need for adaptation and thus an example of the type and size of associated economic and social impacts caused by climate change.

Recent research shows that climate change will be even more pronounced in high-elevation mountain ranges (Bradley et al. 2006). Although much attention has been paid to climate change in the polar region, those mountains that extend into the troposphere have been warming faster than adjacent lowlands. Thus, heavily populated, high-elevation areas in the tropics, such as the tropical Andes, are now experiencing, and will likely continue to experience, dramatic changes in climate. In particular, global warming has been linked to the accelerated retreat of tropical glaciers in the Andes and to an increase in the weather variability and weather extremes affecting the Andean ecosystems, with immense repercussions on ecosystem integrity and the welfare of local populations.

As awareness of these climate impacts increases, the threat of changes in water supply associated with tropical glacier retreat has received more attention. However, global projections rely on models which, due to their coarse resolution, are inadequate to resolve

[33] This is an expanded version of an article published in EOS, July 2007.

the steep topography of long and narrow mountain chains such as the Andes. As a consequence, climate change in high tropical locales is not well simulated in these models. When considering the rate of warming in the free troposphere (e.g., Bradley et al. 2004, 2006) rather than at the surface, it becomes evident that warming in the tropical Andes is likely to be of similar magnitude as in the Arctic, and with consequences that may be felt much sooner and that will affect a much larger population.

Field observations and historical records have been used to document the reduction of tropical glaciers over the length of the Andes. This information shows that glacier retreat rates were moderate for an extended period but have accelerated in recent decades. Glacier retreat in the Andes is consistent both with upward shifts in the freezing point isotherm and the Equilibrium Line Altitude (ELA), where glacier accumulation balances with ablation. Thus, although sensitivity to temperature for specific glaciers is dependent on local climate characteristics, this retreat coincides with an overall warming of the Andean troposphere (Kaser 2001). Modeling projections indicate that many of the lower altitude glaciers in the Cordillera could completely disappear within a few decades (Bradley et al. 2006 and Ramírez et al. 2001).

Tropical glaciers in the Andes (those located between Bolivia and Venezuela) covered an area of over 2,940 km^2 in 1970 but declined to 2,758 km^2 in 1991 (INRENA 2006) and to 2,493 km^2 by 2002 (Kaser 2005). In Peru alone, glaciers covered an area of 2,041 km^2 in 1970 but had declined nearly 22% to 1,595 km^2 by 1997 (INRENA 2006). The largest of these glaciers in the Cordillera Blanca have lost 15% of their glacier surface area in a period of 30 years.[34] Many of the smaller glaciers in the Andes have already been heavily affected and others are likely to completely disappear within a generation. For example, the Chacaltaya glacier (located in Bolivia) has lost most of its surface area (over 95%) since 1982, and may completely disappear by 2010 (Francou and Ramirez 2006). The rapid retreat has resulted in a net increase in hydrological runoff, particularly in the most glacierized watersheds; however, this is a temporary and unsustainable effect tied to current rates of ablation.

Several glaciers in the region, such as the Cotacachi in Ecuador, have already disappeared, providing an early glimpse of upcoming consequences. The area around Cotacachi has experienced a decline in agriculture and tourism and loss of biodiversity (Rhoades and Zapata Ríos 2006; Pouyaud, B. et al. 2005). Waterless streams and decrease in water levels have already led to water conflicts and these are expected to worsen with time (Rhoades and Zapata Ríos 2006). Furthermore, water resource problems are exacerbated in areas where rivers are contaminated and where there is already a potable water deficit.[35]

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[34] The decrease went from 723.4 km^2 to 611.5 km^2 between 1979 and 1997 (Pouyaud, B. et al., 2005). The Cordillera Blanca has the greatest ice coverage in km^2, but the Cordillera Vilcanota (Quelccaya) actually has the largest individual glacier.

[35] International Research Institute for Climate and Society. Impactos del Clima. May. Online at: http://iri.columbia.edu/climate/cid/May2004/sp/impacts.html.
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To assist in better understanding glacier dynamics in the tropics, it is necessary to complement historical observations with a dedicated effort to continuously measure through field stations, photogrammetry, and remote sensing of the glaciated area in the Andes. An initial effort to do this has been undertaken through the Regional Adaptation to Glacier Retreat project (World Bank 2008), which also supports the implementation of pilot adaptation measures in Bolivia, Ecuador, and Peru.

Nature of the Impacts

Runoff from tropical glaciers plays a critical role in mountain ecosystem integrity and its reduction would have lasting and pervasive implications for water supply in the Andes. As discussed earlier, glaciers in the tropical Andes play an important role in freshwater regulation in associated watersheds, assuring year-round water flows for agriculture, potable water, power generation and ecosystem integrity. Under stable climatic conditions[36], glaciers, paramos, mountain wetlands and downstream biomes, such as cloud forests, are at equilibrium in terms of water flows. Once glaciers disappear in the region, there will be a loss of water regulation (figure 1) as well as absence of contributions from glaciers during dry periods (figure 2). The impact on environmental services is discussed below, within specific contexts in the Northern Andes.

Glacier retreat will affect regional water supply. Changes are expected in regional water supplies, including in areas that are already water short, placing already economically and environmentally stressed ecosystems and inhabitants at further risk of inadequate supplies (Vergara et al. 2007). While glacier retreat results in a temporary increase in runoff, once glaciers disappear, run-off regulation will be severely affected, as the glacier contribution will be eliminated and precipitation will not be naturally stored. For large urban centers such as Quito in Ecuador (population 1.8 million) where glaciers and associated paramo ecosystems (Antisana and Cotopaxi in particular) supply one-third of Quito's drinking water, or La Paz and El Alto in Bolivia (population 2.3 million) where the glaciers of the Cordillera Real have until recently supplied 30–40% of potable water, the changing circumstances can affect costs of supply and ultimately the ability of urban centers to maintain vibrant economies.

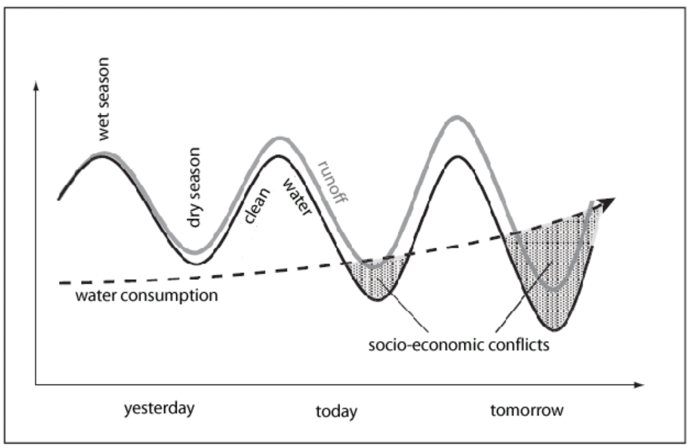
Glacier retreat and other climate changes will impact local agriculture. Semiarid mountainous ecosystems in the region are highly vulnerable to disruption of local hydrological patterns, placing subsistence agriculture and consequently rural livelihoods at risk. Anticipated fluctuations in the hydrological cycle will exacerbate already stressed ecosystems and reduce biodiversity and productivity of highland agricultural lands because of unreliable water supply. In the case of the wetter Andes of Colombia and Ecuador, the elimination of glacier runoff may not be the most serious problem, yet it may signal reductions in relative humidity in downstream watersheds and altitudinal increases in dew points, all pointing to changes in water budgets available to agriculture. The adaptive limitations of less-developed areas will likely increase the disparity in food

[36] Glaciers are really not stable as they fluctuate with climate variability and climate change over extended periods of time. The current unstable conditions reflect an abnormally high pace of change in climatic conditions leading to rapid glacier retreat.

production and food security in rural highlands. Because much of the lowlands' basins depend on tributary streams coming from the Andes, impacts will also be felt downstream.

Potential impact on energy generation. The region relies on hydropower to cover a majority of its power requirements, and some rivers that are used to generate hydroelectricity are glacier- or mountain lake-fed. A majority of power generation in Peru (80%), Colombia (82%) and Ecuador (50%) is met through hydropower. Reduction in water flows may reduce the potential for power generation in the long term, compared to the current situation, where there is an additional runoff due to glacier retreat induced by warming in the Andes. These changes may induce a carbonization of the power sector (countries going back to thermal power plants to make up for reduced hydropower potential), therefore increasing the greenhouse gas emissions of these systems. Recent studies in Ecuador suggest that during the low-water period, the Paute Project (Paute River Basin) would only be providing between 43% and 45% of average power capacity, which represents a deficit of about 27% compared to energy production under normal conditions.

Figure 1. Water runoffs with and without glacier contribution and water demand



As glacier retreat accelerates, the water regulation function of the glacier disappears. Growing demand may outstrip supply during seasonal dry periods and lead to potential socioeconomic conflicts unless measures are taken to adapt to the new situation.

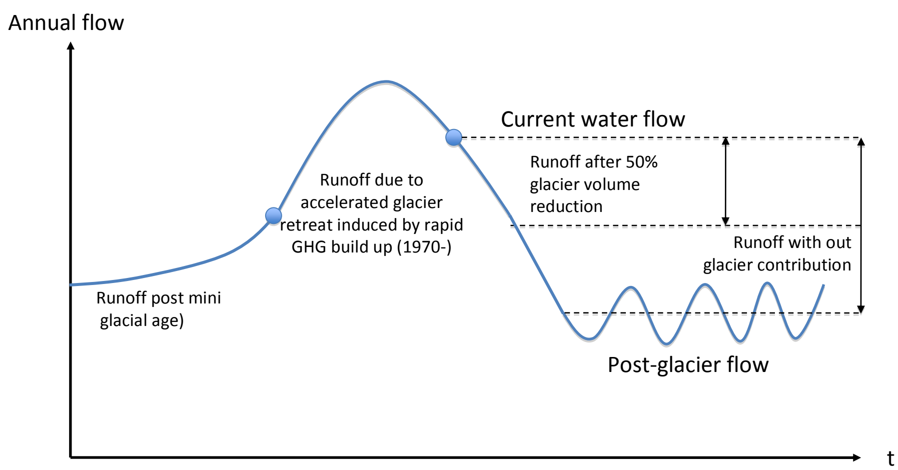
Source: Vuille 2006

An example of anticipated impacts

Our analysis of the hydrology of twelve watersheds in the Río Santa Basin, Peru, with sizes from 66 km^2 to 4,840 km^2, and with glacial coverage ranging from 2% to nearly 40% of the total watersheds, indicates that current runoff in these watersheds includes a substantial glacier contribution and allows the direct consequences of the retreat process to be estimated. The analysis indicates that nearly 220 mm/year of water, measured at the La Balsa station, the lowest altitude gauge in the watershed, are contributed by glaciers (after accounting for measured discharges, precipitation, and estimated evapo-transpiration; see Table 1), representing 6

0% of total ex-glacier runoff.[37] A similar analysis of precipitation patterns in the Río Vilcanota (also in Peru) has shown that dry season runoff could not be sustained without the contribution of glaciers (Leavell and Portocarrero 2003). For example, the actual historic average discharge (592 mm/year (Pouyaud et al. 2003)) at La Balsa, Cañón del Pato (located along the Río Santa), would be reduced to 482 mm/year with a 50% reduction of glacier runoff, and to 371 mm/year once the glaciers cease to contribute water or a "stable climate" is reached. These reductions represent an available discharge of 81% and 63%, respectively, of the recent historic discharge average. If this is typical of the region, the disappearance of glaciers will have serious consequences, which will be most dramatic during the dry seasons.

Figure 2. Impact of changes in glacier mass on runoffs



[37] These findings are supported by other studies and are generally in agreement with volumetric end-member mixing analysis applied to the Río Santa basin (McKenzie and Gómez 2005).

Table 1. Water balance in glacierized basins in the Cordillera Blanca in Perú

Hydrologic response of glacierized watershed in Los Andes

Watershed	Area	Area Glaciers		Rainfall P	Outflow Q	Q - P	ΔS [Q-P+EV]	ΔV [Area x ΔS]
	Km2	1970	1991	mm/year	mm/year	mm/year	mm/year	Mm3/year
Recreta	290	6.0	5.1	613	300	-313	38	10.88
Pachacoto	210	24.3	20.3	929	640	-289	61	12.75
Querococha	66	4.0	2.1	1000	829	-171	179	11.83
Quitaracsa	390	36.0	30.0	1048	877	-171	179	69.81
La Balsa	4840	580.0	**472.3	721	592	-129	221	1070.61
Olleros	176	28.5	**24.5	986	862	-124	226	39.79
Los Cedros	116	26.0	24.0	911	932	22	372	43.09
Colcas	236	51.0	39.0	874	772	-102	248	58.58
Chancos	271	90.5	65.3	888	1016	128	478	129.59
Quillcay	250	92.5	45.9	908	909	1	351	87.80
Llanganuco	87	35.0	33.7	995	1080	85	435	37.84
Paron	48.8	25.0	23.2	1019	1210	191	541	26.40
Artesoncocha *	8.4		6.6	1015	1915	900	1250	10.50

Evapotranspiration estimate 350 mm/year
Precipitaion records for 37 station extending from 1953 to 2001 were used
Discharge records from 1953 to 2001
** These numbers are estimates
* Hydrologic records are very short and were not included in calculations

To understand the recent evolution of some glaciated watersheds, the general hydrologic watermass balance equation is used: Eq. 1. Q = P – Et + ΔS

Where: Q = water discharge measured by a hydrometric station, which integrates the basin's hydrological response to all climatic stimuli; $P = \int p\delta a$, where P is the precipitation over the watershed, p is the point precipitation representative of an extension of δa units. Although high-altitude basins normally lack monitoring stations, we identified previous studies that provide reasonable estimates; Et = water loss from the watershed to the atmosphere in the form of sublimation from glaciers and evaporation from vegetated and non-vegetated surfaces (including glaciers), estimated as 350 mm/year.

The last term in the equation, ΔS, represents the total change in the volume of water stored in the watershed in tanks, reservoirs, groundwater formations, and glaciers. ΔV is the change in volume of water stored multiplied by the area of the watershed to obtain the change in volume per year. Under stable conditions, these terms ought to be zero if integrated over a long period of time, which implies that integrating over a period of several years, the total glacier water volume remains fairly constant.

In Peru, agriculture accounts for 85% of the total water consumption (Peru's Ministry of Agriculture 2006) and is mostly located on the Pacific coastal plains and western slopes of the Andes, where the land is typically dry and dependent on runoff from the Cordilleras. If glaciers cease to act as runoff regulators, agricultural output will be affected unless alternative water supplies are provided. Although Peru accounts for about 5% of the world's fresh water, this resource is poorly distributed, with most of the available water (over 98%) found to the east of the Andes in the Amazon Basin where agricultural activity is marginal (Peru's Ministry of Agriculture 2006). As an example, the main agricultural output in the Santa Basin (valued at over US$92 million dollars annually to producers in Peru[38]), could be curtailed if the loss of water is not compensated.

For Lima (population 7 million), using the long-run marginal cost of water as a proxy, the additional costs for water supply are calculated to exceed US$116 million per year once glacier runoff ceases. This was calculated by estimating the volume of water reduced per year under a "stable climate" (no melting) condition and multiplying it by the opportunity cost of supplying this water.

Likewise, an analysis of the location of hydropower plants in Peru indicates that 15 plants, with an accumulated installed capacity of 2,480 MW, are located in basins that depend on glacier runoff. For example, the Mantaro River, which is expected to be one of the most affected, feeds a hydroelectric plant that generates 7,100 GWh annually, representing ~32% of total electricity generated in Peru and supplying 70% of the national industry. Using data from Peru's power system (Ministry of Energy and Mines 2006), we estimated that the average energy output for the Cañón del Pato hydropower station in Peru would drop from 1,540 GWh to 1,250 GWh, with a 50% reduction in effective runoff rate, and would further reduce to 970 GWh once the glacier contribution completely disappears.

An estimate has been made of the net economic impact of a reduced run-off caused by rapid reduction of glacier mass. It uses as baseline, the current runoffs, which already reflect a non sustainable contribution from glacier retreat.

Three indicators were used to assess the value of the energy not produced due to diminishing glacier runoff in Peru: (a) the price of energy paid to the generator (US$20/MWh), which measures the impact on the investor; (b) the long-run average price for electricity (a measure of the opportunity cost to society) estimated from national optimal expansion studies (US$35/MWh);[39] and (c) the cost of rationing energy (US$250/MWh)[40] to assess the economic consequences of forced rationing due to insufficient power capacity. The resulting estimates are presented in Table 2 below for Cañón del Pato (the second largest in the country). The rationing costs would be triggered if the rapid reduction in runoff continues, and if adaptation measures are not implemented soon.

These costs are to be paid by current and future generations, while those that live during a period of increased discharges due to glacier retreat have access to surplus amounts of water compared to stable condition, even if these are not utilized. In fact once the glacier contribution is eliminated, the situation would be akin to that under stable glacier volumes (stable climate).

