The effects of climate change in the coastal areas of Latin America and the Caribbean

Impacts

UNITED NATIONS

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GOBIERNO DE ESPAÑA
MINISTERIO DE AGRICULTURA, ALIMENTACIÓN Y MEDIO AMBIENTE
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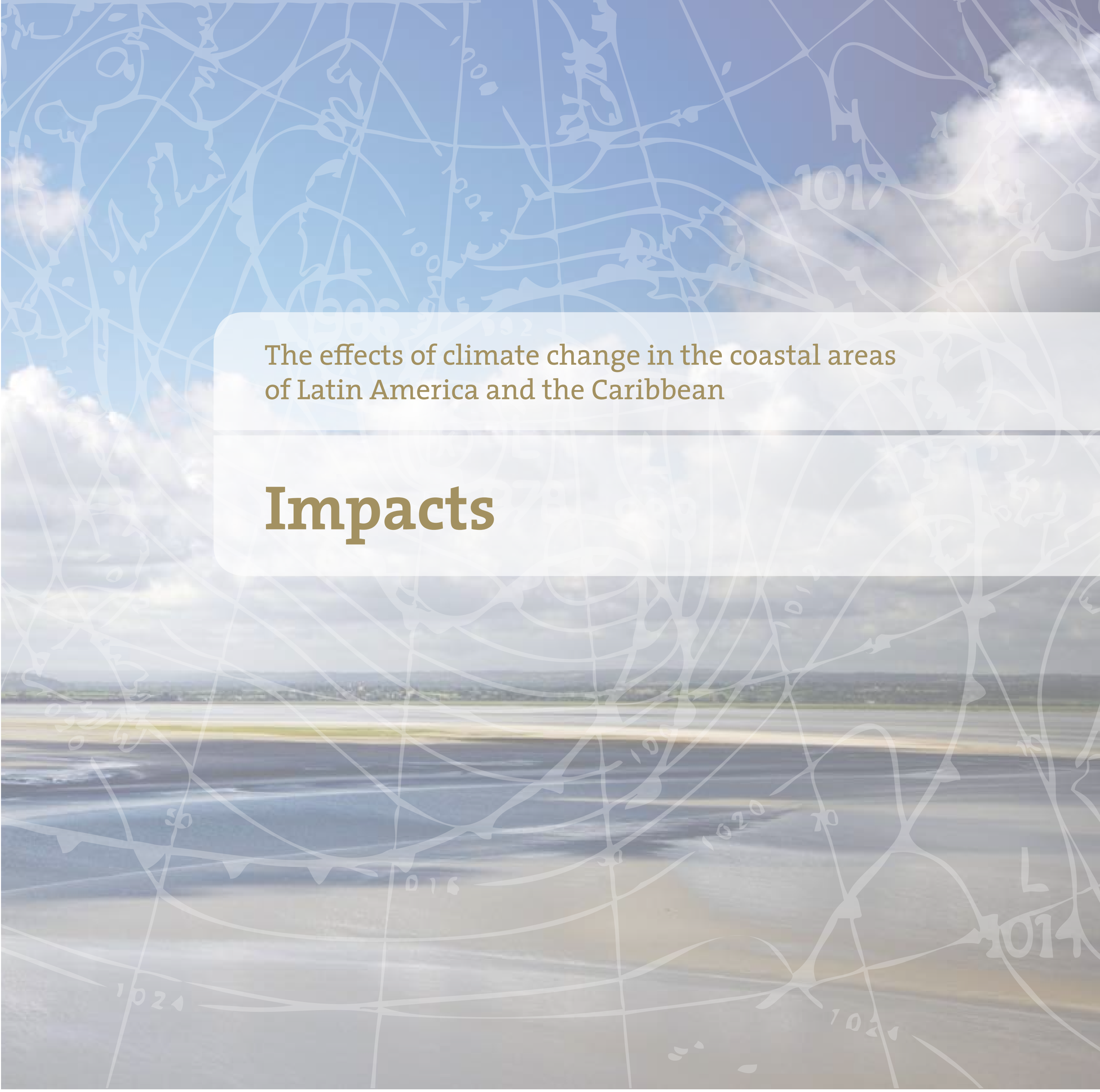

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Acronyms and abbreviations

AR4	IPCC Assessment Report 4
C3A	Project on Coastal Climate Change Impacts in Latin America and the Caribbean
CC	Climate change
CIESIN	Center for International Earth Science Information
ECLAC	Economic Commission for Latin America and the Caribbean
ERI	Economic Repercussions Index
FL	Flood level
GEV	Generalized Extreme Value
GIA	Glacial Isostatic Adjustment
GOS	Global Ocean Surges Database
GOW	Global Ocean Waves (Reanalysis by the Environmental Hydraulics Institute of the University of Cantabria)
GRUMP	Gridded Population of the World and the Global Rural-Urban Mapping Project
IHC	Environmental Hydraulics Institute (Instituto de Hidráulica Ambiental) of the University of Cantabria
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
MSL	Mean sea level
OECC	Spanish Climate Change Office
ROM	Maritime structure recommendations (*Recomendaciones para Obras Marítimas*)
RSLR	Relative sea level rise

SAL	Salinity
SERI	Social and Environmental Repercussions Index
SI	Safety Index
SLR	Sea level rise
SS	Storm surge
SST	Sea surface temperature
STRM	Shuttle Radar Topography Mission
T	Tide
TEU	Twenty-foot Equivalent Unit

Symbols

β_{LT}	Long-term trend (extreme events)
Dir	Wave direction
DirFE	Mean flow direction
D_{50}	Mean diameter of sand
FL	Flood level
H_S	Significant wave height
H_{S95}	95th percentile of significant wave height
H_{S12}	Significant wave height exceeded 12 hours per year
IC	Climate Index
pdf	Probability density function
Prob	Probability
q_n	Quantile *n*
R^2	Coefficient of determination
σ	Standard deviation
Tm	Mean wave period
Tp	Peak wave period
Tr	Return period

Units

km	kilometres
m	metres
mm	millimetres
º	sexagesimal degrees (nautical degrees)
ºC	degrees Celsius

1. Introduction

1.1 Background

The regionwide study of the effects of climate change in the coastal areas of Latin America and the Caribbean has been divided into four main parts in line with the comprehensive risk-assessment methodology that was developed as research progressed. The outputs of this regional study are presented in four core documents: an analysis of the factors that are driving climate change, a study on the vulnerability of coastal areas, an evaluation of the impacts of climate change and an exploration of how all these different factors can be brought together in an assessment of the risks associated with some of the impacts of climate change on the region's coastal areas.

Supplementary outputs include an annex on the effects of climate change which sets out the theoretical approaches used in the study. This annex serves as a manual covering the coastal phenomena, processes and concepts, among many other factors, that were analysed in the study. This manual also covers the expressions that can be used by future local and regional research projects to arrive at approximate impact assessments (using the disturbance method) for initial baseline analyses. In addition, the methodology that was developed for application in the comprehensive risk assessment is described in a methodological handbook. Finally, a web viewer has been developed as part of this project in order to make its findings as widely available as possible to readers in the countries of the region. In sum, the project documents are as follows:

- Document 1 : Climate variability, dynamics and trends in Latin America and the Caribbean
- Document 2 : Vulnerability and exposure of Latin American and Caribbean coastal areas to the effects of climate change
- Document 3 : Impacts of climate change in the coastal areas of Latin America and the Caribbean
- Document 4 : Climate change risk assessment for the coastal areas of Latin America and the Caribbean
- Theoretically derived effects of climate change in coastal areas (supplementary document)
- Methodological handbook of risk assessment (supplementary document)
- Web viewer of project findings

Table 3.1 provides an overview of the project's structure and outputs. This study, which is the third of the project documents, focuses on the impacts of climate change in the region's coastal areas.

TABLE 3.1
PROJECT STRUCTURE AND DOCUMENTS

Climate change: Latin American and Caribbean coastal areas			
Document 1: Coastal agents • Dynamics • Trends • Climate variability in coastal areas	**Document 2: Vulnerability**	**Document 3: Impact**	**Document 4: Risks**

Supplementary documents		
Theoretically derived effects of climate change in coastal areas	Methodological handbook	Project findings web viewer

Source: Prepared by the authors.

1.2 Objective and structure of the study

In this study the different effects, or impacts, of climate change in the coastal areas of Latin America and the Caribbean are analysed by evaluating the various changes that are taking place in coastal dynamics. An impact *i*, caused by one or various agents *hi*, is linked to the agent(s) by means of some sort of cause-effect relationship, and that relationship can therefore be described using an analytical function (derived either empirically or theoretically) for each impact. Thus, the impact-agent relationship can be expressed by a function such as:

$$i = f(a_i) \quad (3.1)$$

Where a_i is the agent(s) that cause(s) a given impact *i* in a coastal area and is/are connected by the analytical function *f*.

In the case of certain impacts —which may be measured, for example, by the amount of time that ports are in operation— it is useful to evaluate the trend of the effect produced in the coastal area (decrease in operationality) as it relates to the mean agent regime (during all hours of the year). However, in the case of other impacts, such as the intensity or frequency of severe flooding, it is better to separate floods associated with extreme events (storms) from the entire dataset (all floods). Hence, different methods need to be used in each case to calculate the mean and extreme regimes (conditions).

The impacts covered in this study are as follows (table 3.2):

TABLE 3.2

IMPACT OF OCEANIC CLIMATE AGENTS ON ECOSYSTEMS AND SOCIOECONOMIC SECTORS

					Agents h=1, Nh							
					OCEAN CLIMATE INDICATORS							
					Coastal dynamics						**Ocean dynamics**	
					MSL	**Extreme- FL**	**DirFE-Qs**	**Mean H_S**	**Extreme H_S**	**H_{S12}**	**SST**	**SAL**
k=1Neco	**ECOSYSTEMS**	**Aquatic system**	Wetlands	Estuaries	Permanent floods	Temporary floods						
				Deltas								
			Mangrove swamps									
		Coastal system (ocean)	Coral reefs								Bleaching	
			Phanerograms									
			Rocky terrain									
			Sediments									
		Coastal system (littoral)	Rocky terrain									
			Beaches/dunes	Rectilinear			Potential transport			Erosion- profile		
				Pocket			Erosion-planform			Erosion- profile		
		Land system	Forests Savannah-grassland Deserts Steppes									
j=1:Nse	**SOCIOECONOMIC SYSTEM**	**Ports**						Operativity	Reliability			
		Industry										
		Tourism	Infrastructure									
			Beaches				Erosion-form			Erosion- profile		
		Agriculture										
		Fisheries-aquaculture -shellfishing										
		Urban + services										

Source: Prepared by the authors.

The statistical distributions and long-term trends have been obtained for each of the impacts. The impacts and the variables examined in each case, based on the formulations described in the supplementary document on theoretically derived effects, are listed below:

- Flooding. The flooding of coastal areas as a result of the following factors is analysed: (1) rising sea levels (permanent flooding); and (2) extreme weather events that cause flooding as a result of a combination of high tides, sea levels and storm waves (temporary flooding). In evaluating this impact, the factors that are analysed include the size of the affected area, the coastal population, highways, railway lines and ecosystems (see the document on the vulnerability of the coastal areas of Latin America and the Caribbean).
- Beach erosion. The analysis centres on the possible erosion of beaches in Latin America and the Caribbean as a result of changes in their equilibrium profile and in their form owing to changes in sea levels and wave action.
- Ports. Conditions that may influence port operations are studied. These factors include access conditions, which may vary depending on wave action or excessive water levels inside the port due to faulty harbour defence works. This portion of the study covers the ways in which the reliability of harbour defence works may be altered by changes in extreme wave regimes driven by climate change.
- Coral reefs. The impact on coral reefs of a 1ºC increase in sea surface temperature is analysed using the approaches outlined in previous studies on the subject.

The results obtained for the various impacts covered in this study are discussed in the following sections.

2. Impact assessment methodology

The impacts covered here are assessed using formulas that make it possible to determine the relationships existing between different agents and coastal effects. A more detailed description of agents and impacts, as well as of the formulas used to link dynamics with impacts, is provided in the supplementary document on theoretically derived effects.

These impacts are analysed on the basis of multiple time frames. For example, coastal flooding may be examined as a very long-term effect (on a scale in which years are the time unit) of rising sea levels driven by the thermal expansion of the oceans and the melting of the polar ice caps, but floods associated with changing weather conditions (changes in storm patterns, intensities and/or paths) can also be analysed using a time scale based on hours or days. The impacts on ports also need to be analysed in terms of variables measured on a scale of hours, since they will be manifested in specific effects that make it necessary to halt port operations or that will result in malfunctions in those operations or in maritime works. Consequently, each impact has to be studied using a variety of time scales that have been tailored to that specific impact. Nonetheless, all of them can be assessed using the 2040, 2050 and 2070 time horizons employed in this study.