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[38] Based on 2003 FAO (http://faostat.fao.org/site/352/DesktopDefault.aspx?PageID=352) producer prices, for over 1.1 million metric tons of agricultural products in 2005 (http://www.inei.gob.pe).
[39] With data from the Ministry of Energy and Mines of Peru. Anuario Estadístico Electricidad 2005. Online at: http://www.minem.gob.pe/archivos/dge/publicaciones/anuario2005/anuario.pdf. (Accessed 2006).
[40] Plan Referencial de Electricidad 2005-2014, Ministry of Energy and Mines of Peru. (June 2006).

Table 2. The cost of glacier retreat for energy sector, Peru (US$ million/year)[41]		
	Cañon del Pato Power Plant	
	Reduced melting	No melting
Wholesale price	5.7	11.5
Opportunity cost	10.1	20.3
Rationing cost[42]	71.5	144.0

Extrapolated at the national level, i.e. assuming the size of the Cañon del Pato Power Plant represents the average in electricity production and glacier water consumption, the wholesale price for glacier retreat (no melting) is estimated at US$ 120 M, the opportunity cost at US$ 212 M. and the rationing cost at 1,503 M. A similar exercise was conducted utilizing the information from the Rimac River water supply system for Lima, Peru, extrapolated for the country at large. From the detailed cost structure estimated for the expansion of Lima's water supply system, the average water tariff is US$0.42/$m^3$; the opportunity cost (long-run average cost) is US$0.64/ m^3; and the rationing price was projected at US$30.50/$m^3$.

Beyond economic costs, glacier retreat will also have harmful social and cultural costs for the Quechua and Aymara cultures, which have long revered the glaciated *apus* (highest peaks) as religious icons. The Andean cosmology is deeply rooted in pre-Columbian times. For the Andean peasants the *apus* are tutelary spirits, held responsible for water sources and fertility of the fields and are the residence for the *Illapa* or thunder and lightning, a powerful god that is revered both for its water-producing facility and for its capability to produce damage to crops through hail. Until recently, the Andean people practiced *Qoyllur Riti*, a popular ritual near Cusco in Peru, which involved tens of thousands of people climbing to a glacier that faces the great glacial peak of Ausangate. During this ritual, "medicinal ice" was collected and carried to their parcels to ensure the fertility of the fields. However, with the ablation of this limited resource the ritual has stopped.

In summary, the consequences of glacier retreat in the Andes represent an externally imposed burden on low carbon-based developing economies already faced with substantial challenges to alleviate poverty, foster development, and improve the well-being of their growing populations. It is therefore of critical importance that the planning, modeling, and development process include measures of adaptation to the changing contexts of mountain environments that are experiencing the effects of accelerated global climate change.

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[41] 221 mm/year of measured runoff is calculated to come from glacier melting. The economic assessment was made under the hypothesis of a 50% reduction in melting rate, and of no melting. Economic data were obtained from the Ministry of Energy and Mines of Peru, 2005. National estimates are an extrapolation of the results described for Cañón del Pato to other glaciered basins feeding hydropower plants.

[42] The rationing costs are based on estimates produced by Peru's Ministry of Energy and Mines, 2006. These values are not expected to occur in Peru. They are hypothetical (and therefore inflated) costs that represent the worst government response scenario – doing nothing while the glacier retreat continues unabated – forcing energy to be rationed for extended periods.

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The Potential Costs of Climate Change in Tropical Vector-Borne Diseases – A Case Study of Malaria and Dengue in Colombia

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Introduction

Malaria and dengue are infectious diseases transmitted by vector organisms, mosquitoes, and caused by parasite microorganisms. Both diseases have spread over tropical latitudes where complex factors determining their incidence involve not only biological but also climate, demographic, and societal conditions (Gubler 1998).

Global and biological modeling has been used to study the spread of the diseases with respect to various variables, such as climate. Results from present-day global distribution of falciparum malaria (Rogers and Randolph 2000) were applied to future climate scenarios to predict future incidence. The results reflect the increase in number of cases in areas where these diseases are currently present, but does not account for possible changes (increases or reductions) in areas at risk. The present study also uses a statistical-empirical approach to estimate the impact of climate change on malaria and dengue epidemics in Colombia. The study tests two types of models (inter-temporal and cross-sectional) to find the relationship between epidemics and climate change variables (temperature and precipitation). The study is divided into five sections: the first is this introduction, the second presents the descriptive statistics of epidemics in Colombia, and the third presents the models used in the analysis. The fourth section presents the statistical results and the last section presents the results of the estimation of climate change costs.

Variation in malaria transmission is partially associated with changes in temperature, rainfall, and humidity as well as the level of immunity (Lindsay and Birley 1996). All of these factors can interact to affect adult mosquito densities and the parasite development within the mosquito known as sporogonic cycle. Mosquitoes do not regulate their internal temperatures and therefore their survival rate depends on external temperature and humidity. Microorganisms have temperature requirements for breeding since this influences reproduction and maturation rates within the vector. Very high temperatures are lethal to the mosquito and the parasite. In areas where mean annual temperature is close to the physiological tolerance limit of the parasite, a small temperature increase would be lethal to the parasite, and malaria transmission would therefore decrease. However, at low temperatures, a small increase in temperature can greatly increase the risk of malaria transmission (IPCC 2001).

The main restrictive factor of mosquitoes' population size is often the availability of breeding spots (Lindsay and Birley 1996). Precipitation has an important role in adult production (IPCC 2001) but its relationship to vector density is more complex and cannot be uniformly established. Rainfall rise may favor breeding by creating spots but an excess may cause floods responsible for drift and loss of immature mosquitoes' stages. Rainfall scarcity may cause drought in breeding spots but during extended periods suitable puddles are formed next to river currents.

On the other hand, dengue is transmitted to humans by *Aedes* mosquitoes carrying four different types of virus. Infection by any single type apparently produces permanent immunity to it, but only temporary cross-immunity to the others. The mosquitoes never recover from the infection since their infective period ends with their death. Viruses are maintained in a human–*Aedes aegypti*–human cycle in most urban centers of the tropics (IPCC 2001).

The geographic distribution of the dengue viruses and mosquito vectors (*Aedes aegypti* and *Aedes albopictus*) has expanded to the point that dengue has become a major tropical urban health problem. Dengue is primarily an urban disease, with more than half of the world's population living in areas of risk. In tropical areas, dengue transmission occurs year-round but has a seasonal peak, in most countries, during the months with high rainfall and humidity. Major factors causing epidemics include population growth, rapid urbanization, lack of effective mosquito control, and movement of new dengue virus strains and serotypes between countries (IPCC 2001). It is also recognized that meteorological factors such as temperature, precipitation, and humidity influence the dengue mosquito vector. However, transmission intensity in tropical endemic countries is limited primarily by herd immunity, not temperature; therefore, projected temperature increases are not likely to significantly affect transmission. Moreover, in subtropical developed areas, where transmission is limited primarily by demographic and societal factors, it is unlikely that the anticipated temperature rise would affect endemicity (Gubler 1998).

The expected impact of climate change on malaria and dengue has been addressed by various studies based on the vectorial capacity or biological modeling developed by Garrett-Jones in 1964. The model aimed to forecast the expected number of new cases that will arise from one current case when introduced into a non-immune host population during a single transmission cycle (IPCC 2001). Its main assumptions are: (i) survival rate is constant over time and vector age, (ii) despite host abundance, mosquitoes bite a fixed number of times, and (iii) mosquitoes randomly feed on the non immune population (Dye 1986). The model is determined by complex interactions of host, vector, pathogen, and environmental factors. Some of its variables are sensitive to temperature, including mosquito density, feeding frequency, human blood index, mosquito survival, and the extrinsic incubation period (EIP) of the parasite in the mosquito (Martens et al. 1999). The EIP is especially important and, within the lower temperature range, it is highly temperature-sensitive. Vector capacity can provide a relative index of the impact of different climate scenarios on disease transmissibility.

Vector capacity has been incorporated in many dynamic models that integrate relevant climate variables with demographic, epidemiological, and entomological information from a given target area, and that seek to answer "what if" kinds of questions. Epidemiology representations through vector capacity models have significantly contributed to deepen the understanding of transmission, and many have been reviewed, discussed, and used recently to support global-scale eradication efforts.

An important objection to biological modeling approaches is their limited capacity to forecast impact of climate change. This is because, although the models include climate variables (temperature), their predictability is limited to a transmission cycle of a few weeks and depends on local variables such as mosquito density. Therefore, the biological models are suitable to predict epidemics in a specific site and in a short period, in contrast to the long-term and regional nature of climate change impacts.

Another type of global modeling studies used a statistical-empirical approach, in contrast to the aforementioned biological models. Rogers and Randolph (2000) used the recorded present-day global distribution of falciparum malaria to establish the current multivariate climate constraints. These results were applied to future climate scenarios to predict future distributions, which showed remarkably few changes even under the most extreme scenarios. The study made the assumption that the actual geographic distribution of malaria in today's world is a satisfactory approximation of its historical distribution prior to modern public health interventions. According to IPCC (2001), this assumption is likely to have biased the estimation of the underlying multivariate relationship between climate variables and malaria occurrence because the sensitive climate-malaria relationship in the lower temperature range in temperate zones (especially Europe and the southern United States) would have been excluded from the empirically derived equation.

As mentioned earlier, the present study also uses a statistical-empirical approach to estimate the impact of climate change on malaria and dengue epidemics in Colombia. With the statistics of the number of cases of malaria and dengue reported by 715 municipalities between 2000 and 2005, the study tests two types of models (inter-temporal and cross-sectional) to find the relationship between epidemics and climate change variables (temperature and precipitation).

Malaria and Dengue in Colombia

Malaria Epidemiology. About 85% of Colombia's territory presents suitable ecological, climate, and epidemiological characteristics for malaria transmission. Four parasite species are known to cause it, three of them existing in Colombia: *Plasmodium vivax, Plasmodium falciparum,* and *Plasmodium malariae*. These infective agents reproduce and mature within the vector organism, a group of mosquito species from the *Anopheles* genre. In the country over twenty known species are environmentally bounded within certain areas that some of them can cohabit (IQEN, 2004). The most important vectors are *A. albimanus*, *A. darlingi*, and *A. nuñeztovari*, transmitting *P. falciparum* (46.5%) and *P. vivax* (53.5%), and rare cases (8–10 per year) of *P. malariae* (Poveda et al. 2000). Municipalities with high risk of transmission have on average 5 cases per 1,000 inhabitants (Quiñones et al. 2005).

Although some authors[43] have shown a direct relationship between *Anopheles* density and precipitation, in Colombia the *A. albimanus* vector has not shown a statistical correlation but rather uniform density throughout rainy and drought seasons. Similarly, the *A. darlingi* and *A. nuneztovari* vectors exhibit a monthly density fluctuation dependent on the habitat's location, suggesting a closer relation to bio-ecology than to climate conditions (Quiñones et al. 2005).

Dengue Epidemiology. Dengue is an important public health problem in Colombia given the cyclical appearance of the disease, with an increased trend in its intensity. Epidemic cycles occur every two to three years with simultaneous circulation of different serotypes. The *A. aegypti* vector is present in over 90% of the national territory below 2.200 m.a.s.l. In each cycle there are more frequent cases of hemorrhagic dengue and dengue shock syndrome outbreaks (INS 2007b).

Since 1978 classic dengue incidence has fluctuated with an increasing trend over time. Hemorrhagic dengue has displayed a rising incidence since its appearance in 1989, from 5.2 cases per 100,000 inhabitants in 2002 to 18.1 cases per 100,000 inhabitants in 2005. Mortality has also increased: in 2002 there were 0.07 deaths per 100,000 inhabitants, while in 2005 there were 0.19 deaths per 100,000 inhabitants. In 2005, 38,827 classic dengue cases were reported, with a national average incidence rate of 164.74 per 100,000 inhabitants (INS 2007b).

Descriptive statistics of malaria and dengue epidemics. This study combined two different databases: one with the number of cases reported by the municipalities to the National Health Institute during the 2000–2005 period, and the other with the temperature and precipitation information recorded by IDEAM meteorological stations during the 1995–2005 period. Although there are statistics of dengue and malaria morbidity in Colombia before 2000, they were collected with a different methodology and are aggregated at departmental level. Of the total number of municipalities in Colombia (1,029), the study database includes information on 715 municipalities, covering 70% of the national territory.

During the 2000–2006 period, 583 municipalities reported malaria cases from *P. falciparum* or *P. vivax*, and 573 reported dengue events, confirming that malaria and dengue are present in more than half of Colombia's municipalities. Of the total municipalities in the database, only 54 (7.6%) did not report any cases during the evaluation period. Table 1 shows the number of municipalities reporting cases for each disease.

[43] Molineaux and Gramiccia (1980) and Charlwood et al. (1995).

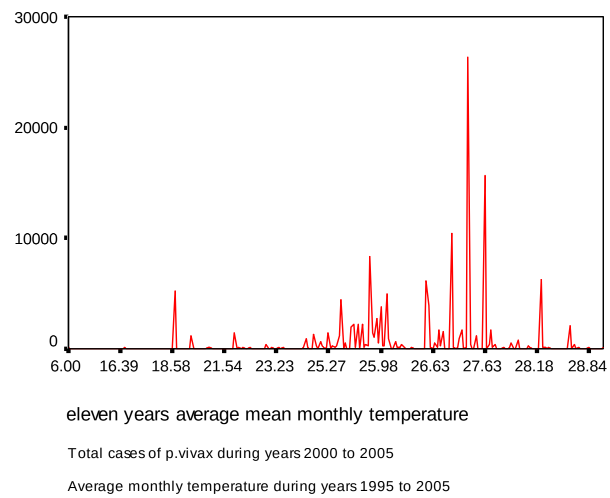
Table 1. Number of municipalities with malaria and dengue report during the 2000–2005 period

Year	Municipalities reporting malaria cases		Municipalities reporting malaria deaths	Municipalities reporting dengue cases	Municipalities reporting dengue deaths
	P. falciparum	P. vivax			
2000	177	295	0	324	0
2001	211	359	0	387	0
2002	225	349	0	432	0
2003	238	354	7	433	5
2004	229	364	21	400	14
2005	228	367	12	420	26
2000 -2005	394	562	29	573	38

Source: INS database

A general idea of the relationship between disease incidence and climate variables can be seen if we plot the number of cases reported with the temperature and precipitation measured in each municipality, as shown in the following graphs:

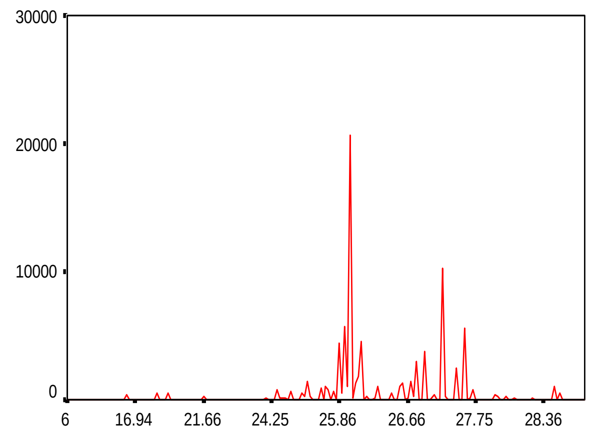
Graphic 1. Relation between cases of malaria and temperature



The above graph shows the relationship between the cases of malaria from *P. vivax* and the average monthly temperature: at a level of 25ºC the number of cases begins to increase with a clear peak in the range of 26.5ºC to 27.7ºC, ending with a decrease above 28ºC.

The next graph shows the relationship of the same variable (average monthly temperature) with cases of malaria from *P. falciparum*.

Graph 2. Relation between cases of malaria and temperature



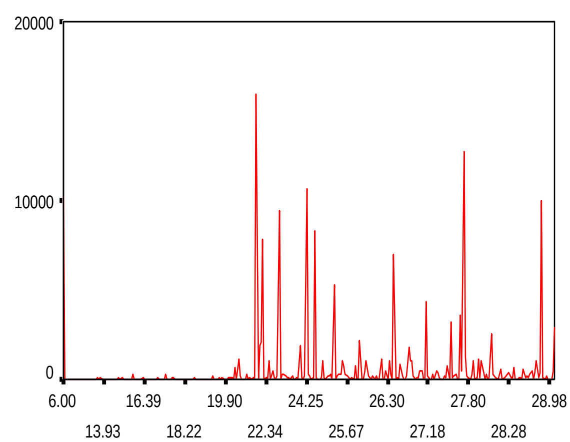
eleven years average mean monthly temperature

Total cases p.falciparum during years 2000 to 2005

Average monthly temperature during years 1995 to 2005

For *P. falciparum*, although the range of the disease is the same as that for *P. vivax*, between 25ºC to 28ºC, the peak of cases is located at 25.8ºC, lower than *P. vivax*. This behavior suggest that *P. vivax* would more likely spread to new areas with the expected global warming, than *P. falciparum* as its peak of incidence is closer to the lower bound of the survival range.