Eight scenarios are used in the study. The first three (A, B, C) correspond to the statistical extrapolation of the long-term trends computed for each impact. Scenarios D and E are based on Intergovernmental Panel on Climate Change (IPCC) projections for sea level rises of 0.5 m and 1 m, respectively. In the case of the impacts associated with these increases in sea levels, statistical projections have been used to calculate the combined effect of both as an upper limit for that impact. In view of the scale of year-on-year variability in the dynamics of the area (see the first document for this regional study, which deals with climate variability, trends and dynamics), scenario F describes the situation that would arise in the presence of an increase in sea levels caused by an El Niño event equal to the peak intensity on record (1998) but in the absence of a projected rise in sea levels for comparative purposes (F1) and a future situation in which sea levels were 1 m higher than they are now, based on IPCC projections (F2). The same analysis was conducted for La Niña event equal to the peak intensity on record G (scenarios G1 and G2). Finally, while hurricanes have not been analysed with the same degree of statistical rigour as other phenomena have been, the impacts that would arise now at each point along the coastline in the presence of the peak increases in sea levels on record have been studied (H1), as have the projected impacts given a 1-m rise in sea levels (H2).

TABLE 3.3
SCENARIOS USED FOR IMPACT ASSESSMENTS

Scenario		Time horizon	Method	Dynamics assessed	Variants-observations
A		2040	Statistical trends	Statistical trends. All	-
B		2050	Statistical trends	Statistical trends. All	-
C		2070	Statistical trends	Statistical trends. All	-
D		2100	Justification - IPCC SLR scenario	Sea level rise of 0.5 m	Statistical trends – other dynamics as of 2070
E		2100	Justification - IPCC SLR scenario	Sea level rise of 1 m	Statistical trends – other dynamics as of 2070
F	F1	2010	El Niño 98	Sea level	El Niño of 1998 at present
	F2	2100	El Niño 98 + IPCC SLR scenario	Sea level rise of 1 m	El Niño of 1998 with CC scenario
G	G1	2010	La Niña 89	Sea level	La Niña of 1989 at present
	G2	2100	La Niña 89 + IPCC SLR scenario	Sea level rise of 1 m	La Niña of 1989 with CC scenario
H	H1	2010	Hurricanes	Sea level and flood level	Hurricanes at present
	H2	2100	Hurricanes + IPCC SLR scenario	Sea level rise of 1 m	Hurricanes with CC scenario

Source: Prepared by the authors.

3. Information used to assess climate change impacts in the coastal areas of Latin America and the Caribbean

The data used to calculate the scale of the various impacts are the time series for coastal dynamics that were detailed in the first project document, which dealt with climate variability, dynamics and trends. These data were compiled by means of numerical reanalyses conducted for the study and drawn from the various key databases outlined in earlier project documents.

The time series for coastal dynamics were used as a basis for the construction of time series for climate change impacts using analytical formulations to relate the two and to analyse long-term trends. For example, the relationships between sea levels and wave activity, taken together, and beach erosion were calculated in order to determine how the changes in those factors produce changes in what are frequently non-linear (i.e. not proportional) erosion patterns. These analytical formulations are described in detail in a supplementary project document on theoretically derived climate changes in coastal areas.

4. Analysis of climate change impacts in the coastal areas of Latin America and the Caribbean

The impacts covered in this study are detailed below. A description of each impact is provided, including the causal agents or dynamics, the functional relationship and the method used to calculate the scale of the impact.

TABLE 3.4
IMPACTS COVERED IN THE STUDY, THE CORRESPONDING DYNAMICS AND THE TECHNIQUES USED TO COMPUTE THE SCALE OF LONG-TERM CHANGES

Impact	Variables	Analytical techniques used
Permanent flooding	Sea level rise (SLR)	Long-term statistical trends
Temporary flooding	Storm surge, sea level rise, tides, wave setup and seasonality of sea levels	Long-term statistical trends
Beach erosion	H_{S12}, sea level rise, wave direction	Long-term statistical trends
Port activity	Overtopping and wave-related navigation conditions	Long-term statistical trends
Reliability of maritime structures	Extreme wave heights (modification of heights used in calculations)	Models of non-stationary extremes
Coral bleaching	Sea surface temperature	Long-term statistical trends
Potential sediment transport	Waves and winds	Disturbance-based trends and long-term statistical trends

Source: Prepared by the authors.

The impact analysis has been conducted at a spatial scale of 50 km and at the country level. ISO code 3166/2 and its abbreviations have been used to identify the countries (see table 3.5).

TABLE 3.5
COUNTRIES COVERED IN THE STUDY: ISO CODE 3166/2 AND ABBREVIATIONS

Id.	Name of country	Abbreviation	ISO code	Id.	Name of country	Abbreviation	ISO code
1	Antigua and Barbuda	ATG	28	23	Honduras	HND	340
2	Argentina	ARG	32	24	Jamaica	JAM	388
3	Bahamas	BHS	44	25	Martinique	MTQ	474
4	Barbados	BRB	52	26	Mexico	MEX	484
5	Brazil	BRA	76	27	Montserrat	MSR	500
6	Belize	BLZ	84	28	Netherlands Antilles	ANT	530
7	British Virgin Islands	VGB	92	29	Aruba	ABW	533
8	Cayman Islands	CYM	136	30	Nicaragua	NIC	558
9	Chile	CHL	152	31	Panama	PAN	591
10	Colombia	COL	170	32	Peru	PER	604
11	Costa Rica	CRI	188	33	Puerto Rico	PRI	630
12	Cuba	CUB	192	34	Saint Kitts and Nevis	KNA	659
13	Dominica	DMA	212	35	Anguilla	AIA	660
14	Dominican Republic	DOM	214	36	Saint Lucia	LCA	662
15	Ecuador	ECU	218	37	Saint Vincent and the Grenadines	VCT	670
16	El Salvador	SLV	222	38	Suriname	SUR	740
17	French Guiana	GUF	254	39	Trinidad and Tobago	TTO	780
18	Grenada	GRD	308	40	Turks and Caicos Islands	TCA	796
19	Guadeloupe	GLP	312	41	United States Virgin Islands	VIR	850
20	Guatemala	GTM	320	42	Uruguay	URY	858
21	Guyana	GUY	328	43	Venezuela (Bolivarian Republic of)	VEN	862
22	Haiti	HTI	332				

Source: Prepared by the authors.

4.1 Coastal flooding

Temporary coastal flooding may be caused by extreme events that raise sea levels to unusual heights. In the rest of this study, this type of flooding will be represented by the designated flood level.

When talking about climate change, however, attention generally focuses on sea level rise as the predominant cause of coastal flooding. In a climate change scenario, this type of flooding is permanent in nature and is also known as submergence.

Both types of flooding —temporary flooding, when extreme events push water levels up to flood levels, and submergence caused by sea level rise and the consequent loss of land— will be taken into consideration in this study.

The following section is structured as follows:

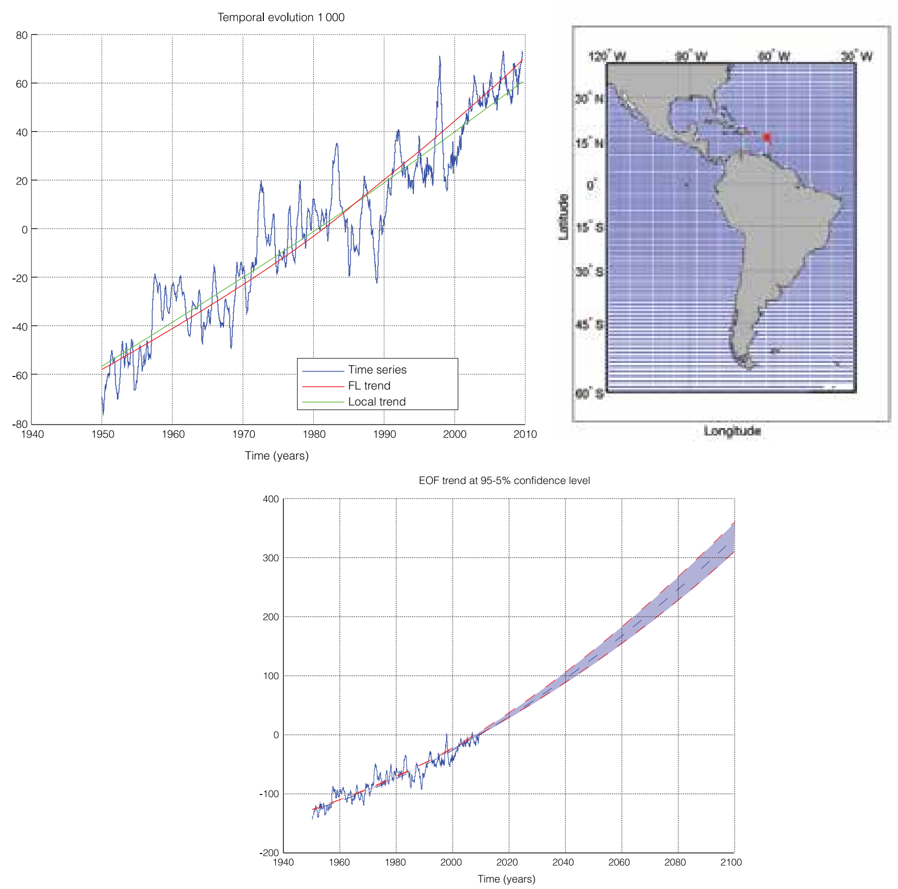
- Flooding caused by sea level rise;
- Analysis of extreme-event flood levels;
- The effects of hurricanes.

4.1.1 Flooding caused by sea level rise

4.1.1.1 Trends in mean sea levels (sea level rise)

Figure 3.1 depicts trends in rising sea levels at one location and their statistical projection (see earlier project documents). In this case, sea level rise (SLR) will accelerate in the future; in addition, the time series reflects anomalies due to the influence of the El Niño/La Niña Southern Oscillation (ENSO).

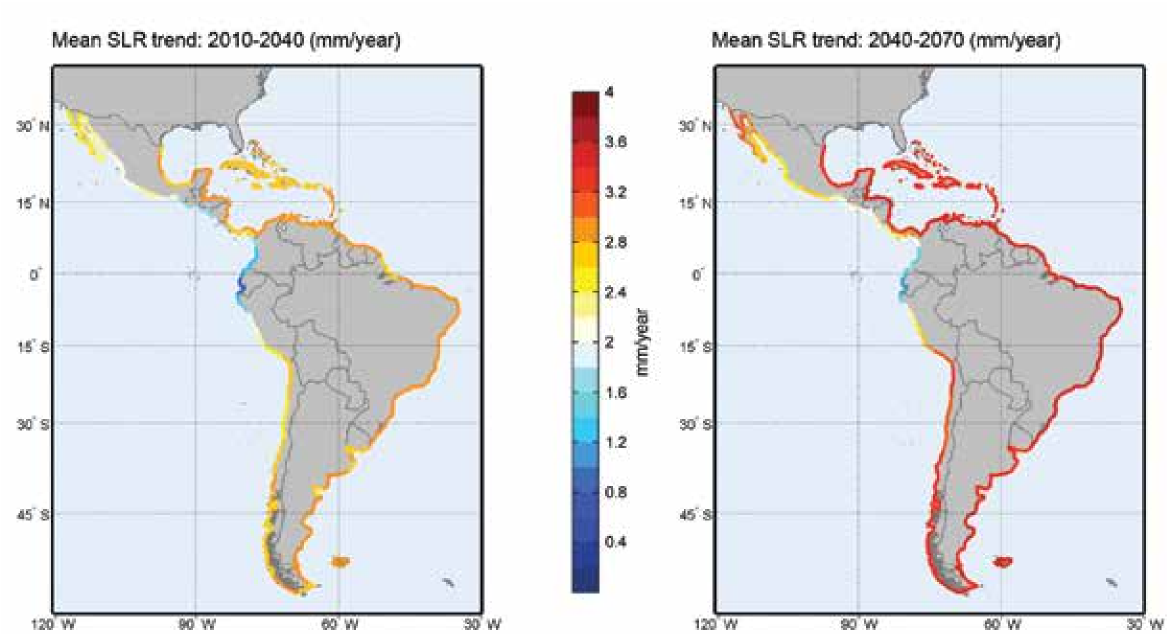
FIGURE 3.1
RISING SEA LEVEL TRENDS FOR A LOCATION ON THE ATLANTIC COAST
(Millimetres)



Source: Prepared by the authors.
Note: The Empirical Orthogonal Function (EOF) trend in sea level rise (SLR) is shown in the upper left figure, the location in the upper right figure and a comparison of the local trend and the EOF trend is shown below.