Graph 3. Relation between cases of dengue and temperature



eleven years average mean monthly temperature

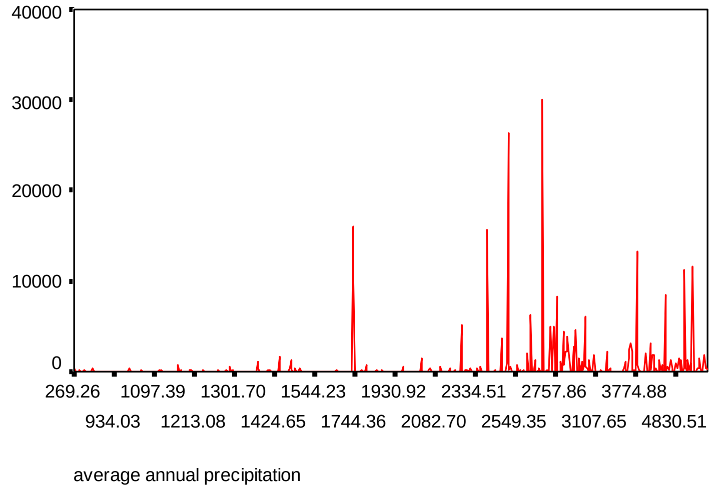
Total cases of dengue during years 2000 to 2005

Average monthly temperature during years 1995 to 2005

The above graphs show that dengue cases in Colombia appear from 20ºC to the maximum temperature reported by the municipalities, 30ºC. The graph also shows that between the temperature ranges, there are no clear peaks of cases.

The relationship between diseases and precipitation is presented in the following graphs:

Graph 4. Relation between cases of malaria and rainfall

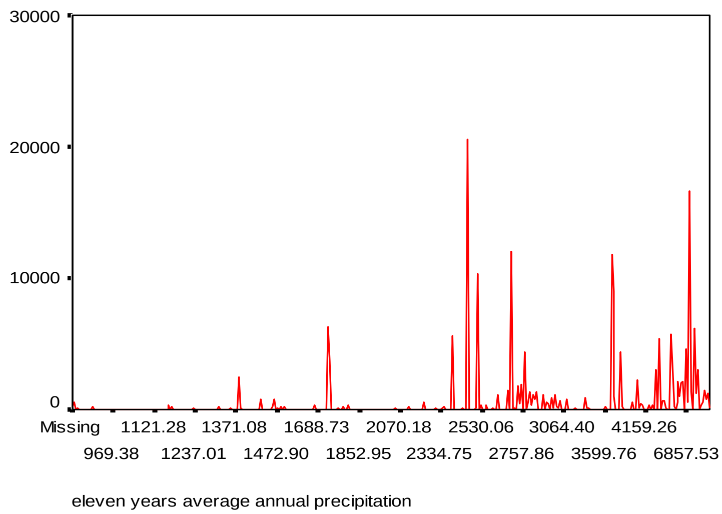


Total cases of p.vivax during years 2000 to 2005

Average annual rainfall (in mm) during years 1995 to 2005

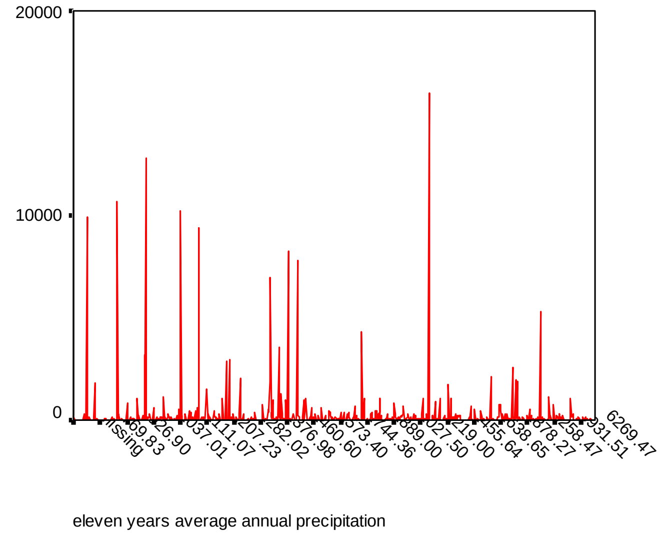
As shown in the above graph, cases of malaria from *P. vivax* appear continuously above an annual precipitation of approximately 2,300 mm. This level could show the required amount of rainfall necessary for the vector breeding conditions.

Graph 5. Relation between cases of malaria and rainfall



The relationship for cases of malaria from *P. falciparum* and rainfall shows the same threshold as that from *P. vivax*: annual precipitation above 2,300 mm.

Graph 6. Relation between cases of dengue and rainfall



Finally, for dengue cases, the graph shows no clear range for the appearance of the disease. It shows that through all the annual precipitation ranges reported by the municipalities (600–4,000 mm), cases appear uniformly.

Although the above analysis shows a preliminary relationship between climate variables and malaria and dengue epidemics, it is necessary to verify those relationships with a formal statistical test. As described in the introduction, this is not an easy task because the actual number of cases depends not only on climate variables, but also on socioeconomic and institutional variables. In recent years, the government has increased the response measures to both diseases by building the capacity of municipalities to prevent and address the outbreaks. Evidence of the response measures may be analyzed by comparing the number of cases in the first three years with the last three years of the evaluation period in the same municipalities, as shown in table 2:

Table 2. Percentage of municipalities showing an increase/decrease in cases between the last and first three years of the evaluation period

	Malaria cases		Dengue cases
	P. falciparum	*P. vivax*	
Increase	27.2	42.1	39.7
Decrease	20.3	33	38
No change	52.5	24.9	22.3

Source**:** Authors' calculations based on INS database

As shown above, 20%, 33%, and 38% of the municipalities have reduced their cases of malaria from *P. falciparum*, *P. vivax,* and dengue, respectively. This result shows that the response measures will heavily affect the actual figure of epidemics in both diseases.

The statistical-empirical models

This section presents the statistical models used to formally test the relationship between climate variables and dengue and malaria epidemics in Colombia. As described in the previous section, the study uses two main sources of information: the cases of malaria and dengue reported by 716 municipalities to the INS during the period from 2000 to 2005, and the monitored temperature and precipitation from 1995 to 2005. The model also uses demographic information calculated by the National Department of Statistics (DANE).

Cross-sectional analysis. The cross-sectional analysis explains the level of epidemics in the municipalities with monitored climate and socioeconomic variables. It tests whether some of the variation in the incidence across municipalities can be explained by the variation in temperature and precipitation across the municipalities. The model's dependent variable was constructed as the rate of morbidity (total cases divided by the municipality's population) during the 2000–2005 period. This rate corresponds to a long-term (six years) exposure to the diseases, which will keep the analysis from being affected by isolated outbreaks in a specific year. On the other hand, the independent variables comprise the monthly mean temperature during the 1995–2005 period and the average annual precipitation during the same period. The monthly period for the temperature variable was chosen in order to approximately match the transmission cycle of the diseases, and therefore to reflect the average temperature that the vector and the parasite face.[44] The precipitation variable was chosen as the total annual rainfall, because previous studies have found no relationship between the rainy and drought seasons (Quiñones et al. 2005). Therefore, the precipitation variable does not account for seasonal variation, but rather for a steady-state rainfall condition in the municipality. Finally, the model includes a socioeconomic variable to incorporate the relationship between the incidence and the socioeconomic condition of the population (housing, sanitation, etc.). The socioeconomic variable corresponds to the basic needs index (NBI), calculated by the National Department of Statistics (DANE) using 1993 census data, and reflects the percentage of the municipality's population living in poverty conditions. The specification of the model is shown below:

Δ Rate of morbidity during period 2000 – 2005 = $\beta 0$ + $\beta 1$ (Average monthly temperature 1995–2005) + $\beta 3$ (Average annual precipitation 1995–2005) + $\beta 4$ (NBI).

The above model was tested for malaria from *P. falciparum*, *P. vivax*, and dengue.

Inter-temporal analysis. The inter-temporal analysis tests the hypothesis that part of the observed changes in morbidity in the municipalities can be explained by the variation of temperature and precipitation within the municipality. The inter-temporal analysis will show whether the actual climate change has already increased the incidence of both diseases during the period of analysis. The dependent variable was

[44] Other versions of the model include daily extreme values (minimum and maximum) of temperatures, but the overall performance was below the model with mean monthly temperature.

constructed as the difference between the rates of morbidity of the 2000–2002 period and the 2003–2005 period. On the other hand, in order to account for the variation in climate variables, the variance was calculated as the difference between the maximum and minimum average of the monthly temperature from 1995 to 2005; and between the maximum and minimum total annual precipitation, both from 1995 to 2005. The NBI was also included in the model to take into account the socioeconomic factors. The following is the representation of the inter-temporal model:

Δ Rate of morbidity during 2000–2005 period = β0 + β1 (Δ Average monthly temperature in years 1995–2005) + β3 (Δ Annual precipitation 1995–2005) + β4 (NBI).

Where:

Δ Rate of morbidity during 2000–2005 period = Total cases (2005 to 2003)/population 2005 + Total cases (2005 to 2003)/population 2005.

Δ Average monthly temperature from 1995 to 2005 = Max (average monthly temp. 2005, average monthly temp. 2004, average monthly temp. 1995) – Min (average monthly temp. 2005, average monthly temp. 2004, average monthly temp. 1995).

Δ Annual precipitation 1995–2005 = Max (total annual precipitation in 2005, total annual precipitation in 2004, total annual precipitation in 1995) – Min (total annual precipitation in 2005, total annual precipitation in 2004, total annual precipitation in 1995).

The above model was tested for malaria from *P. falciparum, P. vivax*, and dengue.

Results

This section shows the results of the statistical tests of the two types of models for malaria and dengue using a regression analysis of Minimum Ordinary Squares.

Results of the cross-sectional analysis – Model 1. The next table shows the summary of the statistical results for the regression model for malaria from *P. falciparum*, *P. vivax*, and dengue. The detailed results are shown in Annex 3.

Model Summary

Diseases	R	R Square	Adjusted R Square	Std. Error of the Estimate	ANOVA Sig.
P. falciparum Malaria	0.543	0.295	0.284	0.02605	0.000
P. Vivax Malaria	0.255	0.065	0.054	0.05178	0.001
Dengue	0.272	0.074	0.063	0.01271	0.000

Coefficients

Model	Coefficient B	t	Sig
P. falciparum Malaria			
Constant	-3.25E-02	-3.098	0.002
Temperature	4.989E-04	1.240	0.217
Precipitation**	1.103E-05	8.100	0.000
NBI	1.170E-04	1.120	0.264
P. Vivax Malaria			
Constant	-3.36E-02	-1.951	0.052
Temperature	1.915E-04	1.072	0.285
Precipitation**	8.271E-06	3.381	0.001
NBI	8.931E-04	1.318	0.189
Dengue			
Constant	-1.42E-03	-0.332	0.740
Temperature**	7.345E-04	4.270	0.000
Precipitation	-3.44E-07	-0.548	0.584
NBI	-1.19E-04	-2.593	0.010

The cross-sectional analysis for *p.faciparum* and *p.vivax* malaria results in a significant relation between the rate of incidence of the disease and the level of annual precipitation. The sign of the coefficient associated to the precipitation confirm that an increase in the level of rainfall will generate an increase of the rate of incidence in the municipalities.

The results of the cross-sectional model for dengue are different than those for malaria. The model has also a low level of prediction but overall it is significant to explain some of the variation. The temperature variable is significant for dengue while the precipitation is not. On the other hand, NBI variable is found significant but with the sign opposed as expected. The sign of the NBI variable can be explained by the fact that dengue epidemics is found on urban populations and the municipalities with greater population in rural areas typically has higher levels of poverty (NBI).

Results of the inter-temporal analysis – Model 2. The following tables show the result of the statistical test of the inter-temporal models applied to *P. falciparum* malaria, *P. vivax* malaria, and dengue:

Results for *P. falciparum* malaria, *P. vivax* malaria and dengue:

Model Summary

Diseases	R[45]	R Square	Adjusted R Square	Std. Error of the Estimate	ANOVA Sig
P. falciparum Malaria	0.182	0.033	0.000	182.98863	0.392
P. Vivax Malaria	0.131	0.017	-0.004	144.99576	0.498
Dengue	0.207	0.043	0.021	84.19979	0.126

As shown above, none of the inter-temporal models is significant enough to explain the variation of the incidence rate within municipalities. This result can be explained by the fact that the period of analysis for the increase in epidemics is too short to reflect the impact of the climate variables. Another hypothesis is that climate change impacts are not yet affecting malaria and dengue epidemics.

Estimation of the cost of climate change on malaria and dengue epidemics

With the results of the cross-sectional models on the relationship between the rate of epidemics and the level of temperature and precipitation for dengue and malaria, it is possible to estimate the expected cost of climate change on these diseases in Colombia. The cost was estimated using the following methodological steps:

Step 1: Calculation of the unit cost associated with a case of malaria and the unit cost associated with a case of dengue.

Step 2: Calculation of the increased number of cases of malaria and dengue, in an unconstrained scenario, with the expected increases in temperature and precipitation due to climate change in 50 and 100 years.

Step 3: Multiplication of the increased number of cases with the corresponding unit costs to estimate the total cost of climate change impact.

The results of each step are described below:

Step 1: Unit costs of malaria and dengue cases.

The costs associated with a case of malaria and dengue may be divided into direct costs of diagnosis and treatment, and indirect costs in terms of reduced time, labor, and transport costs.

[45] Predictors: (Constant), unmet needs index, max/min difference of maximum monthly temperature year averages, average precipitation difference between first and later three years.

Direct costs of diagnosis and treatment. Malaria is diagnosed through a laboratory exam, generally undertaken in the departmental hospital. Once the disease has been identified, the case is treated with conventional antimalarial drugs (primaquine, sulfadoxine-pyrimethamine, and amodiaquine). Treatment cost varies if the infected person is an adult or a child because of the quantity of the doses of the antimalarial drug. Therefore, the unit cost was calculated for an adult's case and for a child's case. Finally, in some regions of Colombia (Pacific Coast, Amazonian, and Antioquia and Córdoba Departments) resistance of *P. falciparum* to conventional antimalarial drugs has been observed. Therefore, in those regions the treatment costs are significantly higher than those for the rest of the country.

On the other hand, dengue is diagnosed through clinical exams and the treatment of the disease is limited to the treatment of its symptoms. As in malaria, the treatment costs vary if the infected person is an adult or a child.

Table 3 presents the direct costs used in the study for each disease.

Table 3. Direct cost per cases of malaria and dengue in Colombia (in US$)
DIRECT COSTS PER CASE

	Malaria		**Dengue**
	P. falciparum	*P. vivax*	
Diagnosis exam	2.05	2.05	26.23
Treatment costs			
Adult	4.96	1.41	0.86
Child	3.22	1.41	0.43
Total direct costs			
Adult	7.01	3.46	27.09
Child	5.27	3.46	26.66

Source: INS statistics

Treatment costs in regions resistant to antimalarial drugs

	P. falciparum
Pacific Coast – Adult	24
Pacific Coast – Chile	12
Antioquia and Córdoba – Both	47.89
Leticia – Both	18.66

Indirect Costs. The indirect costs are associated with the impact on household income when one member is infected by the disease. If the member infected is a working adult, during the period of the disease he will not be able to work and his labor will be lost (the cost will be assumed directly by the household if this is a rural, informal, or independent worker or by the company if this is a formal employee). This cost was estimated by multiplying the minimum legal[46] daily salary by the days that the person is unable to work, adjusted by the percentage of the population not employed.

Similarly, if the member infected is a child, he will require adult care. Therefore, the time cost is equal to that calculated in the adult case, but the treatment cost are different. Therefore the childhood population index, or the proportion of children to the total

[46] Minimum legal salary is used for comparison across the country, although there is a significant group of workers, especially in rural areas, that are not paid with the minimum salary.

population, was used for aggregating the adult and the child cost into a general case cost assuming an equal likelihood of infection in the risk population.

Finally, due to the rural nature of malaria cases, infected persons must travel from their home to the nearest health center for diagnosis and treatment purposes, with an additional indirect cost of transportation. To estimate this cost, a minimum round-trip cost for a short-distance rural trip (from the countryside to the city or town) is assumed, based on the minimum national regulated public transport fee (Resolution 9900 of 2002). Table 4 shows the calculated indirect costs per cases of malaria and dengue:

Table 4. Indirect cost per cases of malaria and dengue in Colombia (in US$)

INDIRECT COSTS PER CASE	
Minimum legal salary (US$/day)	6.88
Days unable to work	3
Employment[47] index	38.72%
Indirect time cost of adult case	$8.00
Children's index	31.84%
Indirect time cost of child case	$2.55
Transportation cost for malaria (round trip)	$2.4

Source: Authors' calculations based on official statistics and INS estimates

Step 2: Calculation of the incremental number of cases caused by climate change.