Figure 3.2 shows the spatial pattern of the mean trend for two time periods: 2010-2040 and 2040-2070.

FIGURE 3.2
MEAN TREND IN SEA LEVELS: 2010-2040 AND 2040-2070
(Millimetres/year)



Source: Prepared by the authors.

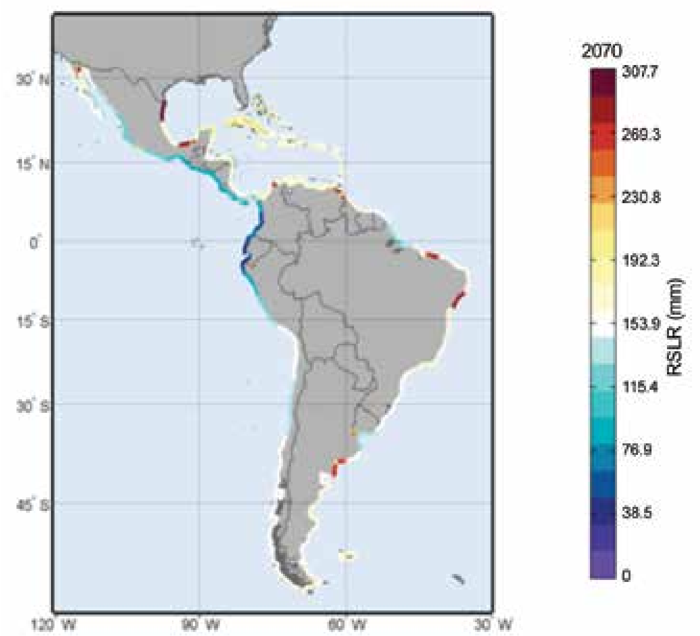
Sea levels are clearly trending upward everywhere in the region. The steepest trends for the first period under study are seen along the Atlantic coast, with values of approximately 3 mm/year along the northern coast of South America and the Caribbean coastline, with lower values for the Caribbean islands. For the second period (2040-2070), trend values climb up to a mean of 4 mm/year. For the rest of the coast, the increase is less than 2.5 mm/year for the first period and nearly 3 mm/year from 2040 on.

For the time horizons used in the study (see earlier project documents), these values add up to a high of nearly 100 mm by 2040 and of over 200 mm by 2070 for the northern coast of South America (where the rise is the steepest). The degree of uncertainty associated with these values, interpreted as possible variations around the mean, is quite small (12 cm maximum), as explained in earlier project documents.

4.1.1.2 Trends in relative sea level rise

The discussion of sea level rise presented in the preceding section does not take into account the decrease or increase in land elevations associated with the glacial isostatic adjustment (GIA). The combined outcome of a rise in sea levels and land subsidence is referred to as the relative sea level rise (RSLR). For this study, the subsidence/elevation values were taken from Peltier (2000) and interpolated using inverse distance weighting (IDW) to obtain a grid with a resolution of 0.5 degrees for the entire study area. The values attributed to each segment of the coastline were obtained by averaging out the values of the grid where they intersect the coastline. For deltas, an additional subsidence of 2 mm/year was added in. These data were obtained using DIVA database software.

FIGURE 3.3
ESTIMATED MEAN VALUES FOR RELATIVE SEA LEVEL RISE BY 2070 BASED ON PROJECTIONS OF STATISTICAL TRENDS
(Millimetres)



Source: Prepared by the authors.

As the above figure shows quite clearly, deltas are areas of particular concern owing to the additional degree of land subsidence to which they are subject. The fact that these are very gently sloping areas, given the way in which they are formed, only exacerbates the situation. Analyses of individual deltas have to be conducted locally and require very specific data. However, based on the results of this study for 5-km units (see earlier project documents), it is possible to estimate the implications of this situation to some extent.

4.1.1.3 Impacts of sea level rise

Sea levels have been rising throughout the past century (see earlier project documents). It is virtually certain that this increase is continuing or accelerating during this century as a result of global warming. The extent of the rise is unclear, however. At the present time, low-lying coastal areas (areas with elevations of less than 10 m) are home to some 10% of the world's population (McGranahan and others, 2007), and sea level rise is therefore one of the main concerns when seeking to evaluate the impacts of climate change in coastal areas. Given the potential severity of the impacts of rising sea levels, the existing uncertainty as to how to go about implementing adaptation measures successfully must be dispelled with the help of further research and analysis (Nicholls and Cazenave, 2010).

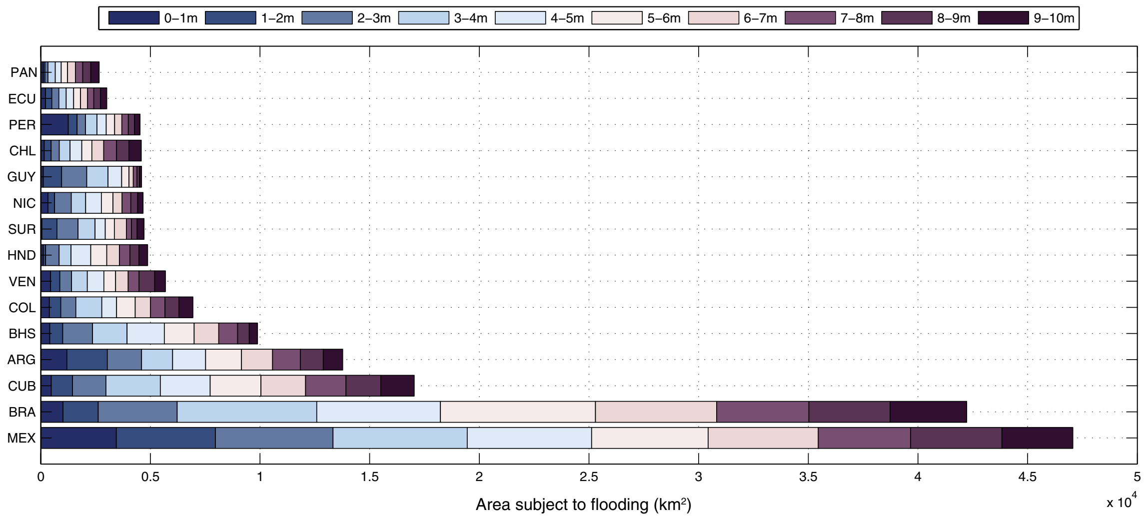
Before analysing the impact of the submergence or permanent flooding of coastal areas due to rising sea levels, it is useful to examine the distribution of flooding and of the population in coastal areas. This was done by looking at the land surfaces with elevations of between 0 m and 10 m, in 1-m increments, and then determining the size of the population located on each of those surface areas (see the second document in the series, which deals with the vulnerability of coastal areas).

Figure 3.4 shows that the distribution by metre of elevation varies a great deal across countries because the mean gradients differ so much. For example, if the reader looks at the upper part of the graph, it becomes clear that the amount of land surface, measured in square kilometres, for the lowest elevations in countries such as Honduras or Guyana is quite small. In fact, the land area having an elevation of less than 1 m in Honduras (HND) is far smaller than the land area at higher elevations, whereas in Peru (PER), just the opposite is true, with a significant part of the total land area being less than 1 m in elevation. The second part of the graph (see the lower panel) shows what percentage of each country's total land area is accounted for by the land area at each of the first 10 metres of elevation. This view provides a clearer illustration of the situation of many countries than the estimates of the total affected land area does. The reader will see that, in this case, the situation of the Caribbean islands takes on great importance, since most of the territory of many of these countries has an elevation of less than 10 m (see the second project document). In these cases, coastal areas account for a much larger percentage of total land area than they do in larger countries such as Mexico, Brazil or Argentina. Of all the Caribbean islands, the Turks and Caicos, the Bahamas and the Cayman Islands are the most vulnerable to the impacts of coastal flooding.

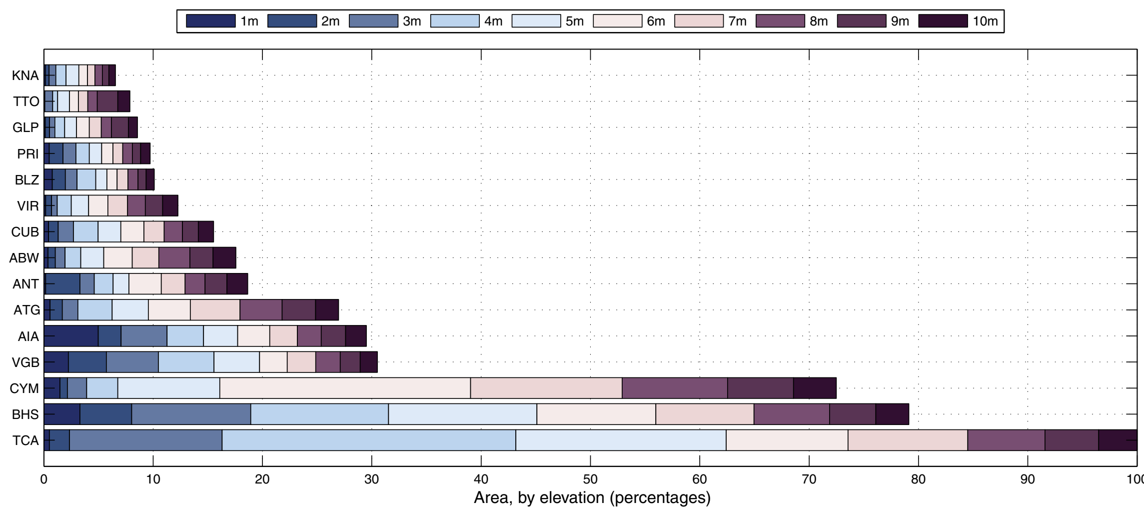
FIGURE 3.4

DISTRIBUTION OF COASTAL LAND AREA AT ELEVATIONS OF BETWEEN 0 AND 10 METRES IN LATIN AMERICA AND THE CARIBBEAN

(a) Square kilometres



(b) Percentage of total land area



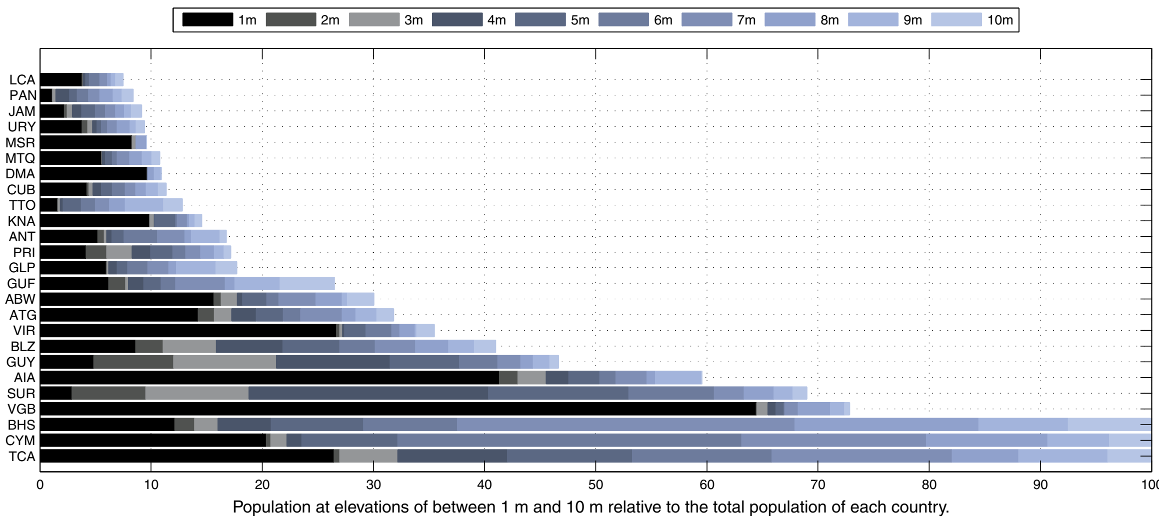
Source: Prepared by the authors.
Note: The unit of measurement is 1 vertical metre.