The IPCC Fourth Assessment Report (IPCC 2007a) estimated for the next two decades a warming of about 0.2°C per decade, for a range of emission scenarios. According to IPCC, even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected (IPCC 2007a). General circulation models of future climate have found that in a world with twice the preindustrial carbon dioxide concentrations, the rate of warming in the lower troposphere will increase with altitude. Thus, temperatures will increase more in the high mountains than at lower elevations (Bradley et al. 2006).

Bradley et al. (2006) estimate changes in mean annual temperatures between 1990–1999 and 2090–2099 along a transect from Alaska (68°N) to southern Chile (50°S), following the axis of the American Cordillera mountain chain. It uses the mean of eight different general circulation models used in the fourth assessment of the Intergovernmental Panel on Climate Change (IPCC), using CO_2 levels from scenario A2 in previous work by Nakicenovic (2000). Based on Bradley et al. (2006), the study will use the specific estimated changes in temperature (2.5–3.5C) for municipalities with altitudes above 2,000 m.a.s.l. and below 3,000 m.a.s.l. For the remaining municipalities, the study will use the IPCC (2007a) estimates.

[47] Calculated as the ratio between the employed population and the total population of the country.

With respect to precipitation, IPCC reports that increases in the amount of precipitation are *very likely* in high latitudes, while decreases are *likely* in most subtropical land regions (by as much as about 20% in the A1B scenario in 2100), continuing observed patterns in recent trends.

As noted above, Colombia is showing a relative increase in precipitation of approximately 5% in the period from December to February. For the period from June to August, the above figure does not show a clear trend: varying for the northern part of the country, it shows a decrease in precipitation; for the southern part an increase; and in the center there are “white areas” where less than 66% of the models agree on the sign of the change. For this study a 5% general relative increase in annual precipitation is assumed in all the municipalities for a 100-year scenario and half for a 50-year scenario. Table 5 presents the impact of climate change on temperature and precipitation used by this study in the different future scenarios.

Table 5. Climate change impacts on temperature and precipitation used in the study

Variable	50-year scenario	100-year scenario
Altitudes between 2000 and 3000 m.a.s.l*	1.25°C	2.5°C
Other altitudes**	1°C	2°C
Relative increase in average annual precipitation**	2.5%	5%

* Based on Bradley et al. (2006) ** Based on IPCC (2007a)

With the previous figures, the additional cases during a six-year period in each disease were calculated using the corresponding temperature and precipitation coefficients that result in the following cross-sectional analysis:

Additional number of cases of *P. falciparum* malaria in municipality in future scenario = $\beta_{p.falciparum, precipitation}$ (1.103E-05) * Increase in precipitation (future scenario) * Average annual precipitation in the municipality * Population (future scenario)

Additional number of cases of *P. vivax* malaria in municipality = $\beta_{p.vivax, precipitation}$ (8.271E-06) * Increase in precipitation (future scenario) * Average annual precipitation in the municipality * Population (future scenario) in future scenario

Additional number of cases of dengue in municipality in future scenario	=	$\beta_{dengue, temperature}$ (7.345E-04)	*	Increase in $temperature_{Altitude}$ (future scenario)	*	Population (future scenario)

The additional cases were calculated only in the municipalities in which the corresponding disease was present in the 2000–2005 period; therefore the estimate of the costs of climate change do not consider the infection in new municipalities. Table 6 shows additional numbers of cases of dengue and malaria in the 50-year and 100-year scenarios for the 715 municipalities in Colombia:

Table 6. Additional numbers of cases of malaria and dengue for 50- and 100-year future scenarios

Vector-borne disease	Historic total number during the 2000–2005 period	Additional number of cases for a 6-year period. 50-year scenario	Additional number of cases for a 6-year period. 100-year scenario
P. falciparum malaria	184,350	19,098	56,901
P. vivax malaria	274,513	16,247	48,207
Dengue	194,330	41,296	123,445
Total	**653,193**	**76,641**	**228,553**

Source: Authors' calculation.

The above table shows that in an unmitigated scenario, climate change will increase the total number of cases of malaria and dengue by 76,614 and 228,553 in a six-year period, for 50- and 100-year future scenarios, respectively. The additional number of cases compared with the baseline period of 2000 to 2006 represents an increase of 11% and 35% for 50- and 100-year future scenarios.

Step 3: Calculation of potential total costs.
The potential total costs of the impact of climate change for 50- and 100-year scenarios were calculated by multiplying the additional number of cases in each municipality by the corresponding unit costs of each case calculated in the previous steps. Because the unit costs are different depending on whether the infected person is an adult or a child, an aggregate unit cost was calculated with the national proportion of children and adults in the actual population, therefore assuming that the additional cases will have the same proportion. Table 7 presents the total costs in both scenarios per disease (totals may be different from sum of costs due to rounding):

Table 7: Climate change costs relative to the 2000–2005 period in Colombia (in millions of US$ of 2005)

Scenarios	Indirect costs of malaria and dengue	Direct cost of *P. falciparum* malaria	Direct cost of *P. vivax* malaria	Direct cost of dengue	Total costs for both diseases
50 years (2055–2060)	1.1	0.2	0.05	1.1	**2.5**
100 years (2105–2110)	3.3	0.7	0.1	3.3	**7.5**

Conclusions

This study formally evaluates the impact of climate change on the incidence of malaria and dengue with the historical reported cases from 715 municipalities in Colombia from 2000 to 2005 and climate variables from 1995 to 2005. Based on a cross-sectional analysis, the study concludes that precipitation related to the incidence of malaria and temperature is significantly related to the incidence of dengue. It also found that in the period of analysis (2000–2005) there is no evidence that climate change is increasing the number of cases of both diseases.

With these results, the study calculates the additional number of malaria and dengue cases (76,641 and 228,553) that the expected climate change increase in global temperature and precipitation will produce in Colombia in 50- and 100-year scenarios, respectively. The direct and indirect unit cost of malaria and dengue cases was calculated to estimate the total costs of climate change, i.e., US$2.5 million and US$7.6 million, for 50- and 100-year scenarios, respectively. Although these figures could be considered small, it is important to highlight that they will be borne mainly by the low-income population, and that the additional cases represent an increase of 11% and 35%, for 50 and 100 years, compared to the 2000–2005 period.

Finally, the cross-sectional model can be improved by adding variables related to response measures (a municipality's expenditures for fumigation campaigns) and variables related to socioeconomic conditions (sanitary coverage; GDP of rural activities) for improving its predictability. The results of the relationship of the precipitation variable to malaria epidemics also suggest a line of research for a more accurate estimate of climate change in precipitation patterns.

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Land under Siege: Recent Variations in Sea Level through the Americas

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Introduction. We are familiar with the regular rise and fall of the sea due to tides, appreciate changes in sea level due to the weather, and occasionally observe more rapid fluctuations in sea level as a consequence of seismic events. However, there are other ongoing changes that lead to longer term variations in the level of the sea that may ultimately impact upon livelihoods, residences, communications links, biodiversity, rights to resources, and ultimately the economy. In planning for future developments, some attention to expected sea level changes would be to our advantage. It would also be beneficial to provide some indication of areas under threat of encroachment, such that assessment of needs can be established.

Aim. Throughout the last century, measurements of sea level were made at numerous ports and harbors with the objective of determining water level for navigation and survey purposes. Data sets acquired provide the level of the water at hourly intervals with respect to a point fixed on an adjacent land mass. The purpose here is to undertake an assessment of the longer term data sets and identify long-term trends in change of sea level. In order to arrive at some realistic conclusions the periodic changes due to gravitational forces of the sun and the moon, and less predictable components of weather, must be extracted.[48] Ultimately, regions that have experienced substantial increase in sea level are identified as potential risks and further assessment of impact of sea level rise is undertaken.

Among the objectives of the study are to:

- Identify causes for variation in sea level.
- Undertake an assessment of scenarios to explore the impacts of change in sea level or its range.
- Explore variability to identify whether climate change is influencing the range of sea level expected at a particular location.
- Identify characteristics that will assist policy makers, planners, and engineers in the design and implementation of developments.[49]

Limitations. There are two ways of considering sea level change. First, in an absolute sense, this would consider the land as a fixed mass and then measure the change in level at a particular location as a result of changes in Earth potential and climate. Second, relative to a land mass that adjoins the sea, in which case the effects of both change in

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[48] Similarly note that sea level measurements taken in areas where the seabed is subsiding could be construed as indicating an apparent sea level rise, and these should also be extracted.

[49] Other objectives are to: undertake analysis of data to extract known components and determine sea level rise; examine results for anomalies and characteristics to identify causes of any variation; and make recommendations to further research the results.

absolute sea level as well as vertical deformation of the land due to tectonic and local geological effects will be observed. Neither of these measures will be uniform across the Earth.

The technique adopted here uses data acquired from sea level gauges, which are typically located at sites of coastal development, such as ports. These are constructed in estuaries and other locations with easy access to the sea, most often on sedimentary deposits that are liable to deformation. In such circumstances ground movement can be very localized, and from the data alone, without further leveling work, it is not possible to confirm that the trend observed is representative of the area.

In many cases the boundary between the land and the sea exists in the proximity of an active tectonic zone. This can lead to a variation in relative sea level rise along a particular coastline.

The specifications for a modern sea level monitoring instrumentation package might incorporate a high quality GPS receiver, or such a system might be in place nearby. Over a period of years, this would enable the determination of vertical land movement in an international frame of reference. Most of the data used in this analysis were acquired prior to the advent of GPS.

This work utilizes data from sea level gauges alone, and results obtained relate to the land mass on which each sea level is fixed. The factors concerning vertical land deformation need to be given due consideration in an assessment of the results presented. Accuracy figures quoted within the results refer to computational components regarding integrity of data at the point of acquisition.

Analysis of Data from the Americas

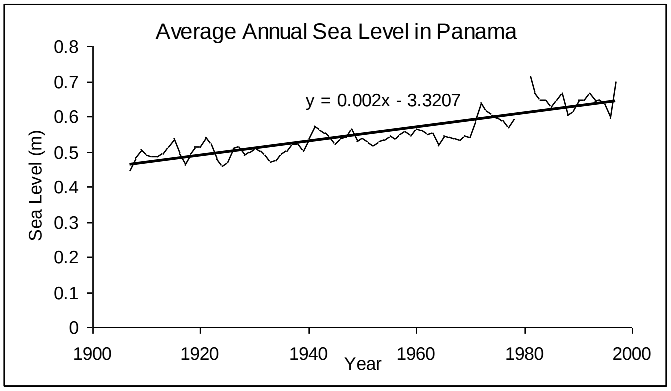
Method. It is common to extract the trend from extensive sea level data sets by simply taking average annual sea levels and plotting the result; a typical result is provided in Figure 1. There are disadvantages with this technique in that:

- Data sets are often incomplete with spaces for periods when instrumentation broke down. Therefore an annual average will be biased toward the climate under which data were acquired.
- Mean sea level is not expected to be the same each year as longer term periods exist for the moon’s perigee and nodes.

The technique is effective if the result required is to draw a straight line through points to obtain a trend, as in Figure 1. For more detailed analysis of variability it is appropriate to identify and extract known components, leaving the meteorological effects as the primary source of noise.[50]

[50] In the work that is presented here, a least squares approach is used to compute coefficients for harmonic constituents with known periods. The usual method for identification of harmonics is through Fourier analysis, but because this method is unable to cope with spaces in data sets, as often occurs in sea level records, the least squares technique is adopted. A further advantage of the use of least squares is that further

Figure 1. Average annual sea levels for Panama with trend



Sea Level Change. Records of sea level exist for numerous sites where coastal infrastructure exists throughout the world. For the purposes of this analysis, the longest records have been selected in an effort to obtain a distribution of data from across the region. Short-term records have only been used where extensive records do not exist in digital form. All data were run through the sea level analysis program. The trend is of primary concern and this has been extracted from the results together with other significant metadata for the records to give summary data available upon request from the author. The data sets used cover different periods of time, and some are more complete than others. Figures 2 and 3 show sea level rise at the locations of the data, with the longer records (indicated in black) being the most reliable. The most unreliable data, shown in yellow, are from records of less than 10 years in duration, and should be treated as an indication only. Variation through time is reported in the next section. In terms of sea level change the following characteristics are evident, and some reasoning can be suggested to explain the features.

Throughout Peru the Andes are still rising, causing a general trend for sea level to drop relative to the land mass. There is a break in this trend at San Juan and Matarina where the direction of the coastline changes, a characteristic that usually indicates some geological feature. At both the northern and southern ends of the Nazca tectonic plate a triple junction exists and a change in direction of vertical land motion is also present. Through Brazil, sea level decreases with latitude, again with the exception of Rio de Janeiro and Madeira where the direction of the coastline changes. With data from just one station available on the Northeast coast it is not possible to draw any general conclusions.

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variables can be included such as trend, which in this case gives rate of sea level rise. Given a record of sea level, a computer program that was written specifically for the task of this analysis then provides:

- Coefficients for 40 harmonic constituents. Full results for all 40 harmonic constituents for data from four sea level stations that are used within this research are provided in Annex 4.
- Datum offset, which gives the point of reference for Mean Sea Level at the reference epoch, taken as 1900 for all data sets. While most tide gauges are leveled to the vertical datum for the country, which is typically MSL, in many cases the land survey datum is inaccurate. It is often derived from short-term sea level data, and in some cases is quite arbitrary.
- Trend, which provides the rate of change of Mean Sea Level, and is the primary output for this work. For long-term data sets it provides the same result as the use of annual mean values.

Plate tectonics of the Caribbean are variable in nature around the boundary, and this is reflected in the rates of sea level change. Data are sparse, and many of the data sets are short, leading to a lack of reliability of results. Only in a few locations is sea level reducing. One station on the northern coast of Venezuela is unlikely to be representative of this coastline in its entirety. At Puerto Armuelles and Puerto Angel this characteristic is likely to exist on these short sections of the coast where changes in direction of the coastline occur. Jamaica is on a double bend in a strike slip fault and is likely to be rising. Data acquired from Point-à-Pitre were acquired immediately prior to the eruption of Montserrat, immediately north of Guadeloupe, and may be indicative of build-up of pressure within the Earth. In Belize, the data set is much too short to be conclusive. Otherwise, sea levels are rising with some notable increases. The rate in Cartagena may be representative of the lowlands north of the Cordilleras. Data from Puerto Cortés may represent a localized feature due to its proximity to a plate boundary, or more localized subsidence. The record from Fort de France is short, but may reflect the trend on that island. The volcanic islands of the eastern Caribbean are likely to act almost independently.