Figure 3.5 summarizes the population data obtained for the 15 countries that have the largest percentages of their populations located at elevations of between 0 and 10 metres. This figure therefore illustrates the differences in the distribution of population groups living at low elevations in the various countries. In some cases, such as the British Virgin Islands (VGB), over 60% of the total population lives at these low elevations. Figure 3.6 shows the distribution of the population in each of the first three metres of land area (elevations of from 0 to 3 m). In view of the elevations that are expected to be affected by the rise in mean sea levels based on the scenarios used in this study (see figure 3.3), the inhabitants of land areas at these very low elevations are the most likely to feel the impacts of sea level rise.

FIGURE 3.5

DISTRIBUTION OF THE POPULATION LIVING AT ELEVATIONS OF BETWEEN 0 AND 10 METRES RELATIVE TO THE TOTAL POPULATION

(Percentages of the total)

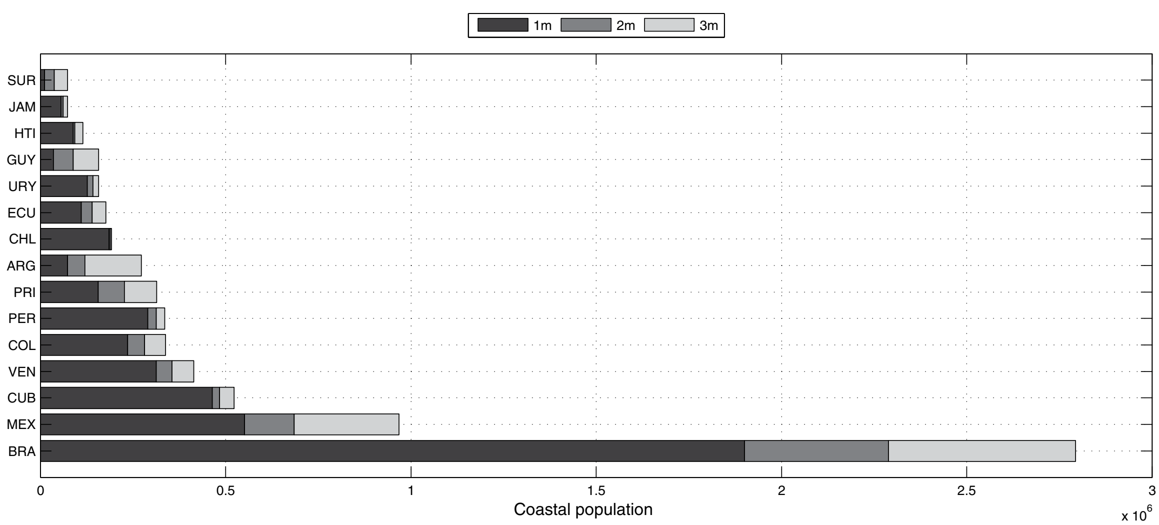


Source: Prepared by the authors.
Note: The unit of measurement is 1 vertical metre.

FIGURE 3.6

DISTRIBUTION OF THE POPULATION LIVING AT ELEVATIONS OF BETWEEN 0 AND 3 METRES

(Number of persons)



Source: Prepared by the authors.
Note: The unit of measurement is 1 vertical metre.

The data used to evaluate the degree of vulnerability of the region's coastal areas (see the second project document) have been cross-checked with the data used to construct sea level rise scenarios (see table 3.3). The results for each country or territory are shown below.

Because the demographic information dates from 2001 and the resolutions of the topographic model (STRM-90) and of the population density data (CIESIN) differ, it is preferable to analyse the distribution by metre of elevation rather than to compare the population values per se. The results, expressed as a percentage of the estimated population living in areas up to 10 metres in elevation, have therefore been used as an indicator of the projected impacts. With updated data on the distribution of the population and topography at the local level, precise results for the impacted population could be obtained. The presentation of the impact results shown in table 3.7 also has an added advantage, since the countries are ranked in order of the relative size of the population groups that would be affected. However, when the percentages of the affected coastal population groups are analysed, it becomes clear that the countries with the largest affected populations in percentage terms are not the same as the countries with the largest affected populations in absolute terms. These dual perspectives are clearly both useful and necessary.

TABLE 3.6
POPULATION LIVING IN COASTAL AREAS AT ELEVATIONS OF 10 METRES OR LESS

Country	ISO country code	Elevation up to 10 m (Number of persons)	Country	ISO country code	Elevation up to 10 m (Number of persons)
BRA	76	10 464 998	NIC	558	115 462
MEX	484	3 363 474	BLZ	84	107 743
ARG	32	2 812 740	CRI	188	92 078
CUB	192	1 704 496	GLP	312	86 520
VEN	862	1 192 815	GUF	254	46 834
COL	170	1 039 008	MTQ	474	58 767
PRI	630	759 651	VIR	850	63 114
PER	604	877 139	AIA	660	54 350
DOM	214	560 644	CYM	136	40 000
HTI	332	562 235	ANT	530	36 213
ECU	218	520 242	ABW	533	40 784
CHL	152	537 077	ATG	28	25 941
GUY	328	374 798	BRB	52	29 611
URY	858	421 393	VGB	92	21 271
SUR	740	272 555	LCA	662	16 082
PAN	591	265 903	TCA	796	12 496
BHS	44	260 886	DMA	212	13 336
JAM	388	280 531	GRD	308	10 939
HND	340	245 089	KNA	659	8 825
SLV	222	200 002	VCT	670	8 730
TTO	780	171 772	MSR	500	623
GTM	320	148 406			

Source: Prepared by the authors.

TABLE 3.7
INCREASE IN THE AFFECTED POPULATION, BY COUNTRY, FOR EACH SCENARIO
(Percentage of total population at elevations up to 10 m)

		Scenario										
ISO country code	Country	A	B	C	D	E	F1	F2	G1	G2	H1	H2
76	BRA	1.87	2.58	4.12	10.88	21.76	0.35	13.33	0.00	13.11	-	-
484	MEX	1.46	2.01	3.21	9.50	18.99	1.09	12.43	0.04	11.79	17.97	26.53
32	ARG	0.22	0.31	0.49	1.34	2.69	0.04	2.25	0.00	2.20	-	-
192	CUB	3.03	4.16	6.65	18.61	37.23	0.93	19.90	0.00	19.40	37.48	42.30
862	VEN	2.95	4.06	6.48	16.65	33.29	0.20	19.41	0.04	19.32	7.54	37.92
170	COL	2.43	3.34	5.34	14.43	28.85	0.89	18.24	0.00	17.74	27.51	37.45
630	PRI	1.97	2.71	4.33	12.06	24.12	0.82	18.10	0.00	17.51	41.36	52.78
604	PER	3.06	4.22	6.73	24.04	48.09	6.77	28.37	0.00	24.80	-	-
214	DOM	0.93	1.28	2.05	5.74	11.48	0.60	6.52	0.00	6.20	12.77	14.11
332	HTI	1.51	2.08	3.31	9.31	18.61	1.01	10.36	0.00	9.82	20.56	25.83
218	ECU	0.70	0.96	1.53	12.31	24.62	5.62	20.21	0.00	16.31	-	-
152	CHL	4.18	5.76	9.20	26.05	52.09	1.35	26.95	0.00	26.26	-	-
328	GUY	0.89	1.22	1.95	5.19	10.38	0.00	12.85	0.10	12.97	-	-
858	URY	3.37	4.64	7.41	20.18	40.36	1.07	23.31	0.01	22.72	-	-
740	SUR	0.36	0.49	0.79	2.09	4.18	0.00	6.92	0.02	6.96	-	-
591	PAN	0.97	1.33	2.12	6.49	12.98	1.17	7.49	0.00	6.88	4.36	14.38
44	BHS	1.10	1.52	2.43	6.06	12.13	0.16	7.59	0.00	7.50	16.18	19.96
388	JAM	1.98	2.72	4.34	12.04	24.08	1.24	14.00	0.00	13.32	29.45	36.64
340	HND	0.61	0.84	1.35	3.59	7.19	0.31	4.64	0.00	4.44	7.24	10.70
222	SLV	0.76	1.04	1.66	7.16	14.32	3.05	8.62	0.00	7.08	12.22	14.30
780	TTO	0.63	0.86	1.38	6.25	12.51	0.00	3.63	0.01	3.64	3.24	7.37
320	GTM	0.43	0.59	0.95	3.19	6.38	1.19	4.27	0.00	3.66	5.26	7.52
558	NIC	0.96	1.33	2.12	8.67	17.34	2.91	9.83	0.00	8.35	16.17	19.51
84	BLZ	2.40	3.30	5.27	10.49	20.97	0.24	17.12	0.00	16.97	39.03	53.53
188	CRI	1.11	1.52	2.43	9.34	18.67	3.11	11.75	0.00	10.11	4.43	21.30
312	GLP	2.86	3.93	6.27	16.80	33.59	0.87	17.48	0.00	17.04	34.56	37.29
254	GUF	2.03	2.79	4.46	11.69	23.37	0.05	14.64	0.00	14.61	-	-
474	MTQ	4.43	6.08	9.71	25.76	51.51	0.99	26.34	0.00	25.84	51.86	53.16
850	VIR	6.24	8.58	13.70	37.56	75.13	2.47	39.24	0.00	38.00	76.65	76.96
660	AIA	5.77	7.94	12.67	34.71	69.43	2.48	37.40	0.00	36.12	75.09	78.77
136	CYM	1.84	2.53	4.04	10.19	20.37	1.06	11.74	0.00	11.20	23.16	24.65
530	ANT	2.67	3.68	5.87	15.51	31.02	0.00	17.26	0.01	17.27	34.23	35.63
533	ABW	4.51	6.21	9.92	26.06	52.12	0.74	27.52	0.00	27.13	54.05	58.63
28	ATG	3.76	5.18	8.26	22.39	44.77	1.46	25.47	0.00	24.67	52.52	58.70
52	BRB	5.99	8.24	13.15	34.49	68.97	0.10	35.47	0.00	35.42	70.84	70.84
92	VGB	7.34	10.10	16.12	44.23	88.46	2.94	45.74	0.00	44.27	89.45	90.57
662	LCA	4.41	6.05	9.66	25.40	50.79	0.45	26.33	0.00	26.09	52.19	54.24
796	TCA	2.63	3.61	5.77	13.22	26.45	0.87	16.72	0.00	16.28	35.04	43.42
212	DMA	7.58	10.43	16.65	44.15	88.31	1.69	45.00	0.00	44.15	88.31	88.31

Table 3.7 (concluded)

ISO country code	Country	Scenario A	B	C	D	E	F1	F2	G1	G2	H1	H2
308	GRD	7.06	9.72	15.51	40.66	81.31	0.00	40.66	0.00	40.66	81.31	81.31
659	KNA	5.70	7.85	12.52	33.93	67.84	2.18	35.01	0.00	33.93	69.45	70.84
670	VCT	6.45	8.89	14.18	37.16	74.32	0.04	37.18	0.00	37.16	74.32	75.80
500	MSR	7.19	9.88	15.87	43.41	86.53	2.69	44.61	0.00	43.41	89.22	90.12

Source: Prepared by the authors.

The results indicate that Brazil, Mexico and Argentina are the three countries in which the largest number of people are likely to be impacted by rising sea levels in the coming decades. However, the proportion of the population in Peru, Chile and Uruguay that is likely to be affected under the assumptions made in scenario E (1 m of elevation) relative to the total coastal population (up to 10 m of elevation) is strikingly large. In addition, on islands such as Barbados, the British Virgin Islands, Dominica and others, more than 70% of the total coastal population are likely to be exposed to extremely severe impacts.

TABLE 3.8
INCREASE IN THE LAND AREA AFFECTED, BY COUNTRY, FOR EACH SCENARIO
(Square kilometres)

ISO country code	Country	Scenario A	B	C	D	E	F1	F2	G1	G2	H1	H2
484	MEX	272.04	374.11	597.22	1 725.00	3 449.47	214.79	4 327.98	11.18	4 072.47	4 768.54	9 085.75
76	BRA	87.42	120.43	192.25	509.00	1.017.48	16.96	1 334.49	0.00	1.310.91	-	-
192	CUB	39.42	54.21	86.54	240.00	480.86	20.49	756.35	0.00	725.02	1 266.36	2 613.09
32	ARG	100.59	138.70	221.42	596.00	1 192.96	18.58	1 536.24	0.26	1 522.41	-	-
44	BHS	34.71	47.73	76.20	206.00	412.72	5.19	509.23	0.00	502.22	1 393.89	2 819.87
170	COL	31.33	43.07	68.75	196.00	391.97	15.77	468.97	0.00	451.45	420.27	993.10
862	VEN	39.41	54.19	86.51	225.00	450.83	2.34	453.92	0.70	452.13	211.10	770.73
340	HND	10.59	14.57	23.26	59.00	118.58	3.65	119.45	0.00	115.78	232.95	529.90
740	SUR	4.56	6.28	10.02	26.00	52.85	0.00	374.64	0.30	377.50	-	-
558	NIC	27.62	38.02	60.70	164.00	328.23	2.01	312.45	0.00	309.98	335.72	877.16
328	GUY	9.95	13.69	21.85	59.00	117.70	0.00	465.71	0.97	469.78	-	-
152	CHL	13.15	18.12	28.92	79.00	158.61	1.55	240.26	0.00	237.98	-	-
604	PER	59.69	82.20	131.23	629.00	1 258.12	270.21	987.99	0.00	813.72	-	-
218	ECU	6.44	8.85	14.12	109.00	218.41	50.48	321.76	0.00	260.19	-	-
591	PAN	8.65	11.88	18.97	59.00	117.81	11.58	104.51	0.00	95.21	30.02	172.75
84	BLZ	15.71	21.61	34.50	86.00	172.17	1.60	228.56	0.00	226.57	581.65	949.83
214	DOM	3.05	4.19	6.69	19.00	37.45	1.90	56.36	0.00	53.62	133.71	228.77
858	URY	6.65	9.18	14.65	41.00	81.17	1.78	202.27	0.09	199.17	-	-
254	GUF	10.36	14.26	22.77	60.00	119.71	0.14	88.42	0.00	88.33	-	-
320	GTM	0.07	0.10	0.16	1.00	1.39	0.26	2.53	0.00	2.11	1.89	7.77

Table 3.8 (concluded)

ISO country code	Country	Scenario A	B	C	D	E	F1	F2	G1	G2	H1	H2
188	CRI	1.20	1.66	2.64	10.00	20.35	3.29	27.34	0.00	23.70	9.55	56.15
332	HTI	0.78	1.08	1.72	5.00	9.69	0.53	18.52	0.00	17.55	53.90	154.07
222	SLV	0.16	0.21	0.34	1.00	2.92	0.63	4.59	0.00	3.77	3.33	9.69
630	PRI	3.70	5.09	8.12	23.00	45.23	1.52	83.53	0.00	80.77	206.19	315.66
388	JAM	4.55	6.27	10.00	28.00	55.05	2.77	48.46	0.00	46.14	120.80	181.54
796	TCA	0.28	0.38	0.61	2.00	3.27	0.09	7.87	0.00	7.66	46.79	171.71
780	TTO	0.12	0.16	0.26	1.00	1.62	0.00	1.88	0.00	1.88	1.88	4.96
136	CYM	0.39	0.54	0.86	2.00	4.65	0.23	3.61	0.00	3.45	9.69	17.16
530	ANT	0.11	0.15	0.24	1.00	1.30	0.00	13.03	0.00	13.06	23.95	35.44
28	ATG	0.26	0.35	0.56	2.00	3.05	0.10	4.69	0.00	4.54	13.97	27.24
312	GLP	0.18	0.25	0.40	1.00	2.15	0.06	4.45	0.00	4.34	13.02	24.83
474	MTQ	0.05	0.07	0.11	0.00	0.58	0.01	0.84	0.00	0.83	2.76	6.22
660	AIA	0.80	1.09	1.75	5.00	9.57	0.34	7.04	0.00	6.80	19.02	25.99
92	VGB	0.34	0.47	0.76	2.00	4.15	0.14	5.45	0.00	5.27	16.48	25.66
850	VIR	0.04	0.06	0.10	0.00	0.53	0.02	1.14	0.00	1.11	3.48	6.92
533	ABW	0.07	0.09	0.15	0.00	0.77	0.01	1.07	0.00	1.05	1.97	3.71
662	LCA	0.02	0.03	0.05	0.00	0.27	0.00	0.38	0.00	0.38	1.67	3.34
659	KNA	0.04	0.05	0.08	0.00	0.45	0.01	0.76	0.00	0.73	2.52	4.92
52	BRB	0.00	0.01	0.01	0.00	0.06	0.00	0.09	0.00	0.09	0.28	0.58
308	GRD	0.01	0.01	0.02	0.00	0.08	0.00	0.18	0.00	0.18	0.45	0.85
212	DMA	0.02	0.02	0.04	0.00	0.19	0.00	0.22	0.00	0.21	0.88	1.49
670	VCT	0.01	0.01	0.02	0.00	0.12	0.00	0.20	0.00	0.20	0.52	0.99
500	MSR	0.01	0.01	0.02	0.00	0.12	0.00	0.18	0.00	0.18	0.57	0.82

Source: Prepared by the authors.

The results for the various scenarios indicate that the impact under scenarios D and E (increases in sea level of 0.5 m and 1 m, respectively) would be greater than the impacts extrapolated from statistical trends (see the first project document, which deals with climate variability, dynamics and trends). If the changes are of the same magnitude as those reflected in statistical trends (continuation of past changes), then the necessary adaptation measures called for in the presence of a 1-m increase in sea level will be much less rigorous. The values obtained for all the scenarios except scenario F are interpolations between the 1-m and 2-m elevations, since the digital model uses 1-m increments. While this proportion is linear, it nonetheless provides some idea of the scale of the impacts and thus provides a basis for comparisons of the different scenarios.

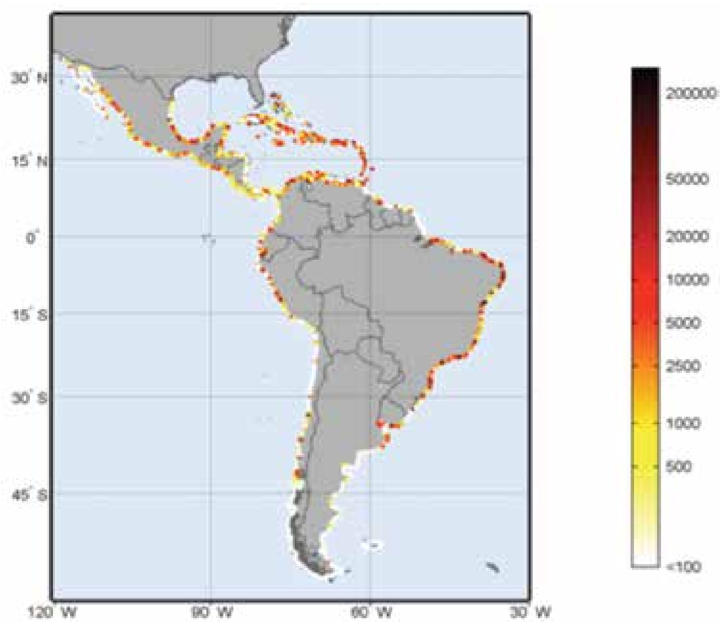
Under a scenario of a 1-m increase in sea level and a possible El Niño effect, the impacts are not proportional to the damage caused in areas within that first metre of elevation. In this case, both the size of the land area and the size of the population that would be impacted increase, with one influential factor in this case being the differing distributions of these variables in the countries of the region. This same effect will also come into play in the analysis of coastal flooding caused by extreme events.

A consideration of the historical data on hurricane-driven storm surges in combination with a scenario of a 1-m sea level rise leads to a number of conclusions. First of all, the ratio between the affected land area and the affected population varies across countries. In Honduras, for example, the impacted land area would be almost four times as great if the effect of hurricanes is combined with this new specification. The size of the affected population would remain much the same, however, rather than increasing in proportion to the land area in question. By the same token, Mexico and Cuba would see almost no change in the size of the affected population, whereas the extent of the land area concerned would increase by factors of approximately 2.5 and 5, respectively. This would not be the case in all the countries, however. For example, in Belize, the size of the affected population would nearly double if hurricanes were to occur when sea levels had risen by 1 m. The size of the affected population in Puerto Rico would double as well. Jamaica and Haiti are other examples of this kind of situation.

When the effects of hurricanes under current sea-level conditions and under the scenario of a 1-m sea level rise are compared, the results show that the impacted land area would at least double. The size of the affected population does not increase by the same proportion, however, but the actual increments depend on the distribution of the population in each country. The countries in which the extent of the impact would increase the most in the presence of higher sea levels and hurricanes are Honduras, Panama, Belize, Costa Rica and the Bolivarian Republic of Venezuela, among others. Other countries, such as the Cayman Islands, would see no significant change in terms of the impacts of hurricanes on their populations.

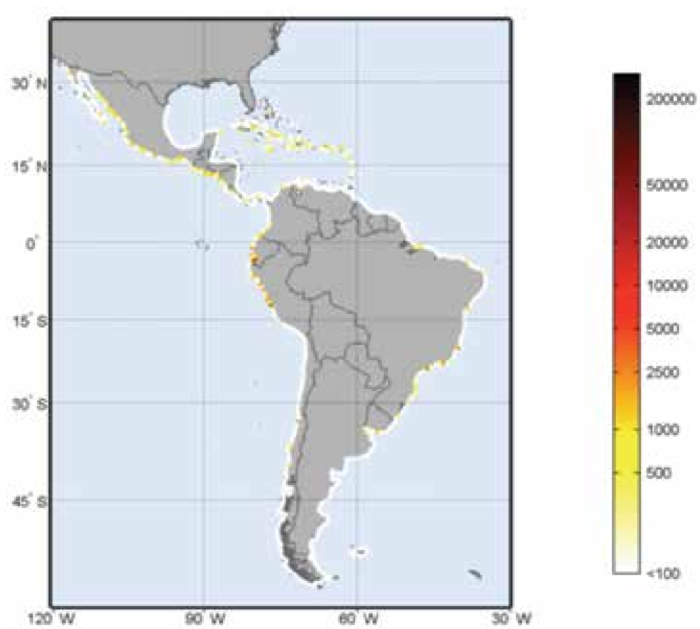
As is illustrated in figure 3.7 and figure 3.8, the situation with respect to rising sea levels varies a great deal depending on the location concerned. In terms of the size of the affected population, a 1-m rise in sea level would have a severe impact on the large urban population centres located along the coasts of Brazil. Other areas that would be strongly impacted include the Caribbean islands, especially those further to the east, and large parts of Mexico, especially along the eastern coast, and a number of specific areas in Peru and Ecuador, as well as many of the largest human settlements in Chile. A comparison of this situation with the one that would arise if sea levels were pushed up by an El Niño event of the same magnitude as the strongest recorded El Niño (1998) indicates that the western coast would be much more severely affected than the eastern coast but that the extent of the impact would be far less than the impact of a 1-m rise in sea level rise, since the extent of an El Niño-driven rise would be much smaller. Even so, a significant proportion of the populations of Ecuador and of some locations in Peru would be adversely affected, although not as many as would be under scenario E.

FIGURE 3.7
POPULATION AFFECTED IN AREAS LOCATED WITHIN THE FIRST METRE OF ELEVATION UNDER SCENARIO E
(Number of persons)



Source: Prepared by the authors.

FIGURE 3.8
POPULATION AFFECTED IN AREAS LOCATED WITHIN THE RANGE OF ELEVATION ASSOCIATED WITH SCENARIO F1 (1998 EL NIÑO)
(Number of persons)



Source: Prepared by the authors.

The impacts on infrastructure (roads and railways) have also been analysed for each scenario. The results are shown in stretches of roadways or railway lines that approximate the 5-km units of measurement used in the study (see tables 3.9 and 3.10). The conclusions that can be drawn from these results are analogous to those obtained for impacted land areas and populations. A 1-m rise in sea level would have much greater impacts than those associated with a continuation of the very gradual rate of increase obtained by extrapolating from the changes occurring now. When hurricanes are factored into the equation, the results indicate that the situation in countries such as the Bolivarian Republic of Venezuela, Honduras, Panama and Costa Rica would change significantly if sea levels rise by 1 m, whereas, in some other countries, the impact would not differ so considerably from the effects associated with current sea levels (see, for example, the case of the Dominican Republic).