Figure 2. Sea level changes in Central America

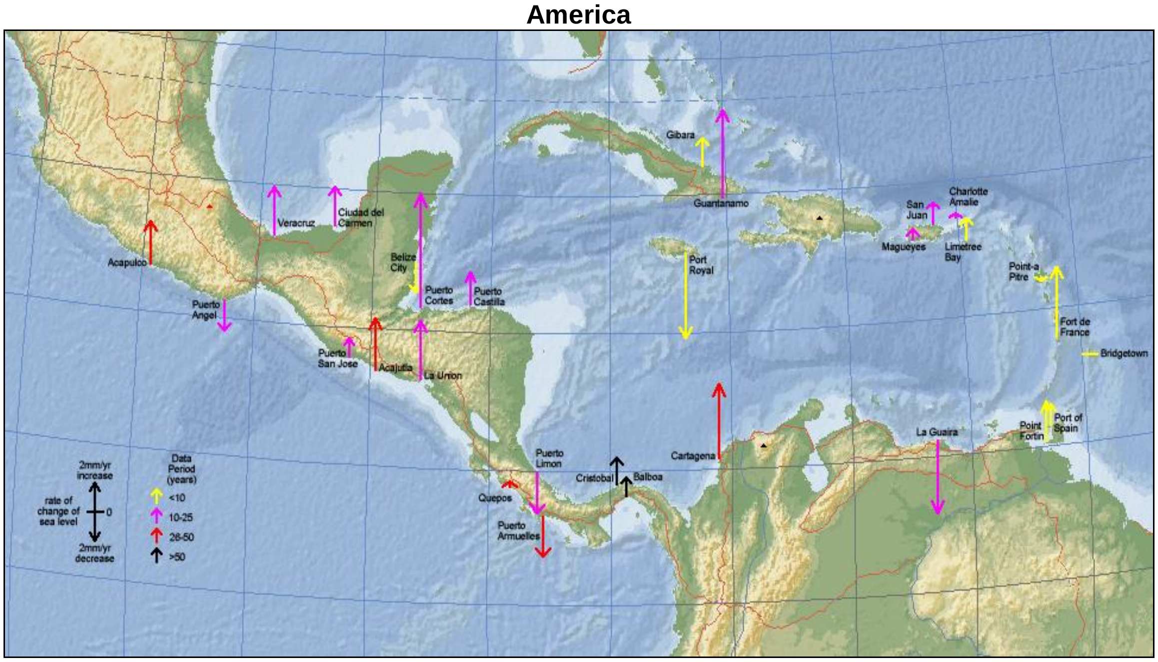
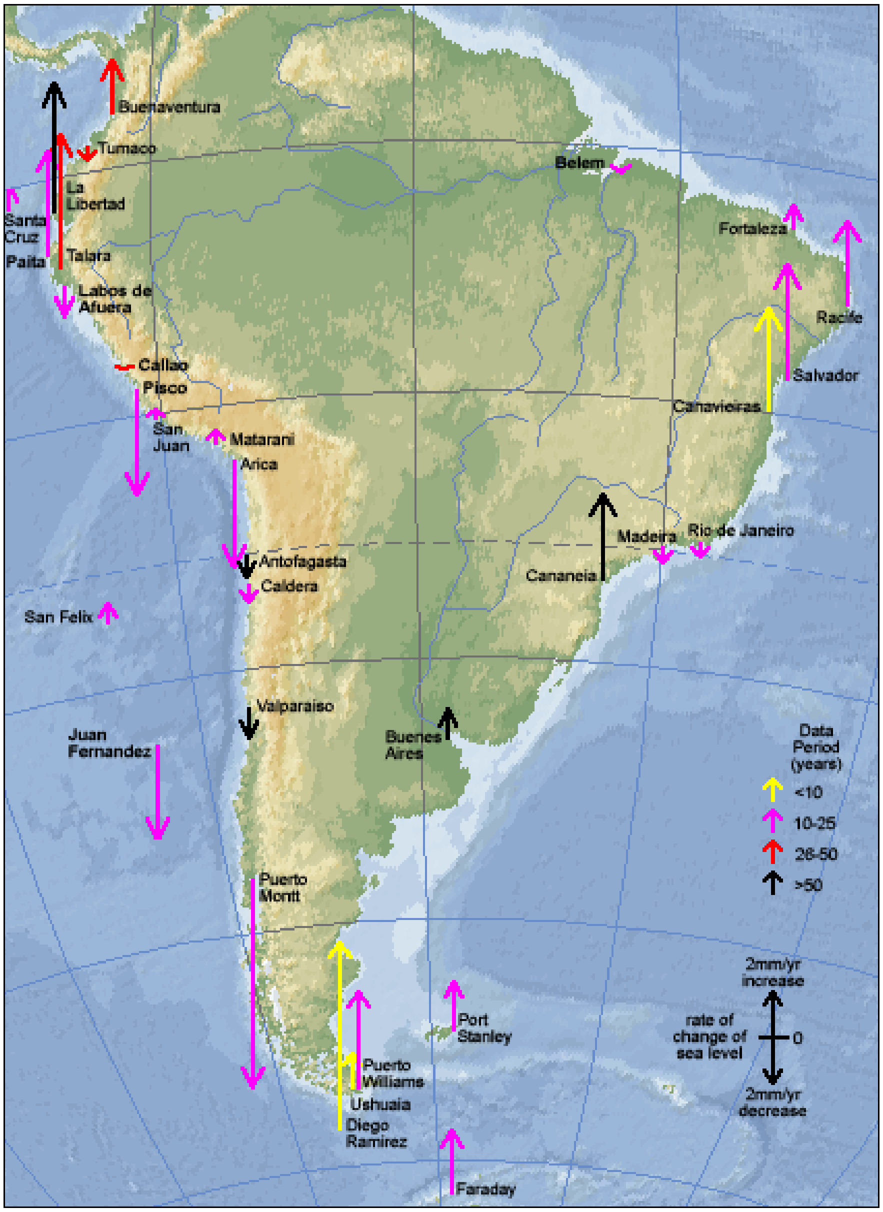


Figure 3. Sea level changes in South America



On the western coast of Mexico and the USA, the trend is for sea level to rise, but at a reduced rate at higher latitudes. The direction is reversed in Crescent City, which lies on the Juan de Fuca microplate between the Pacific and North American plates.

Review of Locations in the Americas. Figures 4 to 7 provide images of the cities in the Americas where sea level rise and population are greatest. There are common features of these locations. All are in an estuarine setting, and in most the estuaries are enlarged, suggesting that the land has been sinking into the sea for some considerable time. Each location provides a different example of the potential threat of increase in sea level.

Case Studies. These examples are taken from around the Americas, and each makes a different point about potential threat of sea level rise. They make use of data compiled within this report, satellite images provided, and some background information. No site visits or other local data relating to height information have been acquired, and they should therefore be treated as typical of impending threats and not of scenarios for the specific locations identified.

Georgetown is the capital city of Guyana, with a population of about 190,000 (1993 estimate). Part of the city is already 1.5 m below high-water mark, protected by a sea wall. With a tidal range of ±1.8 m it is just above mean sea level. Given this situation it is strange that a historical record of sea level is not readily available.

Guayaquil is Ecuador's largest city with a population of about 1.9 million (1995 estimate), and like Guyana, there is extensive agriculture in surrounding areas that provide goods for export from the port. The meandering rivers suggest low-lying land, but the city extends into the steeply sloping hills beyond the river valley. With sea level rising in this area at about 6 mm a year, and on the basis that similar thresholds of 1 m above highest observed water levels have been used in construction, then parts of the city may start to see more regular flooding in about 150 years. Given the typical scenario, the low-lying agricultural areas will be affected first, perhaps at the start of the next century.

The population of Salvador, Brazil was 2.2 million in 1996, but the city is built on steeply sloping hillside, so a rise in sea level will only impact on the immediate coastal infrastructure. Standard deviation of residuals is 1.2 m, suggesting that surges occasionally occur, and the sea level rise is 5.5 mm a year. Given that the coastal infrastructure is designed for ocean-going ships, and that the land slopes steeply to the sea, it may well be that the infrastructure along the city is some height above sea level.

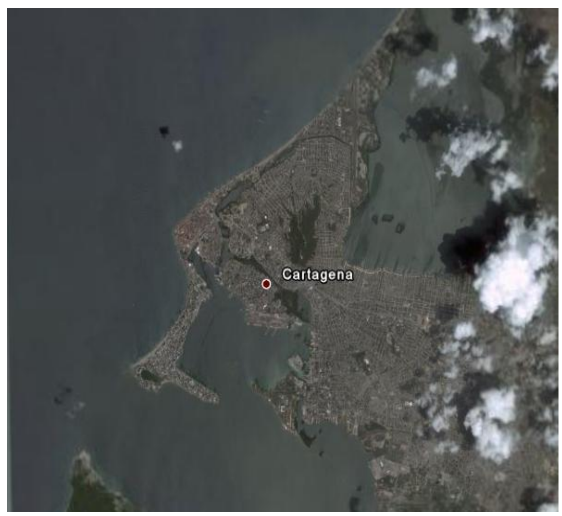
A large part of the city of Cartagena, Colombia and its population of 800,000 (1997 estimate) is close to sea level, which is made possible by the small tidal range and sheltered location. Heights of 2 to 3 m found in Port of Spain are typical of coastal developments in the Caribbean, which would place parts of the city of Cartagena under threat of regular flooding within the next two centuries. The nature of the coastline would make the use of sea defenses such as those adopted in Georgetown, Guyana impractical, and a rise in sea level to the city edge would end the extensive tourist industry.

Figure 4. Georgetown, Guyana

Figure 5. Guayaquil, Ecuador

Figure 6. Salvador, Brazil

Figure 7. Cartagena, Colombia



Conclusions and Recommendations

The general trend is toward an increase in sea level, with an increased rate toward equatorial regions. Superimposed on the trend is a more significant geologically related component. Particular locations are sinking at a much higher rate than is indicated by the general trend. Given the data sets analyzed, coastal areas of concern are: i) Guayas region in Ecuador; ii) Bahia region of Brazil; iii) Santa Catarina and Rio Grande do Sul regions of Brazil; iv) Bolívar, and possibly a much larger part of the Caribbean coastline of Colombia; and v) Baja California and Sonora in Mexico.

Georgetown, Guyana is likely to be on the list, but a lack of data means that this cannot be confirmed. Substantial records are required to determine the trend in sea level change at a particular location; results for any observations that commence immediately would not be available for the next decade, and a further decade is required for full confirmation. There will also be some areas where sea level rise is more localized, such as Puerto Cortés in Honduras; and in conjunction with sea level monitoring, land leveling work needs to be conducted to establish the extent of subsidence.

The rate of change of sea level is not constant, but varies with seismic activity and weather, which are both unpredictable. It has been suggested that the climate has changed over the last two decades, and that this will have had an impact on the rate of change of sea level. From analysis of the data available there has been no noticeable change in recent times, but the data were not acquired for scientific purposes and are not of the quality required to be able to resolve change with the necessary precision. In some areas where sea level is driven by meteorology rather than the tides, the level of the sea at any given time is highly unpredictable, and the range varies considerably. If climate change is occurring, and meteorological conditions are becoming more variable as a consequence, then this will impact on variability of sea level with particular influence on locations such as Argentina and Uruguay.

Results presented[51] give the rates of sea level change relative to a point on the land mass, so that both deformation of the land and sea level change are being quantified simultaneously. Engineering works are clearly being designed in such a way that they are above the highest level normally reached by the tide, and some additional amount is included for meteorological effects. Although it will take some considerable time to the point of inundation by the sea, flooding on a regular basis will commence much sooner. It is common to place agricultural land at the lower levels, and frequent flooding occurs in many such areas due to rainfall. However, there is a significant difference between fresh water flooding and saltwater intrusion, with the latter damaging soil fertility. The low-lying agricultural regions will suffer the first impact of sea level rise, which at the current rate will impact on production within the next 500 years. Areas of urban development, communications routes, and industry will be affected within this millennium.

[51] A list of coefficients of harmonic constituents for tide stations in Port of Spain, Balboa, Cartagena, and Port Isabel are available upon request from the author.

Annex 1: Estimated Total Annual Impacts of Climate Change on CARICOM Countries circa 2080 (in thousand US$ 2007 prices)

		Anguilla	*Antigua and Barbuda*	*Bahamas*	*Barbados*	*Belize*	*Bermuda*	*Cayman Islands*	*Dominica*
Total GDP loss due to climate change related disaster s									
of which	Tourist expenditure	3,586.2	17,429.7	97,380.1	39,437.8	10,603.5	18,277.2	26,818.9	3,116.0
	Employment loss	503.7	2,091.5	14,972.3	3,380.2	692.1	6,857.1	11,392.4	227.0
	Government loss due to hurricane	369.0	2,185.9	12,661.0	5,933.1	2,583.3	5,138.2	10,617.0	936.8
	Flood damage								
	of which Agricultural loss								
	Drought damage								
	of which Agricultural loss								
	Wind storm damage								
	of which Agricultural loss								
	Death (GDP/capita) due to increased hurricane related disaster (wind storm, flood and slides)	0.1	0.3	2.1	1.8	19.2	0.5	0.2	21.6
	Floods DALY (GDP/ capita)								
Sea level rise									
	Loss of land	4.8	20.5	467.2	20.1	1,064.6	2.5	12.1	35.0
	Loss of fish export (rising temperatures, hurricanes, and sea level)		259.0	31,966.1	305.6	4,348.4			0.4
	Loss of coral reefs (rising temperatures, hurricanes, and sea level)								
	Hotel room replacement cost	403.3	1,747.4	8,272.0	3,171.1	2,747.6	1,567.7	2,734.8	496.6
	Loss of tourist sea related tourism entertainment expenditure	245.9	2,630.5	37,668.5	3,595.9	1,600.3	2,758.4	4,047.5	470.3
	Housing replacement	500.4	3,059.4	11,970.3	9,880.9	10,875.8	2,420.9	1,683.1	2,649.0
	Electricity Infrastructure Loss		4,904.6			1,876.2			2,067.5
	Telephone line infrastructure Loss investment need		97.7	359.8	346.8	85.6		97.7	53.9
	Water connection infrastructure loss investment		47.7	199.0	169.3	169.6			44.0
	Sanitation connection infrastructure loss investment needs		87.2	359.0	296.3	153.3			66.7
	Road infrastructure loss investment needs		3,070.1		4,216.5				
	Rail infrastructure loss investment needs								

Temperature rise									
	Loss of tourist expenditure	14,031.5	78,754.3	380,042.3	177,982.8	41,425.6	2,167,927.8	107,089.1	11,639.7
General Climate changes									
Agricultural loss			3,037.4	12,469.4	12,549.3	18,708.2			3,596.9
of which	Loss of Maize production					2,381.0			
	Agricultural Export loss		84.4	3,667.9	5,773.6	9,683.4			1,221.9
Water Stress: Cost of additional water supply			173.9	226.8	0.0	618.2			50.2
Health									
	Malaria DALY (GDP/capita)								
	Other diseases costs	6.2	38.2	149.5	123.4	135.8	30.2	21.0	33.1
Total		19,651.1	119,635.4	609,165.3	261,410.7	97,707.2	2,204,980.4	164,514.0	25,504.6

Grenada	*Guyana*	*Haiti*	*Jamaica*	*Montserrat*	*St Kitts and Nevis*	*St Lucia*	*St Vincent and The Grenadines*	*Suriname*	*Trinidad and Tobago*	*Turks and Caicos Is*	*Virgin Is (UK)*	*Pre Sub Total*	*Sub Total*	*Total*
														4,939,856.8
8,102.5	65,353.5	2,923.2	74,235.2	444.4	5,524.0	16,830.3	4,940.1	2,539.6	13,450.8	15,709.0	20,292.5		446,994.3	
213.2	42.4	42.4	5,903.3	60.2	851.2	1,444.3	356.7	220.0	4,146.7	928.2	3,759.5		58,091.4	
993.6		8,005.4	22,596.7	170.3	1,334.2	1,703.3	1,022.0		2,157.5	1,249.1	1,674.9		81,331.0	
													363,196.9	
												1,712.3		
													3,750.0	
												523.2		
													2,612,175.6	
												1,902.5		
0.6	0.1	27.0	14.0	0.1	0.2	1.0	1.3	0.0	1.8	0.0	0.0		91.9	
													805.5	

15.9	9,187.5	1,286.3	505.5	4.8	16.8	28.5	18.2	7,280.9	239.4	20.1	7.1		20,237.7
	22,811.2	1,309.7	3,268.4		68.0	0.0	159.1	23,891.3	5,436.9				93,824.1
													941,627.2
458.7	389.4	937.7	13,306.8	183.5	935.6	2,119.7	1,002.3	680.6	2,869.2	1,039.6	996.9		46,060.3
1,222.8	7,981.9	441.2	13,835.6	67.1	1,003.6	2,012.3	745.6	383.3	2,030.0	2,370.8	3,062.6		88,174.0
3,957.1	27,485.5	316,388.7	97,466.2	349.0	1,770.7	6,074.5	4,377.5	16,522.8	47,888.0	795.7	861.8		566,977.3
3,384.4			13,179.3		660.3	5,442.0	1,622.4						33,136.9
84.1	283.2	359.9	879.3		64.3	131.4	57.9	208.4	831.7				3,941.6
64.4	391.0	2,928.0	1,553.5		30.3	102.0		260.5	746.8				6,706.3
113.9	577.0	2,846.7	2,338.5		50.5	162.1		465.8	1,436.2				8,953.4
			55,331.1				2,184.7	11,342.4					76,144.8
	1,081.8		1,573.5										2,655.2
36,401.2	26,217.2	274,190.4	313,968.0	1,658.9	16,744.8	76,181.7	23,575.2	88,290.8	95,252.7	16,526.0	79,451.6		4,027,351.5
2,557.0	17,365.2	77,773.6	46,507.4		959.2	3,916.7	2,957.5	11,483.9	6,634.3				220,515.9
	298.0											2,679.0	
	15,173.0	1,594.5	21,276.2		850.5	2,769.5	1,619.6	1,439.2	9,257.6			74,411.3	
125.0	2,951.2	91,921.6	4,309.1		0.0	76.7		834.9	2,722.1				104,009.7
													2.6
49.4	343.2	3,950.2	1,216.9	4.4	22.1	75.8	54.7	206.3	597.9	9.9	10.8		7,078.9
57,743.9	182,461.4	785,332.2	671,988.2	2,942.6	30,035.8	116,302.4	43,074.9	164,611.6	186,442.1	38,648.3	110,117.6	**Grand total**	**11,187,254.4**
												% of GDP	11.3%

Annex 2. Economic Impact Assessment of Coral Reef Losses

Coastal protection. To analyze the economic contribution of shoreline protection services, Burke et al (2004) estimated the extent of the Caribbean region's shoreline protected by coral reefs, the value of the shoreline protection services provided by these reefs (based on costs required to replace them by artificial means), and potential losses in the annual benefits of shoreline protection services due to reef degradation. Using data on shoreline and coral reef location, and identifying coastline within 2 km of a mapped coral reef as "protected" by the reef, Burke et al (2004) estimated that coral reefs protect about 21% of the Caribbean coastline (about 18,000 km in length). To estimate the economic value of the shoreline protection services provided along these coastlines, Burke et al (2004) relied on earlier estimates of past expenditures for artificial replacement of this protection. These estimates ranged from about US$50,000 to US$800,000 or more for each kilometer of coastline protected by coral reefs. The value of the coastal protection service varies with the level of development along the shoreline, population density, and presence of a tourism industry. Values used by Burke et al. (2004) ranged from US$2,000 to US$1,000,000 per kilometer of coastline protected by coral reef, as follows:

- For low development areas (fewer than 100 people within a 5-km radius) values range from US$2,000 to US$20,000 per kilometer of coastline.
- For medium development areas (100 to 600 people within a 5-km radius or located within 5 km of a dive center) values range from $30,000 to $60,000 per kilometer of coastline.
- For high development areas (more than 600 people within a 5-km radius) values range from US$100,000 to US$1,000,000 per kilometer of shoreline

About 29% of shoreline in the region "protected by" coral reef was in low development areas, 27% in medium development areas, and 44% in high development areas. Burke et al. (2004) combined these coastline development classifications with the values (ranges) to estimate the value of coastal protection service provided by healthy coral reefs.