TABLE 3.9

ROADWAYS IMPACTED IN EACH COUNTRY UNDER EACH OF THE SCENARIOS

(Segments of approximately 5 km in length)

	Scenario										
Country	**A**	**B**	**C**	**D**	**E**	**F1**	**F2**	**G1**	**G2**	**H1**	**H2**
MEX	25	35	55	171	341	30	350	1	344	322	419
BRA	16	22	36	94	187	3	188	0	187	-	-
CUB	5	7	11	32	64	2	64	0	64	77	101
BHS	9	13	20	55	109	1	109	0	109	143	174
ARG	5	7	10	28	56	0	56	0	56	-	-
VEN	5	7	11	29	58	0	59	0	59	14	81
PER	5	7	11	38	76	11	77	0	76	-	-
COL	8	11	18	49	97	2	96	0	96	81	109
CHL	2	3	5	15	30	0	30	0	30	-	-
HND	3	4	6	18	35	1	35	0	35	37	50
DOM	1	2	3	9	18	1	18	0	18	20	22
ECU	0	1	1	6	12	2	13	0	11	-	-
CRI	1	2	3	14	28	5	26	0	26	2	29
HTI	2	3	4	12	24	1	24	0	24	32	35
JAM	2	3	5	15	30	2	30	0	30	36	44
PRI	2	2	4	10	20	1	20	0	20	31	38
PAN	1	1	2	7	13	2	15	0	15	6	16
NIC	1	1	2	6	12	1	13	0	12	13	20
URY	2	3	4	12	23	0	23	0	23	-	-
SUR	0	0	0	1	1	0	2	0	2	-	-
GUY	1	2	3	8	15	0	14	0	14	-	-
GTM	1	1	2	6	12	3	14	0	14	8	15
SLV	0	0	0	3	6	1	4	0	4	4	4
GUF	0	0	1	2	3	0	3	0	3	-	-
TTO	0	0	1	2	4	0	4	0	4	1	5
GLP	1	2	2	7	13	0	13	0	13	16	17
ANT	0	0	0	1	1	0	1	0	1	7	9
VIR	1	1	2	6	11	0	11	0	11	11	11
BLZ	1	1	1	4	7	0	7	0	7	7	12
CYM	0	0	1	2	3	0	3	0	3	3	3
MTQ	0	1	1	3	5	0	5	0	5	5	5
ATG	0	0	0	1	2	0	2	0	2	3	5

Table 3.9 (concluded)

	Scenario										
Country	A	B	C	D	E	F1	F2	G1	G2	H1	H2
LCA	0	0	0	0	0	0	0	0	0	2	3
DMA	1	1	2	5	9	0	9	0	9	9	9
VGB	0	1	1	3	6	0	6	0	6	6	6
TCA	0	0	1	2	4	0	4	0	4	4	5
AIA	0	1	1	3	5	0	5	0	5	6	6
ABW	0	0	0	1	1	0	1	0	1	3	3
KNA	0	0	0	1	1	0	1	0	1	1	1
GRD	0	0	0	0	0	0	0	0	0	0	0
BRB	0	0	0	0	0	0	0	0	0	0	0
VCT	0	0	0	0	0	0	0	0	0	0	0
MSR	0	0	0	1	1	0	1	0	1	1	1

Source: Prepared by the authors.

TABLE 3.10
RAILWAYS IMPACTED, BY COUNTRY, UNDER EACH SCENARIO
(Segments of approximately 5 km in length)

	Scenario										
Country	A	B	C	D	E	F1	F2	G1	G2	H1	H2
CUB	2	3	5	15	30	1	30	0	30	32	43
MEX	2	2	4	11	22	2	23	0	22	19	30
BRA	2	2	4	11	21	0	21	0	21	-	-
ARG	0	0	1	2	3	0	3	0	3	-	-
PRI	1	1	2	5	9	0	9	0	9	19	25
CRI	0	0	1	2	4	1	4	0	4	2	8
GUY	0	0	1	2	4	0	4	0	4	-	-
HND	0	0	0	0	0	0	0	0	0	0	0
DOM	0	0	0	1	2	0	2	0	2	3	3
URY	0	0	1	2	3	0	3	0	3	-	-
HTI	0	0	1	2	4	0	4	0	4	4	5
CHL	0	1	1	3	6	0	6	0	6	-	-
VEN	0	0	0	0	0	0	0	0	0	0	0
JAM	0	0	0	1	1	0	1	0	1	1	1
PER	0	0	0	2	3	0	3	0	3	-	-
COL	0	1	1	3	6	0	6	0	6	5	6
TTO	0	0	0	0	0	0	0	0	0	0	0
PAN	0	0	0	0	0	0	0	0	0	1	1
GTM	0	0	0	2	3	1	3	0	3	2	3
LCA	0	0	0	0	0	0	0	0	0	0	0
MTQ	0	0	0	0	0	0	0	0	0	0	0
ATG	0	0	0	0	0	0	0	0	0	0	0
SUR	0	0	0	0	0	0	0	0	0	-	-
VIR	0	0	0	0	0	0	0	0	0	0	0
TCA	0	0	0	0	0	0	0	0	0	0	0
VCT	0	0	0	0	0	0	0	0	0	0	0
AIA	0	0	0	0	0	0	0	0	0	0	0
KNA	0	0	0	0	0	0	0	0	0	0	0

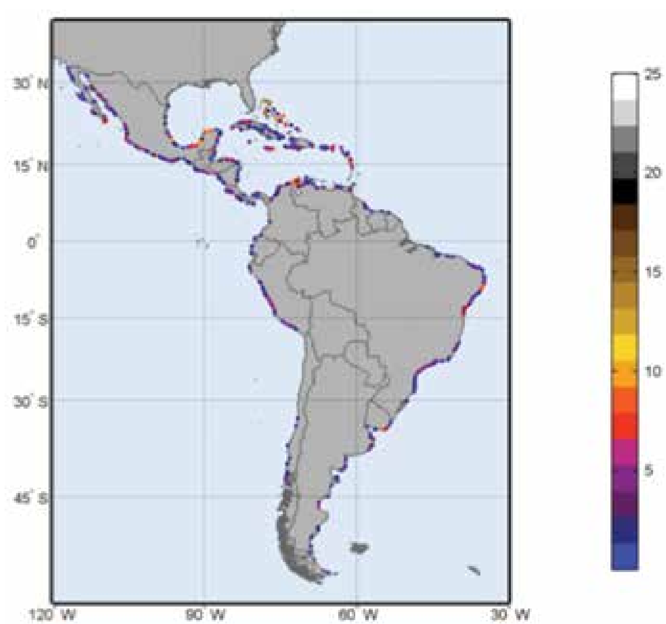
Table 3.10 (concluded)

	Scenario										
Country	A	B	C	D	E	F1	F2	G1	G2	H1	H2
NIC	0	0	0	0	0	0	0	0	0	0	0
ABW	0	0	0	0	0	0	0	0	0	0	0
ANT	0	0	0	0	0	0	0	0	0	0	0
MSR	0	0	0	0	0	0	0	0	0	0	0
GLP	0	0	0	0	0	0	0	0	0	0	0
GRD	0	0	0	0	0	0	0	0	0	0	0
GUF	0	0	0	0	0	0	0	0	0	-	-
SLV	0	0	0	0	0	0	0	0	0	0	0
ECU	0	0	0	0	0	0	0	0	0	-	-
DMA	0	0	0	0	0	0	0	0	0	0	0
CYM	0	0	0	0	0	0	0	0	0	0	0
VGB	0	0	0	0	0	0	0	0	0	0	0
BLZ	0	0	0	0	0	0	0	0	0	0	0
BRB	0	0	0	0	0	0	0	0	0	0	0
BHS	0	0	0	0	0	0	0	0	0	0	0

Source: Prepared by the authors.

Figure 3.9 shows the spatial distribution of the roads at elevations of up to 1 m that would be affected. As indicated, these impacts would be concentrated along certain parts of the coasts of Brazil, Mexico and the Bolivarian Republic of Venezuela, as well as some Caribbean islands.

FIGURE 3.9
ROADWAYS IMPACTED UNDER SCENARIO E (1-METRE RISE IN SEA LEVEL)
(Number of segments of approximately 5 km in length)



Source: Prepared by the authors.

As indicated in the second project document, which deals with the vulnerability of the region's coastal areas, fewer segments of railroad tracks than stretches of roadways would be affected, although the former's relative importance is disproportional, since the impact on the transportation network can be expected to be more severe. However, only in the cases of Cuba, Mexico and Brazil, and of Puerto Rico under a hurricane scenario, are the results comparable with the other variables.

4.1.1.4 Flooding in the region's major deltas

Using much the same approach as for the analysis of each country's degree of vulnerability and spatial distributions, the results obtained for the study units (5 km) can be aggregated for other geographical areas, such as the region's deltas, which are ecologically and/or economically important low-lying areas subject to subsidence effects, in addition to the effect of rising sea levels. Very specific types of information are required at the local level in order to undertake a targeted study of each delta, but the data compiled here on some of the region's major deltas may provide some guidelines. The deltas covered here are the São Francisco River Delta, River Plate Delta, the Orinoco River Delta, the Magdalena River Delta, the Grijalva River Delta, the Atrato River Delta and the Amazon Delta.

Sea level rise is likely to have a more severe impact on the areas where major Latin American and Caribbean rivers empty into the sea, because these deltas are low-lying, and the terrain is quite flat. In order to quantify the effects, an analysis has been undertaken of the areas that would be flooded and the populations that would be impacted by a 1-m sea level rise (scenario E) and by a rise of 2 m, which is a value that provides a safety margin in the event of additional subsidence.

As explained in earlier project documents, the calculations for each of the deltas yielded the area that would be flooded under these two assumptions, the level of flooding and the population that would be impacted. Table 3.11 gives the values obtained for each of these deltas.

TABLE 3.11
IMPACTED AREAS AND POPULATIONS IN THE MAJOR DELTAS OF LATIN AMERICA AND THE CARIBBEAN: SEA LEVEL RISES OF 1 M AND 2 M

	0 m to 1 m		0 m to 2 m	
Deltas	Flooded area (*ha*)	Impacted population	Flooded area (*ha*)	Impacted population
São Francisco	3 403.62	60 516	12 005.84	108 279
River Plate	79 824.22	103 180	130 481.38	148 472
Orinoco	3 454.77	339	6 373.20	365
Magdalena	16 901.40	103 962	36 292.86	128 334
Grijalva	28 928.93	27 490	6 5401.78	37 897
Atrato	5 588.19	6 894	17 761.60	8 131
Amazon	7 353.99	103 482	14 382.73	103 668

Source: Prepared by the authors.

The following figures show the contour lines for areas at elevations of up to 1 m and 2 m for these deltas, which represent the posited high-water marks. The deltas of the Río de la Plata and the Magdalena River would be the areas in which the largest populations would be impacted by a 1-m rise in sea level, while the River Plate River Delta would experience the most flooding in terms of land area.

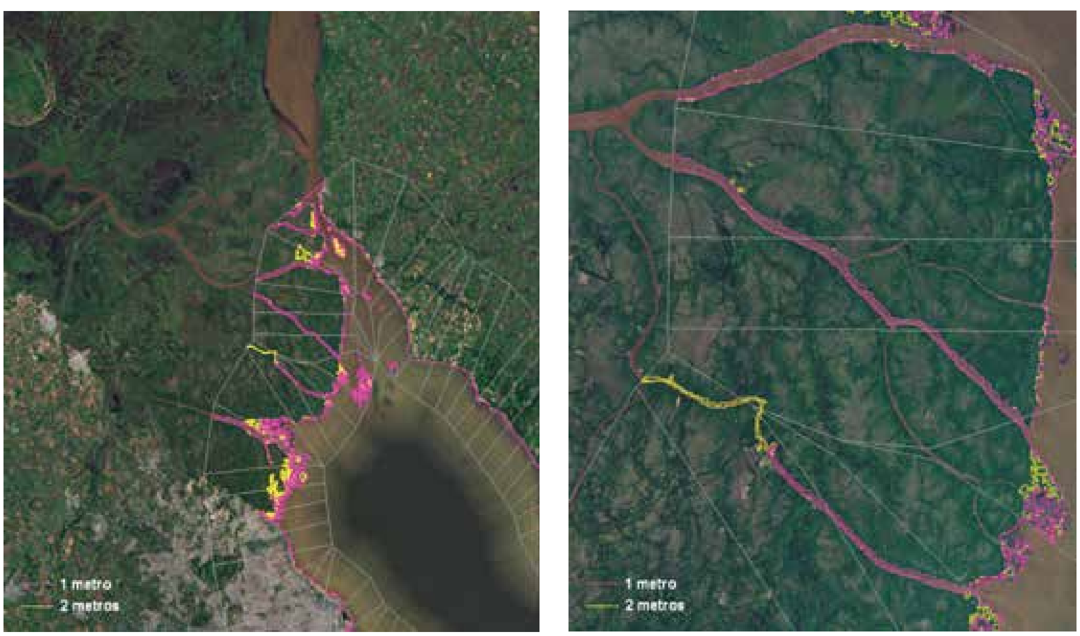
FIGURE 3.10

1-METRE AND 2-METRE CONTOUR LINES FOR THE SÃO FRANCISCO RIVER DELTA

Source: Prepared by the authors.