Because only a few shoreline segments are highly developed, Burke et al. established ranges: a low level indicating 100% of shoreline is at low end of value range and a high level indicating that 75% are at the low and 25% at the high end of the range arriving at a total value of US$ 750M to US$ 2.2 Billion. These total values in US$ 2000 prices were adjusted to US$ 2008 prices and the table shows 50% and 90% of these values as lost economic contribution of shoreline protection services provided by Caribbean coral reefs.

Tourism. Burke et al (2004) used a "financial revenue" approach and focused on the gross revenue and net benefits associated with dive tourism. The estimated numbers of divers in the region and associated gross revenue is based on integration and cross tabulation of several data sources (Burke et al. 2004). Burke et al. (2004) estimated net benefits to the local economy by adjusting these estimated gross expenditures for costs such as transportation, fuel, boat expenses, etc. (assumed to be 65**%** of total expenditure) and then accounting for a multiplier effect due to expenditures rippling through the local economy (assumed to be 25%). The lowest value of the range was derived from Cesar et al (2003), which adjusted data from Reefs at Risk in Southeast Asia (Burke et al 2002) for Caribeean. Unfortunately, information on the methodology and data is somewhat unclear. As in the estimates on coastal protection, these values in Burke et al. (2004) and Cesar et al (2003) were adjusted to US$ 2008 prices and the table 2 presents 50% and 90% of these values as lost economic contribution of tourism and recreation provided by Caribbean coral reefs.

Fisheries. In estimating economic value of fisheries associated with both healthy and degraded coral reefs, the highest estimate in the range was obtained from Cesar et al (2003), which adjusted data from Reefs at Risk in Southeast Asia for Cribeean (Buke et al. 2002) but again how these data and methodologies are adjusted are a little unclear. The economic value of fisheries was derived from Burke et al. (2004), using an "effect on production" approach. Fishery productivity on Caribbean coral reefs ranged between 0.5 and 5.0 mt/km2/yr. Degraded coral reefs produced much less, averaging between 17% and 44% of the productivity of healthy reefs. Burke et al. (2004) used the following productivity coefficients:

- For coral reefs classified as healthy and/or as being under low threat, productivity of 4 mt/km2/yr was used.
- For reefs under medium threat, productivity was assumed to decline to between 2.3 mt and 2.9 mt/km2/yr.
- For reefs classified as under high threat, productivity of 0.7 and 1.7 mt/km2/yr was used.

For estimating fisheries revenue, Burke et al (2004) used the market prices for reef-related fish of about $6/kilogram (kg) for all calculations of gross revenue. Although decline in productivity (and associated harvest) could reduce supply and serve to increase price, overfishing of reefs will also result in catches of smaller and less valuable fish, and offset price increases. Costs incurred by fishing activities vary widely and range between 20% and 90%. Thus Burke et al. (2004) chose 50% net return of gross revenues as an average for the region. The resulted net revenues from fisheries associated with coral reefs in Burke et al. (2004) and Cesar et al. (2003) were adjusted to US$ 2008 prices and the table 2 presents 50% and 90% of these values as lost economic contribution of net revenue of fisheries associated with Caribbean coral reefs.

Pharmaceutical uses. Ruitenbeek and Cartier (2001) estimate the value of pharmaceutical use to be US$ 215,000/acre (in 1998 prices) for coral reefs in the Bahamas. This value is extrapolated to the coral reef areas of the Caribbean (26,000km), and adjusted to US$ 2008 prices. Table 2 presents 50% and 90% of these values as lost economic contribution of net revenue of fisheries associated with Caribbean coral reefs.

Annex 3. Statistical results of regression model for malaria from *P. falciparum*, *P. vivax,* and dengue

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.543[a]	.295	.284	.02605

a. Predictors: (Constant), unsatisfied necessities index, eleven years average annual precipitation, eleven year avg mean monthly temperature

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.053	3	.018	25.842	.000[a]
	Residual	.126	185	.001		
	Total	.178	188			

a. Predictors: (Constant), unsatisfied necessities index, eleven years average annual precipitation, eleven year avg mean monthly temperature

b. Dependent Variable: annual falciparum parasitic incidence average

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3.25E-02	.010		-3.098	.002
	eleven year avg mean monthly temperature	4.989E-04	.000	.078	1.240	.217
	eleven years average annual precipitation	1.103E-05	.000	.510	8.100	.000
	unsatisfied necessities index	1.170E-04	.000	.071	1.120	.264

a. Dependent Variable: annual falciparum parasitic incidence average

For *P. falciparum* malaria, although the percentage of prediction of the model is low (Adjusted R square 0.28), the overall significance of the model is high (significance of F statistic of less than 0.000), indicating that even though the model cannot accurately predict the levels of the rate of incidence in the municipalities, it significantly explains some of its variance. The analysis of the variables included in the model shows that the precipitation is significant in the model (significance of t statistic of less than 0.000) but the variables other than the constant variable are not significant. In conclusion, the cross-sectional analysis for *P. falciparum* malaria results in a significant relationship between the rate of incidence of the disease and the level of annual precipitation. The sign of the coefficient associated with the precipitation confirms that an increase in the level of rainfall will generate an increase in the rate of incidence in the municipalities.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.255[a]	.065	.054	.05178

a. Predictors: (Constant), eleven year avg mean monthly temperature, eleven years average annual precipitation, unsatisfied necessities index

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.047	3	.016	5.855	.001[a]
	Residual	.678	253	.003		
	Total	.725	256			

a. Predictors: (Constant), eleven year avg mean monthly temperature, eleven years average annual precipitation, unsatisfied necessities index

b. Dependent Variable: annual vivax parasitic incidence average

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-3.36E-02	.017		-1.951	.052
	eleven years average annual precipitation	8.271E-06	.000	.208	3.381	.001
	unsatisfied necessities index	1.915E-04	.000	.067	1.072	.285
	eleven year avg mean monthly temperature	8.931E-04	.001	.082	1.318	.189

a. Dependent Variable: annual vivax parasitic incidence average

A similar result is found for *P. vivax* malaria, confirming the consistency of the relationship between climate variables and the vector. The overall prediction of the model is very low (adjusted R squared of 5%), but the model is significant (significance of F statistic of 0.001) to explain some variation in the dependent variable. The annual precipitation is the only independent variable with a significant coefficient (significance of t statistic of 0.001). The sign of the coefficient indicates that an increase in annual precipitation will increase the rate of incidence of *P. vivax* malaria.

We can conclude from both results that the climate variable which is significantly related to malaria epidemics is annual precipitation, reflecting the importance of natural breeding habitats in the incidence of the disease. On the other hand, the other variables of temperature and NBI are found to be insignificant.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.272[a]	.074	.063	.01271

a. Predictors: (Constant), unsatisfied necessities index, eleven years average annual precipitation, eleven year avg mean monthly temperature

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.003	3	.001	6.886	.000[a]
	Residual	.042	258	.000		
	Total	.045	261			

a. Predictors: (Constant), unsatisfied necessities index, eleven years average annual precipitation, eleven year avg mean monthly temperature

b. Dependent Variable: dengue morbility rate

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.42E-03	.004		-.332	.740
	eleven year avg mean monthly temperature	7.345E-04	.000	.267	4.270	.000
	eleven years average annual precipitation	-3.44E-07	.000	-.033	-.548	.584
	unsatisfied necessities index	-1.19E-04	.000	-.162	-2.593	.010

a. Dependent Variable: dengue morbility rate

The results of the cross-sectional model for dengue are different than those for malaria. The model has also a low level of prediction but overall it is significant for explaining some of the variation. The temperature variable is significant for dengue while the precipitation variable is not. On the other hand, the NBI variable is found to be significant but with the sign opposite to that expected. The sign of the NBI variable can be explained by the fact that dengue epidemics are found in urban populations, and the municipalities with larger populations in rural areas typically have higher levels of poverty (NBI).

In conclusion, the results of the cross-sectional model for dengue indicate a significant relationship between the municipality’s temperature and the rate of incidence of dengue, which imply that an increase in temperature will produce an increase in the incidence of dengue in the municipalities.

Finally, the low model predictability of all the cross-sectional models can be explained by the fact that the models do not incorporate variables to address the response measures of the municipality and/or the community. Response measures include vector fumigation, water management best practices, and mosquito nets.

Annex 4. Causes of Variation in Sea Level

Known Periodic Constituents. The dominant changes in sea level are caused by the gravitational attraction of the sun and the moon on the water mass. As the Earth rotates about its own axis and orbits the sun while the moon orbits the Earth, these forces vary periodically with time. The periods are well understood, but the amplitudes and variations in phase of each force will change with location and geographical constraints of the land mass surrounding the body of water. It is normal to model the vertical change in water level at a particular location using harmonic analysis, whereby the variables of amplitude and phase are determined for known periods at a particular location.

While the Earth rotates about its axis on a daily basis, the resulting dominant period is two tides a day, a semi-diurnal regime. The dominant gravitational force is due to the moon, which returns to the same longitude with respect to the Earth in a period of 24 hours and 50 minutes, so the component with the largest amplitude will typically have a period of half of this. A component with the full period, known as a diurnal constituent, will also exist due to changes in the moon's declination and parallax. Similarly for the sun, semi-diurnal and diurnal constituents will exist with periods of 12 and 24 hours, respectively.[52]

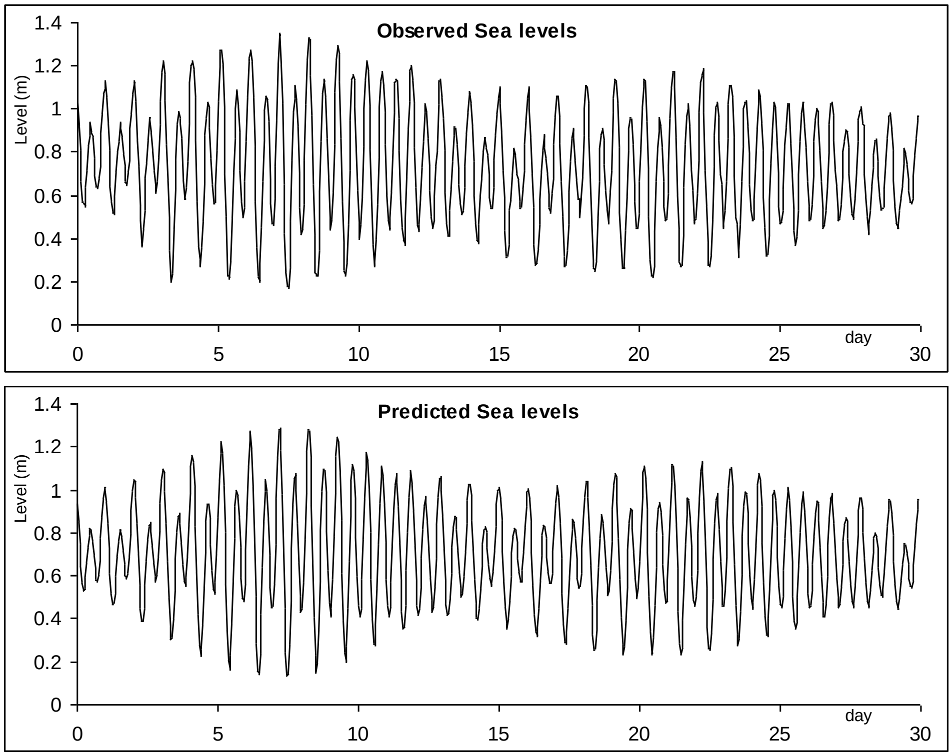
[52] Further variations in the amplitude and direction of the gravitational forces arise due to orientation of the Earth with respect to the sun and the moon as rotations and orbits do not exist in the same plane; the orbits are also elliptical. The harmonics that result can all be described in terms of five fundamental periods with the following speeds:

- Mean rate of rotation of the Earth, at 15º per mean solar hour (*S*), with a period of 24 mean solar hours, a mean solar day;
- Rate of rotation of the mean moon about the Earth, at 0.5490º per mean solar hour (*s*), with a period of 27.32 days, a tropical month;
- Rate of orbit of the Earth about a mean sun, at 0.0411º per mean solar hour (*h*), with a period of 365.24 days, a tropical year;
- Rate at which the moon's elliptical orbit rotates about the Earth, at 0.0046º per mean solar hour (*p*), with a period of 8.85 years;
- Rate at which the moon's mean ascending node orbits the Earth, at -0.0022º per mean solar hour (*N*), with a period of 18.61 years.

The fundamental rate is that of Earth rotation, and the other rates are superimposed on this to give further constituents. Coefficients of phase and amplitude for 40 harmonic constituents that are considered to be the most significant are given in the Appendix, with *S, s, h, p,* and *N* representing the five speeds above, respectively. Five of the constituents are independent of *S*.

Amplitudes (*h*) and phases (*g*) for each constituent, computed from 8 years of data acquired in Port of Spain, Trinidad, are also given in Appendix A, and over a period of 30 days (about 1 synodic month) give the tide curve provided in Figure 1, where it is compared with the predicted equivalent. The characteristics show a semi-diurnal tide with two high and two low waters a day, as well as a 29.5 day period of 2 spring and 2 neap tides.

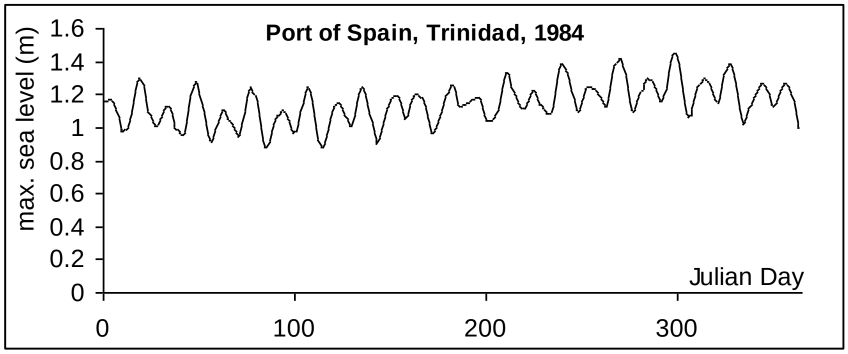
Figure A4.1. Observed and predicted sea levels for 30 days in Port of Spain



Differences in the diagrams in Figure A3.1 exist, and can be seen on close inspection. The computed values for the harmonics have identified coefficients from a long data set on which other, more random fluctuations exist, primarily due to meteorological influences. A longer data set is therefore required to average between this noise.

Expanding the time scale for Figure A3.1 to show the maximum amplitude in each tidal cycle of 24 hours and 50 minutes gives Figure A3.2. Here an annual component is clearly visible, and while there will be a variation with this period due to the Earth's orbit about the sun, this is unlikely to be so large. In using data to compute values, other regular periods will also be incorporated; in this case the climate, which also has an annual period. The corresponding constituent, labeled *Sa* in the Appendix, is variable in amplitude between locations, but similar in phase. This is likely to be due to fresh water input as well as other climatic factors. Fresh water increases sea level locally, particularly if the port, and hence sea level gauge, is located in a river or estuary.

Figure A4.2. Predicted maximum sea level on each tidal cycle over a synodic month



The tidal range is the difference between high and low waters on a high spring tide, and this will vary considerably between different locations. The primary factor is the ability of the basin in which the gauge is located to support a wave of a particular period. The highest tides in the world exist in the Bay of Fundy in Canada where resonance within the Bay and the Gulf of Maine combine with tidal characteristics of the Atlantic Ocean to give a range of 13.46 m to the semi-diurnal component. In other instances the semi-diurnal component might be damped, leading to a diurnal tide. The form factor (*F*) compares the sum of amplitudes of primary diurnal constituents (*K1* and *O1*) with that of the semi-diurnal (*M2* and *S2*) to classify tidal regimes into four categories:

- Semi-diurnal $0 \leq F < 0.25$;
- Mixed mainly semi-diurnal $0.25 \leq F < 1.5$;
- Mixed mainly diurnal $1.5 \leq F < 3$;
- Diurnal $3 \leq F$.

Using the data from ports in the region, as examples the following characteristics are seen:

- Port of Spain–the primary semi-diurnal components (*h* of *M2* and *S2*) dominate, so the tide will be diurnal. However, the diurnal components (*h* of *K1* and *O1*) are not insignificant. This is what is seen in Figure A3.1, two tides daily with one being of lesser amplitude than the other. With a value for *F* of 0.42, the tidal regime is mixed mainly semi-diurnal.
- Balboa–the semidiurnal components are significantly larger than the diurnal, so there will be two tides daily of similar magnitude, and with *F* of 0.07, the regime is semi-diurnal. The values of *M2* and *S2* are much larger than those for Port of Spain, so the tidal range will be much greater than in Port of Spain.
- Cartagena–the semi-diurnal and diurnal constituents are of similar magnitude, so there will be two tides daily, but one about half of the amplitude of the other. *F* is 1.72, so the regime is mixed mainly diurnal.
- Port Isabel is dominantly diurnal with *K1* and *O1* dominating *M2* and *K2*, the value for *F* is 3.26, so there will be one primary tide in each cycle and the second will be much smaller in amplitude.

From these examples, it is shown that the range of amplitudes and tidal regimes is variable throughout Central America.

Climate and Meteorology. While regular climatic variations are averaged and incorporated within coefficients computed for harmonic constituents, the immediate meteorological conditions have a direct impact on sea level in four primary components:

- Rain–depends on the location of the observing site with respect to major rivers entering the port, the watershed for these rivers, and the geographical location of the sea level gauge within the basin or estuary.
- Pressure–under static or slowly changing conditions, pressure will change sea level by about 0.05m for every 5 mbar change in atmospheric pressure.
- Wind is more complex than pressure because this depends on the fetch of the sea, on the duration of the sustained wind, and on water depth.
- Temperature of the water–as water temperature increases it expands, and the increase in volume will have an effect on sea level.

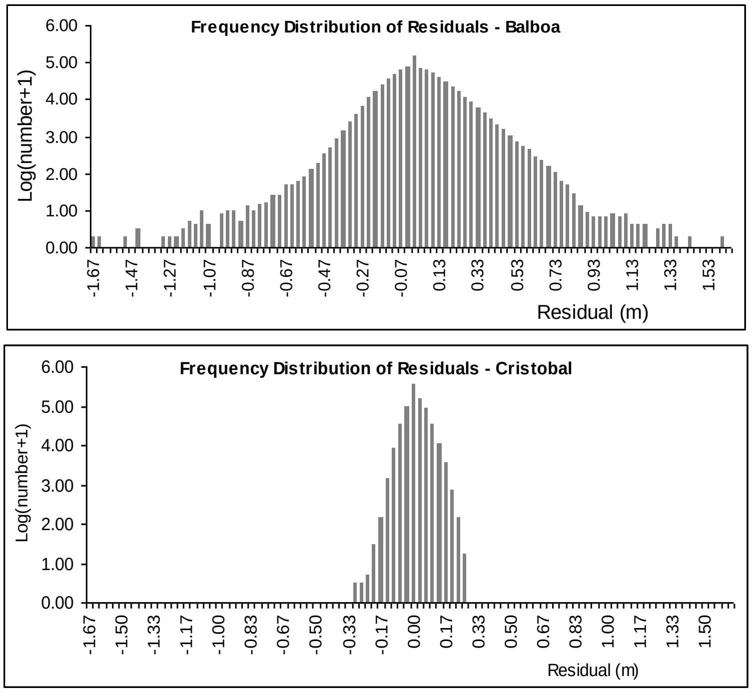
Under highly dynamic conditions of pressure and wind fluctuations, sea level can respond respectively, and by substantial amounts, to provide a significant difference from expected sea levels under tidal influence. When this difference is greater than 0.6 m, then a surge is deemed to occur.

When analyzing sea level records it is useful to compare expected with actual values and examine the residual. The expected values are derived from coefficients provided by harmonic analysis of an extensive sea level record, and the residual is an indication of variation due to meteorological conditions. Sea level at different locations will respond differently to meteorological effects.

Residuals for data from two tide gauges located at opposite ends of the Panama Canal, both providing 90 years of data, are shown in Figure A3.3. The count in each band is plotted on a logarithmic scale so that the surges observed on rare occasions at Balboa are shown at the extremities of the histogram. Locations with a greater tidal range are more responsive to changes in meteorological conditions, as is the case here. Furthermore, Balboa is on the Pacific coast, while Cristobal is located in the comparative calm of the Caribbean Sea. Neither of the distributions is normal but shows an asymmetry about the mean.

Mean sea level, which is a reference used by most land survey work, must be computed over an extensive period of time to average tidal and meteorological influences.

Figure A4.3. Histograms of residuals at Balboa and Cristobal



Fluvial Discharge. A port is typically located in an estuarine setting in shelter from the elements. Most sea level gauges are located in ports where they provide data in support of survey work, and more recently real-time information to pilots for navigational purposes. In addition to observing sea level, the gauge also records the height of water in the river, and this often changes seasonally. Distributions of residuals shown in Figure A3.3 are not normal due to bias in some meteorological factors. In an estuarine location, discharge from a river can only increase the level of water above sea level. Rainfall cannot be negative, and residuals clearly have a positive bias. To the left-hand side of the zero line, the distribution better reflects the standard form of a normal distribution, with the effect of surges shown to the extreme left-hand side in the harsher environment at Balboa. The right-hand side of the distribution shows an increase in frequency due to rainfall within the watershed, with influences of storm surges to the extreme right.

If the sea level gauge were to be located in a setting with little fresh water input, the distribution would be expected to be closer to a normal distribution, reflecting the more random nature of many meteorological conditions. Although wind has a prevailing condition, some bias will still exist.

Change in Mean Sea Level. The following characteristics of the Earth, including the atmosphere and human use, are considered to be the primary factors that lead to change in mean sea level:

1.Global Warming

Glacial rebound	The Earth is still responding to the loading that was imposed during the last ice age.

Melting of polar ice	As a consequence of redistribution of the mass of water that is locked up in polar ice, gravitational force at the poles will be reduced, and the poles will therefore attract less of the water mass. Sea level will then reduce in the higher latitudes and increase in equatorial regions.
Thermal expansion	As sea temperatures increase the water expands, increasing the volume of water.
2. Earth's Core	
Movement of magma	The Earth's mantle is dynamic and not uniform in density. Movement therefore changes the gravitational force acting on the water in the seas, varying the level. This can also generate localized effects as magma moves through fissures in the Earth's crust.
Redistribution of magma	The magma will respond equally to changes in density on the surface of the Earth, so as polar ice melts the magma will be redistributed away from polar regions.
3. Earth's Crust	
Tectonic activity	Movement of the Earth's crust causes change in the density of the surface, and allows interaction with the Earth's core. It further changes the shape of the space in which the sea is contained, and therefore has an impact on sea levels in a relative sense with respect to an adjoining land mass.
Local land deformation	Sedimentary deposits that are formed on the Earth's crust are susceptible to more local effects of slippage and compaction that again give rise to relative change in sea level in coastal regions.
4. Anthropogenic	
Mineral extraction	Removal of minerals such as oil, water, coal, and salt, which form in sedimentary deposits, can lead to local land deformation as internal pressure is reduced. It will also change local gravity characteristics.

Given that the data available are from sea level gauges alone, it is not possible to individually discern contributing components, but an appreciation of the overall trend and variability is sufficient information to support planning for development work. To isolate the long-term trend, the tidal and meteorological perturbations need to be removed.

Annex 5. Variability in Sea Level Change

Variability in Sea Level Change. Changes in the rate of sea level change will occur due to variations in the climate and seismic activity. With the datum offset and periodic components available from analysis of the full data set, these have been removed from the sea level record and rate of change of the result evaluated in a three-year widow. So, a rate is available for each year, which has been computed using data for a period of three consecutive years. This has been carried out for stations that have a record of at least 25 years, with the exception of Puerto Montt, which is slightly less. Results of some of the longer records that represent the region are provided in Figures A4.7 and A4.8.

Figure A5.1. Sea level change over three-year intervals (selected sites in South America)

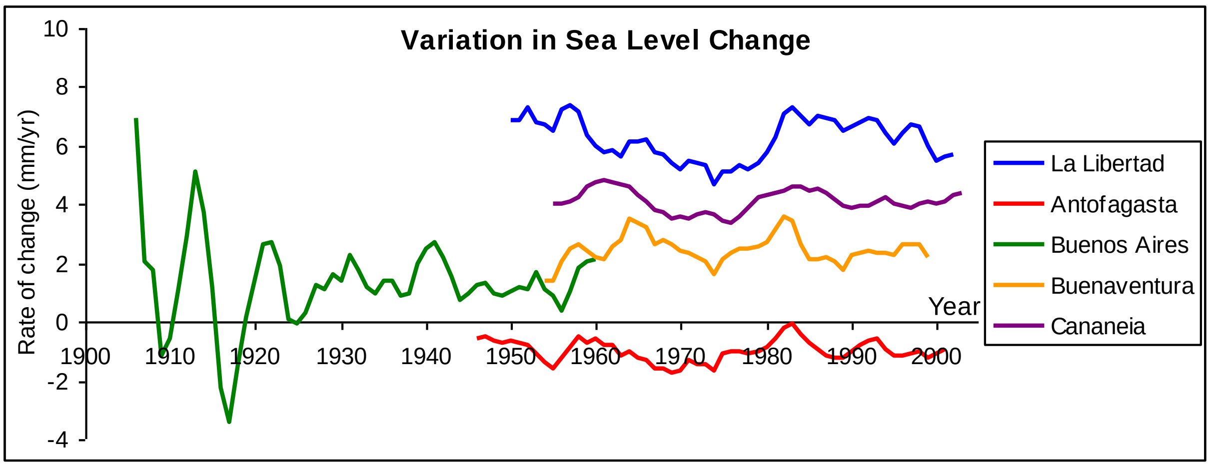
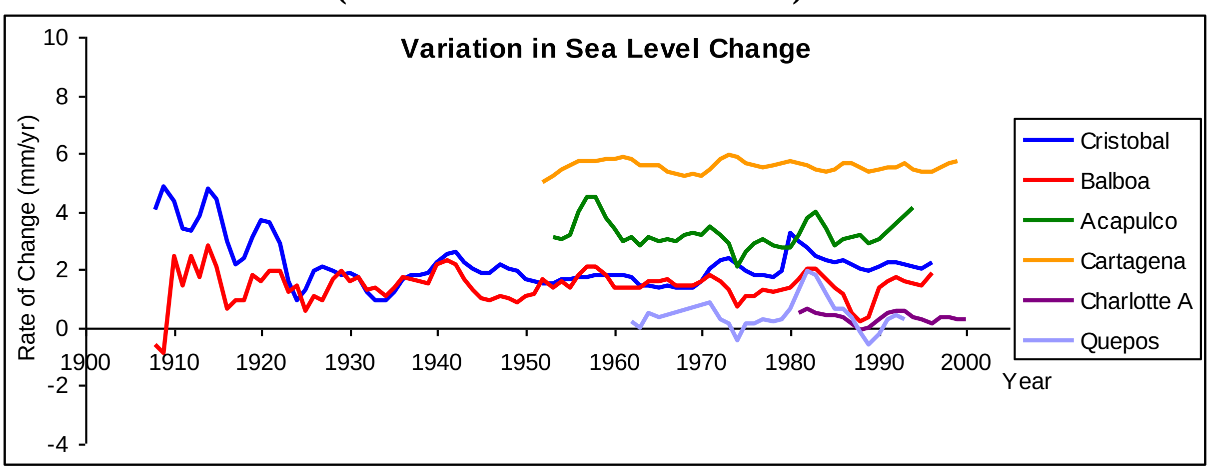


Figure A5.2. Sea level change over three-year intervals (selected sites in Central America)



The following figures illustrate variability in sea level change for locations where data in excess of 25 years are available.

Figure A5.3. Sea level change over three-year intervals (West Colombia and Ecuador)

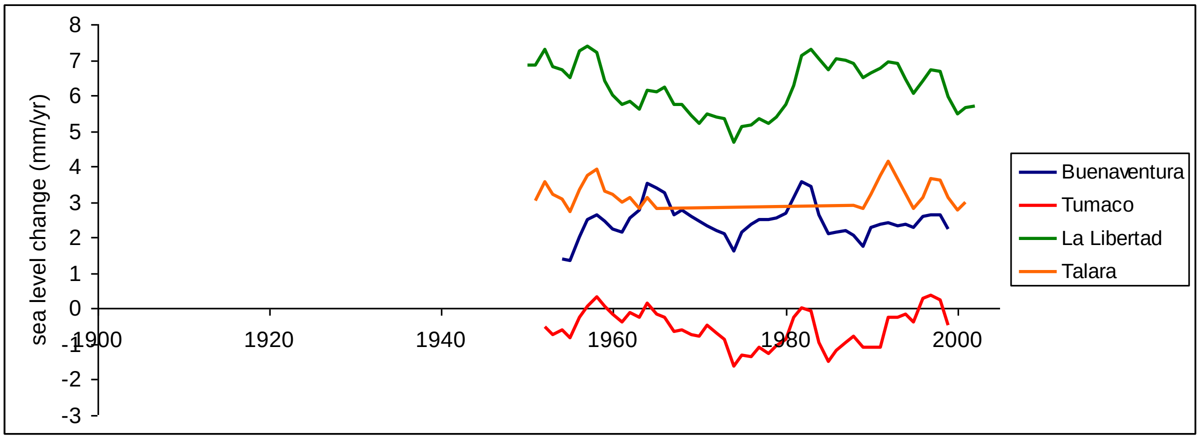


Figure A5.4. Sea level change over three-year intervals (Peru and Chile)

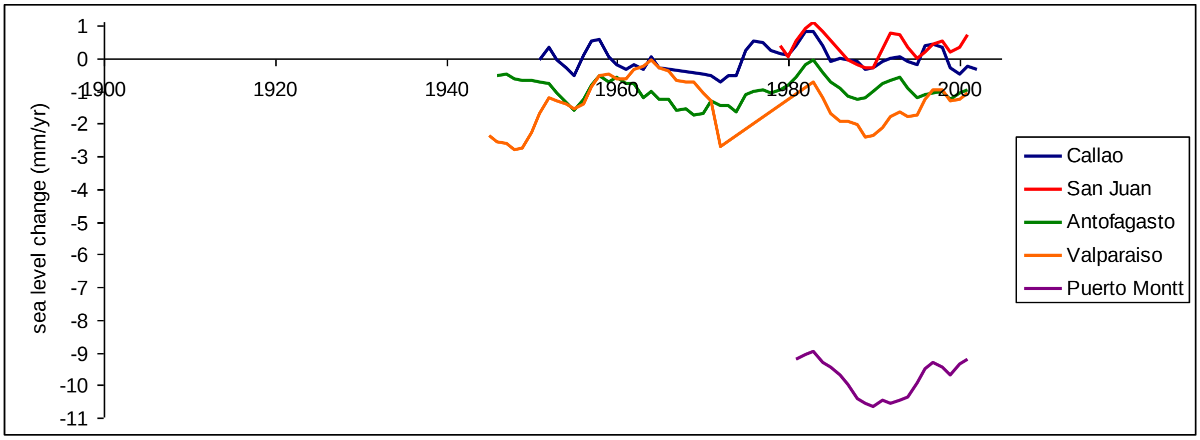


Figure A5.5. Sea level change over three-year intervals (Argentina and Brazil)