FIGURE 3.11

1-METRE AND 2-METRE CONTOUR LINES FOR THE RIVER PLATE DELTA

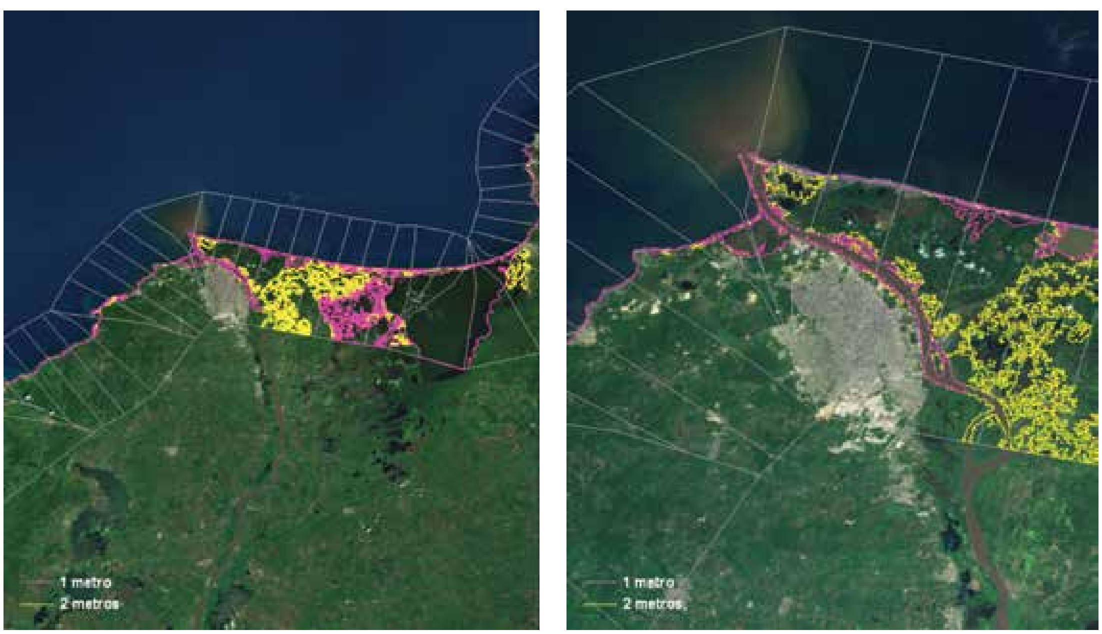


Source: Prepared by the authors.

FIGURE 3.12
1-METRE AND 2-METRE CONTOUR LINES FOR THE ORINOCO RIVER DELTA

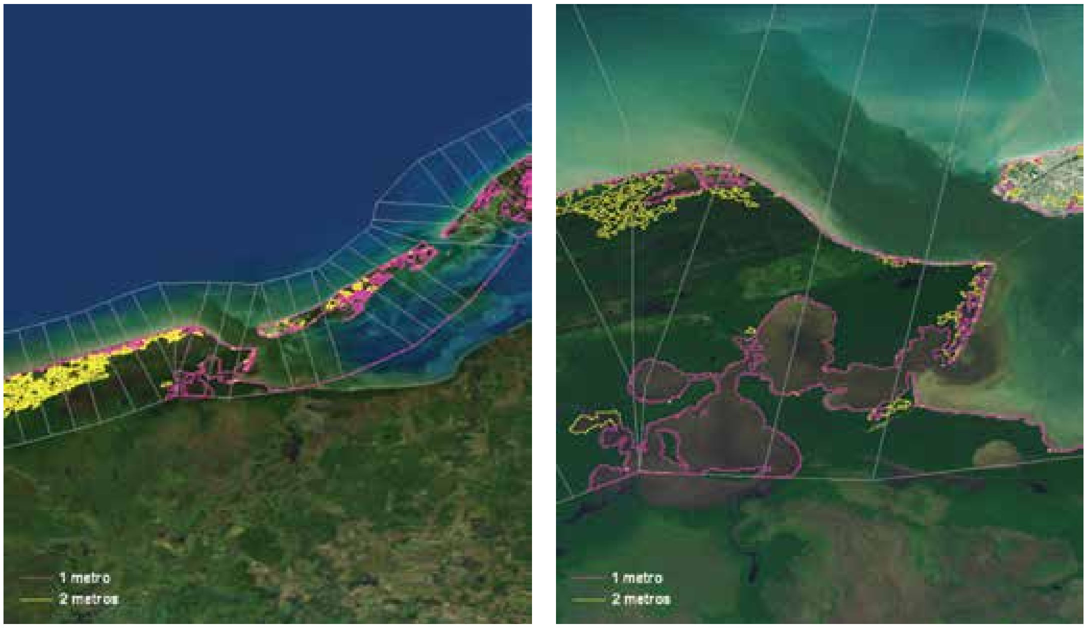
Source: Prepared by the authors.

FIGURE 3.13
1-METRE AND 2-METRE CONTOUR LINES FOR THE MAGDALENA RIVER DELTA



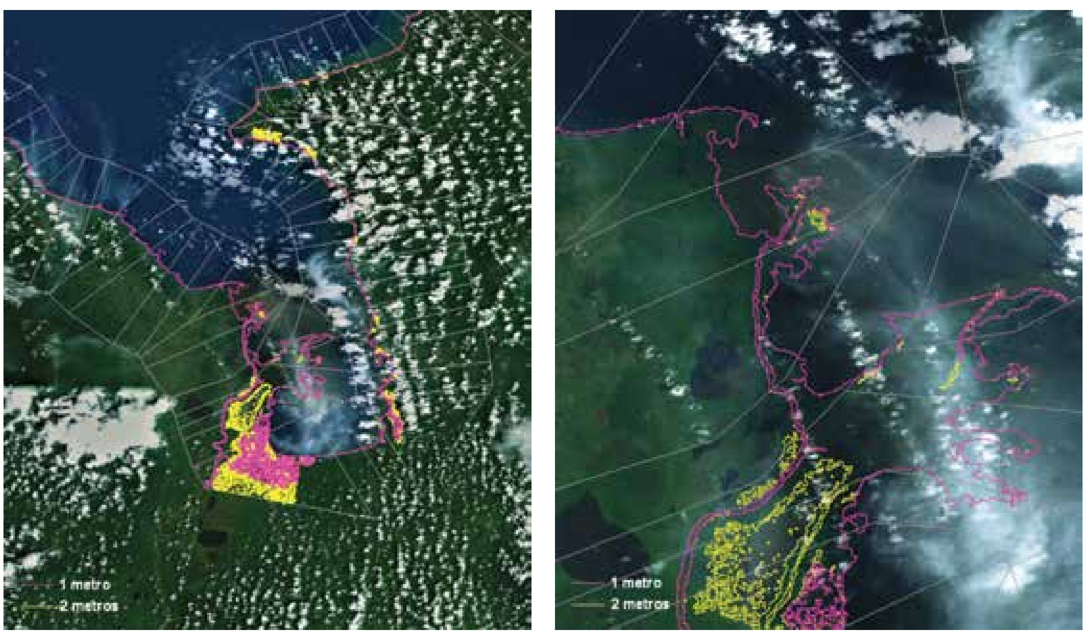
Source: Prepared by the authors.

FIGURE 3.14
1-METRE AND 2-METRE CONTOUR LINES FOR THE GRIJALVA RIVER DELTA



Source: Prepared by the authors.

FIGURE 3.15
1-METRE AND 2-METRE CONTOUR LINES FOR THE ATRATO RIVER DELTA



Source: Prepared by the authors.

FIGURE 3.16
1-METRE AND 2-METRE CONTOUR LINES FOR THE AMAZON DELTA

Source: Prepared by the authors.

4.1.2 Determination of total sea levels and flood levels

Permanent flooding of coastal areas is analysed on the basis of the following factors:

- Sea Level Rise (SLR): The benchmark or mean level relative to the effects associated with all other variables.
- Tide (T): A deterministic variable that fluctuates on an hourly scale around the mean sea level.
- Storm Surge (SS): A factor associated with a rise or descent in sea levels due to the effects of wind and/or barometric pressure.
- Wave set-up (*set-up*): This component raises the mean water level along the coastline as a result of the wave energy released when waves break. Based on offshore swell conditions, the coastline set-up can be determined using the formulation developed by Guza and Thornton (1981):

$$\eta = 0{,}17\ H_0 \tag{3.2}$$

Where H_0 is the height of the wave as it breaks.

- Wave run-up ($Ru_{2\%}$): This determines how much the surface of the water rises above the beach slope as a result of wave action. It does not constitute an increase in sea levels per se, but it does affect beach water levels.

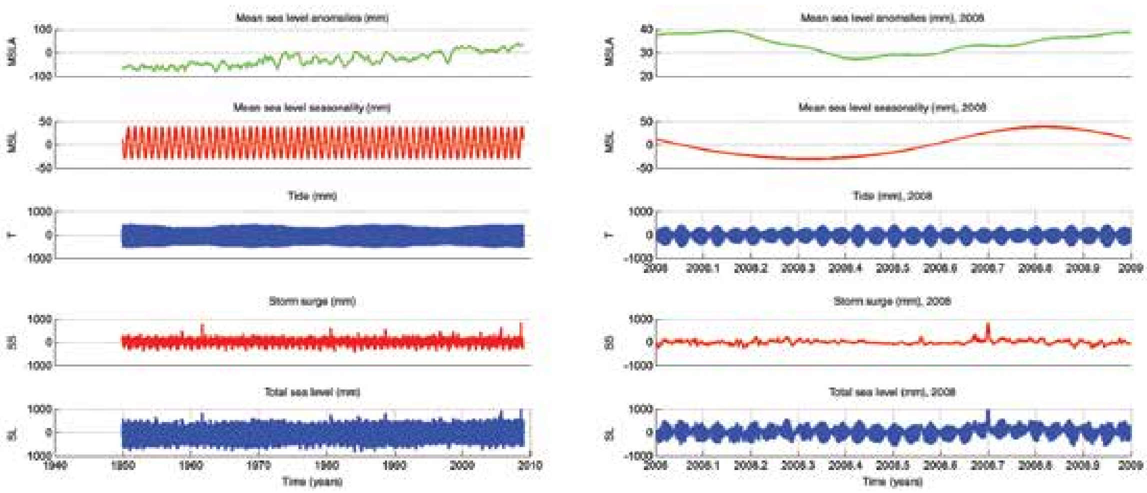
In the absence of more specific data, the run-up can be considered to be the high-water mark for breakers amounting to a run-up of 2% calculated on the basis of the empirical work of Nielsen and Hanslow (1991), which has been described in the supplementary project document on theoretically derived effects.

The variations in sea level can be measured by combining these factors into an aggregated sea-level variable, such that, in the absence of beaches:

SL = MSL + T + SS + Set-up	(3.3)

Flood levels can be used to construct a time series that can be analysed using the risk-assessment methodology developed as part of this research effort. Some specific aspects need to be taken into account, however. First of all, tides are a deterministic variable and should therefore not be aggregated into the calculations of uncertainty. Second, trends are evaluated only for the MSL (SLR), such that this trend is the basis for evaluating the uncertainty of the residual made up of storm surge, mean level and set-up. The following figure gives an example of series for each component and the flood level series calculated up to 2008.

FIGURE 3.17
TIME SERIES FOR FLOOD-LEVEL COMPONENTS: 1948-2010 AND 2008



Source: Prepared by the authors.