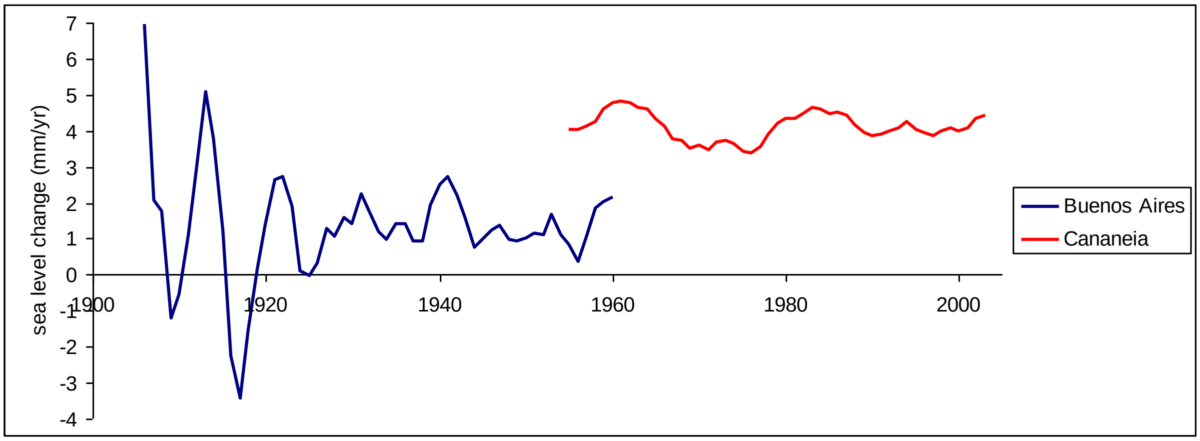


Figure A5.6. Sea level change over three-year intervals (El Salvador and St. Thomas)

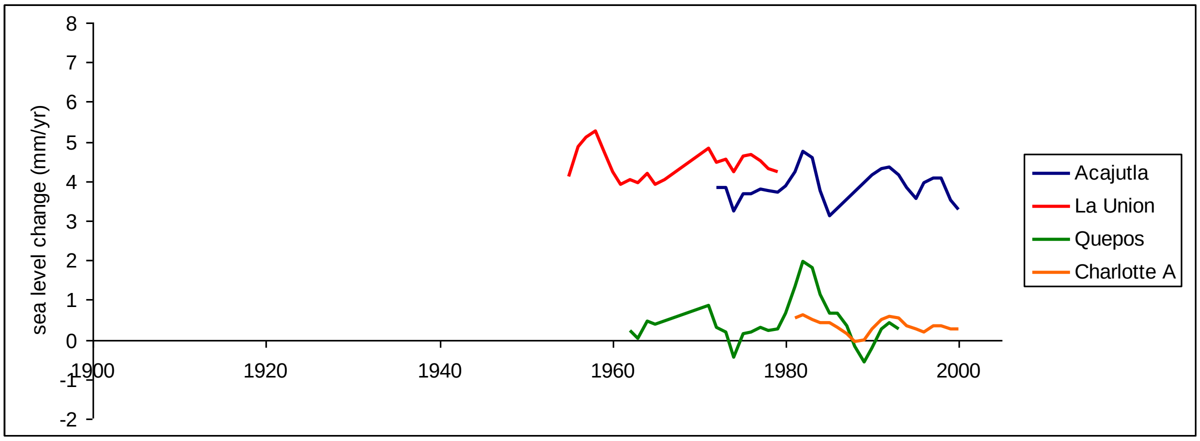


Figure A5.7. Sea level change over three-year intervals (Panama and Northern Colombia)

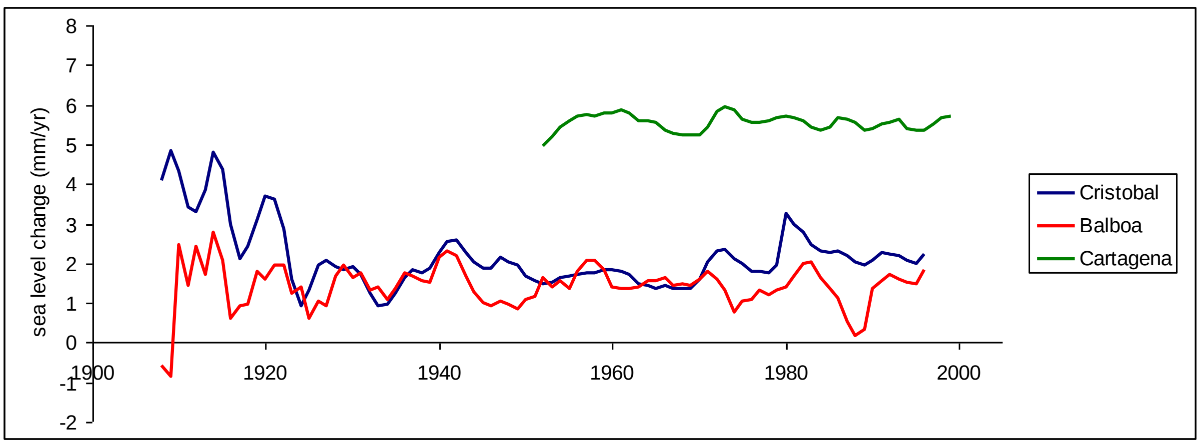
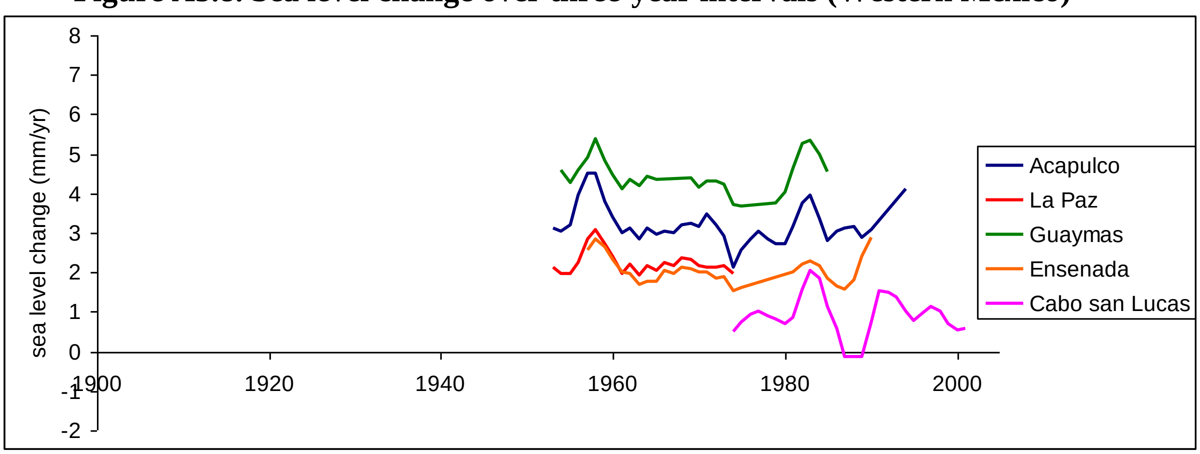


Figure A5.8. Sea level change over three-year intervals (Western Mexico)



Annex 6. Seismic and Meteorological Influences on Sea Level

Seismic Influences on Sea Level. A striking feature within these records occurs in the first quarter of the twentieth century starting with an increase in the rate of change of sea level in San Francisco to over 9 mm/yr in 1904 and maintaining similar levels in 1905 and 1906 before plummeting to -0.7 mm/yr in 1909. The seismic event of magnitude 8.2 that occurred on April 18, 1906 is reported to have moved the ground some feet horizontally, but it may have also produced a significant vertical impact. Stress that built up over three years prior to the event caused an increase in sea level rise that reduced on release, and shows oscillation for the next two decades.

The seismic event in San Francisco was not a lone incident, and other sea level records of the time show similar characteristics. Of the 14 events of magnitude 8 or more that occurred in North and Central America during the twentieth century, 10 were within the first decade. In order of occurrence these were:

- 1900 offshore Venezuela (8.4) and Durango, Mexico (8.3);
- 1902 Chiapas, Mexico (8.4) and Guatemala (8.3);
- 1903 offshore southern Mexico (8.3);
- 1904 southern coast of Panama and Costa Rica border (8.3);
- 1906 offshore Ecuador (8.9) and San Francisco (8.2);
- 1907 Guerrero, southern Mexico (8.3);
- 1907 Guerrero, southern Mexico (8.1).

There was one event of magnitude 8.3 on the west coast of South America in 1906, while others are distributed throughout the remaining 90 years of the twentieth century. Circumstantial evidence for a relationship between seismic activity and sea level rise exists within the data sets, but without further correlation of variables and assessment of climate for the period it is not conclusive. There are anomalies at Galveston and Buenos Aires, which appear to respond to events over a considerable distance, and while this is plausible, the influence of meteorology on sea levels at Buenos Aires that is investigated below suggests that climate is an alternative explanation.

Meteorological Influences on Sea Level. Residuals of sea level are evaluated to obtain an appreciation for the amount that sea level deviates from expected values. These are placed in the context of tidal range, which was suggested as being significant. Standard deviations are calculated using the root of the mean sum square error, but it must be remembered that the distribution is not normal, so this cannot be considered as a 68% confidence limit. Nevertheless, it is a still a useful way to consider the spread.

Table A6.1. Bounds of sea levels and standard deviations of residuals

Location		Sea level Range (m)		Residual
UHSLC	Place	Expected	Observed	s.d. (m)
91	La Libertad	2.795	3.437	0.096
80	Antofagasta	1.591	1.963	0.063
81	Valparaiso	1.866	2.29	0.08
285	Buenos Aires	1.509	8.07	0.472
281	Cananeia	1.835	4.74	0.211
266	Panama	0.627	0.97	0.051
302	Balboa	6.383	6.917	0.099
316	Acapulco	1.138	2.194	0.086
265	Cartagena	1.24	1.46	0.049

Results presented in Table A5.1 give the range in sea level over the period for which data are available. Rather than use analytical methods for the 40 constituents included, sea levels have been calculated at 6-minute intervals and the expected range is then the difference between maximum and minimum values. Observed ranges are differences between the maximum and minimum values within the data sets from the hourly observations.

Although Balboa has the greatest tidal range, Buenos Aires has the largest observed range and spread in residuals. A plot of observed and expected sea levels at Buenos Aries over 500 hours at some time in 1950 is provided in Figure A5.1, and the frequency distribution of residuals for the entire data set in Figure A5.2. Residual values show that the surges seen in Figure A5.1 are characteristic of the entire data set, and that sea level in Buenos Aries is highly unpredictable due to meteorological effects, which will include fluvial discharge from the watershed of the river on which the sea level gauge is located.

Figure A6.1. Observed and expected sea levels in Buenos Aires

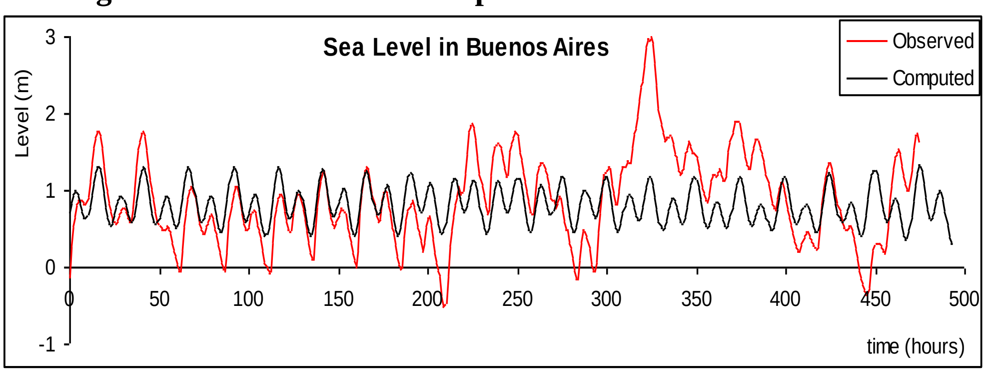
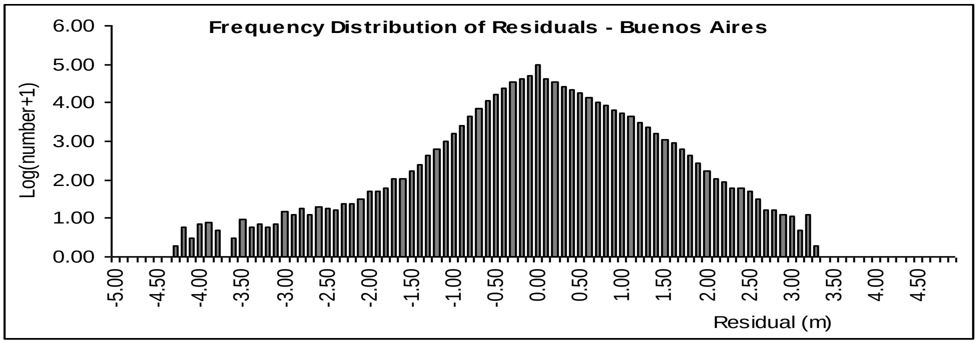


Figure A6.2. Frequency distribution of residuals in Buenos Aires



In an attempt to assess any change that may have occurred in variability of the climate during the last century, residuals are evaluated for the long data sets only, with the standard deviation being computed for each decade. Results are provided in Figures A5.3 and A5.4, which are not plotted to the same scale.

These results show that:

- Meteorological effects in Buenos Aires, which are likely to be caused by both fluvial discharge and surges due to storms, extend throughout the period of observations and are consistent throughout the duration.
- Surges and variation in water level in the river on which the port lies are also a characteristic of Cananeia, but at a much reduced level to that in Buenos Aires.
- In Central America, Balboa shows an increase in variation in sea level at the start and end of the century, and the same characteristic exists at Portland in North America between 1940 and 1950. Further investigation revealed that these anomalies are the result of clock errors in instruments; in Portland the clock at this site was one hour wrong for 2 years in 1942 and 1943, and about 30 minutes in Balboa in 1908 and for one year in the 1990s.
- There is generally a reduction in the spread of residuals after 2000, but because data only extend for three years into this decade, there is insufficient information for this result to be conclusive as yet.
- After identification and removal of the clock errors, and neglecting the small data sets that have been acquired in the current decade, all sites except three have a tendency for a small increase in residual values. Further statistical analysis should be undertaken to show if this is significant.

The general increase in residuals may be due to a change in climatic conditions, but because residuals are based on square differences, this could indicate either an increase or a decrease in levels about predicted values. Changes are small and have been shown to include instrument errors as well as other variations about predicted tidal sea levels. Averages across results from different sites would need to be taken to reduce effects of instrument errors, but in doing this the variables influencing the change could not be identified. There is a requirement for better scientific instrumentation to undertake such analysis, or to use numerical modeling techniques as an alternative.

Figure A6.3. Standard deviations of residuals for each decade (South America)

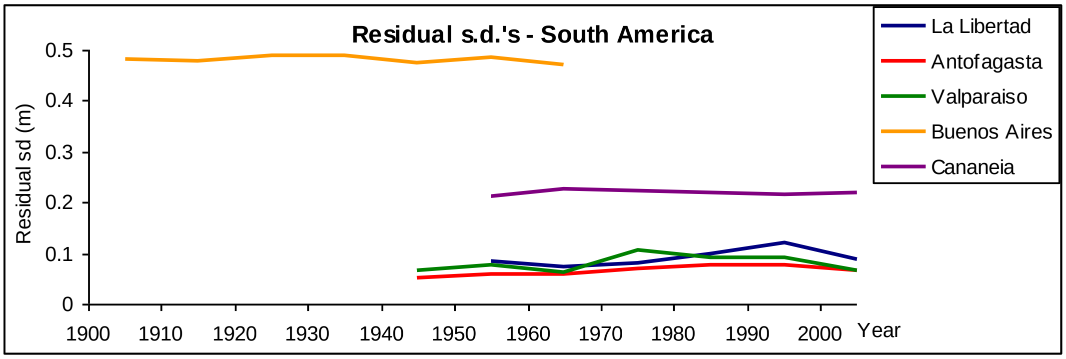
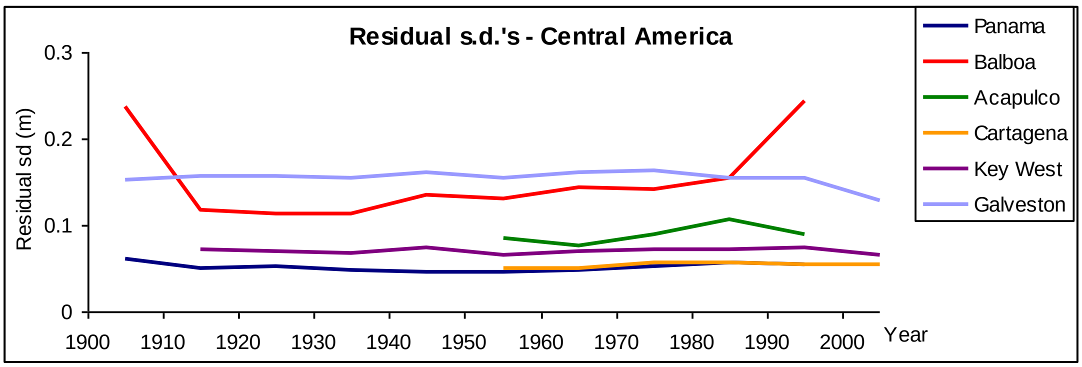


Figure A6.4. Standard deviations of residuals for each decade (Central America)



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