4.1.3 Flood levels (temporary floods)

This impact is analogous to mean levels except that it refers to extreme events and is therefore analysed on the basis of the extreme regime for the flood level variable:

(a) If the coastline included in the study unit has beaches:

FL = MSL + T + SS + Run-up	(3.4)

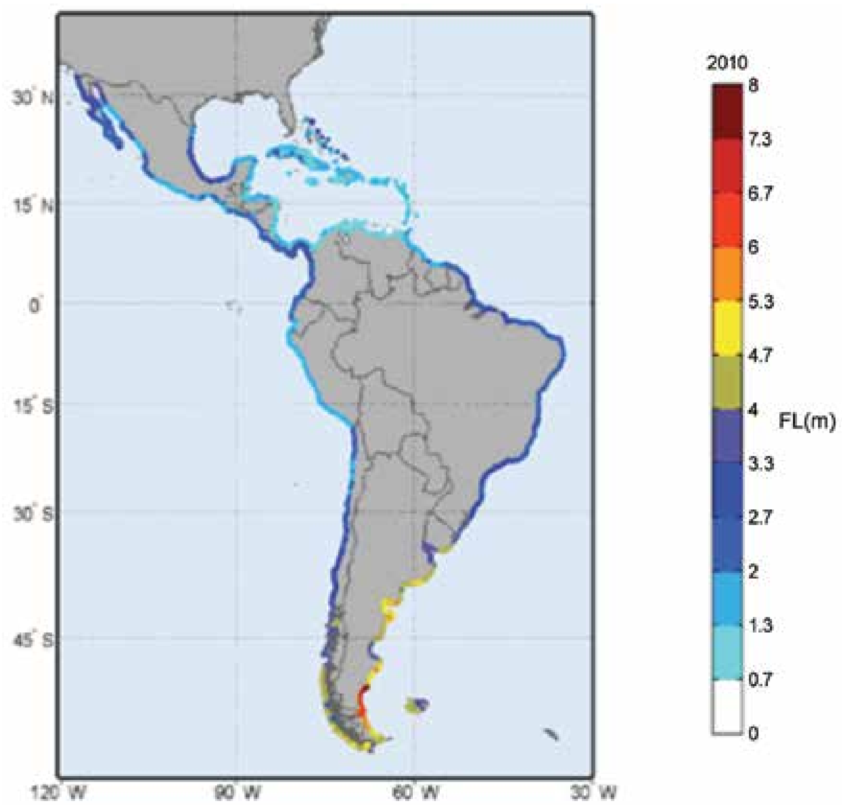
(b) If the coastline included in the study unit does not have beaches:

FL = MSL + T + SS + Set-up	(3.5)

This variable can be analysed using a special method that allows the most extreme values for flood levels to be separated out, thereby providing a basis for a study of the frequency and intensity of extreme flooding events triggered by storm surges along the coast of Latin America and the Caribbean.

Figure 3.18 shows the flood levels for a 50-year return period (with an annual probability of the event being exceeded of 0.02) along the coasts of Latin America and the Caribbean. As was observed in the first project document on coastal variability, dynamics and trends, flood levels, which are influenced by the various components that determine sea levels, exhibit a marked degree of spatial variability. The highest values —above 4 m— are recorded for the coasts of Chile, Argentina and Uruguay. The values for the Caribbean Sea are around 1 m, while the values for the coasts of Brazil and the Pacific are around 3 m.

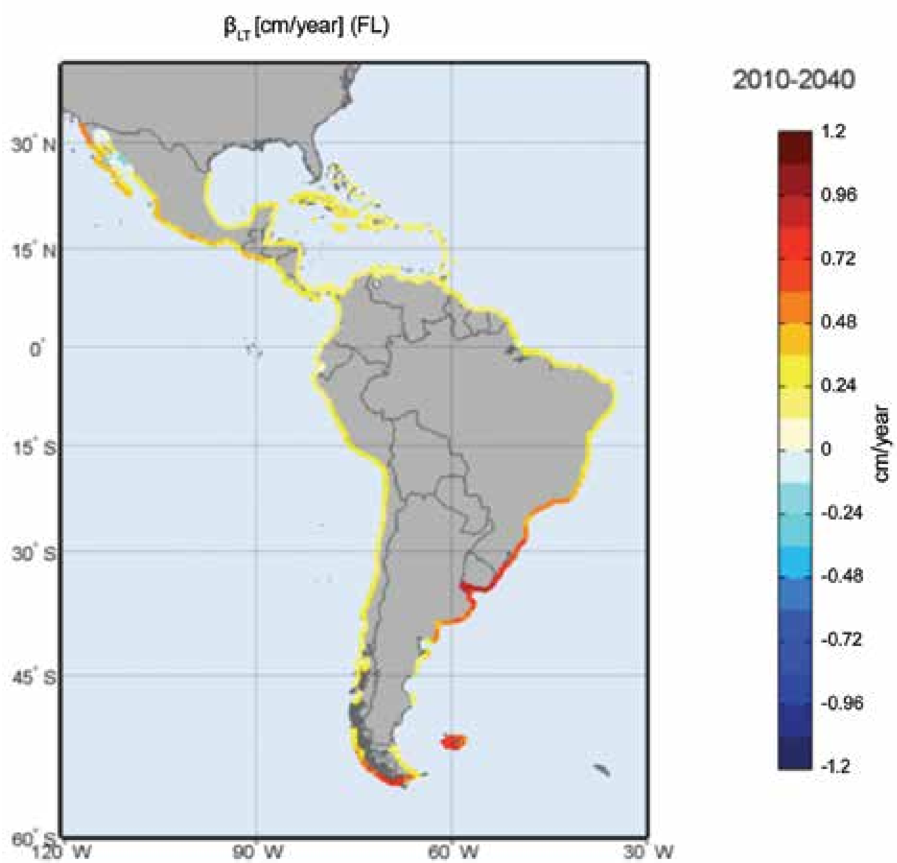
FIGURE 3.18
FLOOD LEVELS: 50-YEAR RETURN PERIODS MEASURED FROM 2010
(Metres)



Source: Prepared by the authors.

Figure 3.19 reflects the rate of change obtained for extreme events. The areas with the most marked rates of change (up to 1 cm/year) are in the vicinity of the River Plate, and they are precisely those areas that have the highest flood-level values. For the rest of the region, the trends are generally below 0.5 cm/year.

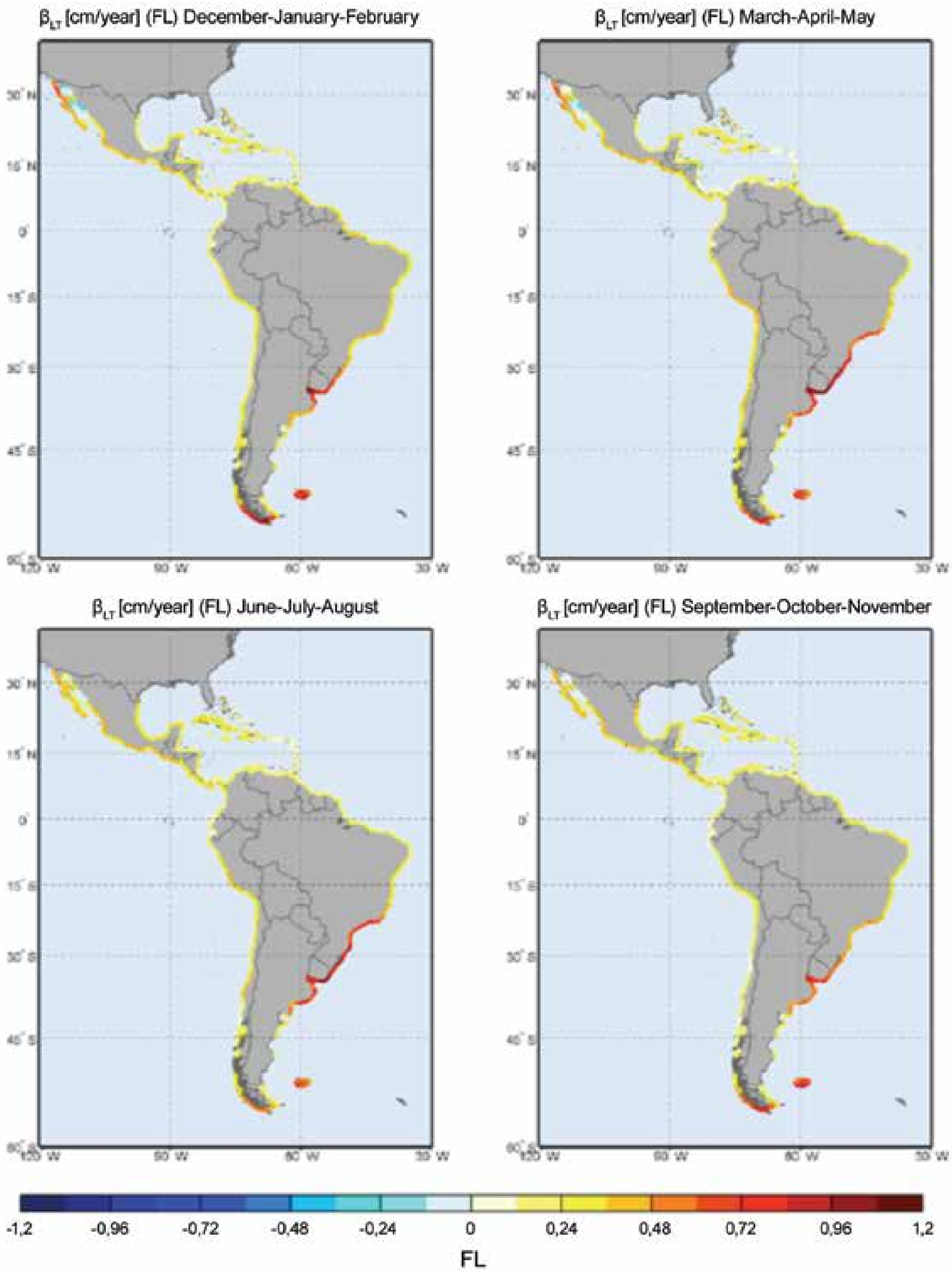
FIGURE 3.19
FLOOD-LEVEL EXTREMES: LONG-TERM TRENDS
(Centimetres/year)



Source: Prepared by the authors.
Note: Locations for which the trend is not statistically significant are marked in black.

Figure 3.20 shows the same trends on a seasonal basis, with the highest values being seen during the winter and spring in the River Plate Delta and the Gulf of California. Along the southern coast of Brazil, the trend seen in the spring and summer weakens during the rest of the year. This degree of seasonal variability is significant because it signals an increase in the annual range of variation; in other words, conditions during one portion of the year will not vary while, during certain seasons, extreme values will rise. At other locations, these changes are sustained throughout the year. In the River Plate Delta, seasonal variations are not very pronounced, and the trend can therefore be regarded as virtually constant in all months of the year.

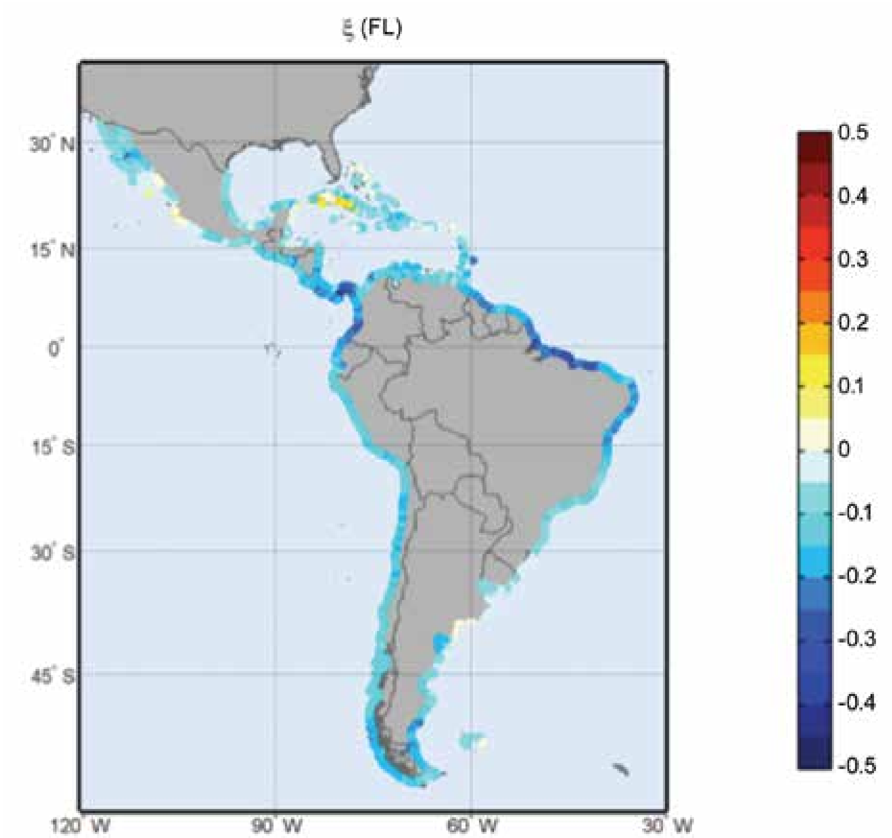
FIGURE 3.20
LONG-TERM TRENDS IN SEASONAL FLOOD LEVELS
(Centimetres/year)



Source: Prepared by the authors.
Note: Locations for which the trend is not statistically significant are marked in black.

Figure 3.21 shows the parameter used to analyse extreme flood levels. Negative values are recorded for much of the coastline of Latin America and the Caribbean; the exceptions are the southern coast of Cuba and some locations along the coast of Baja California, where the values are positive and virtually null, respectively. This indicates that, for most of the region's coastline, the distribution of extreme flooding events is quite limited, since, as can be seen in figure 3.22, there is a Weibull-type distribution of extreme values.

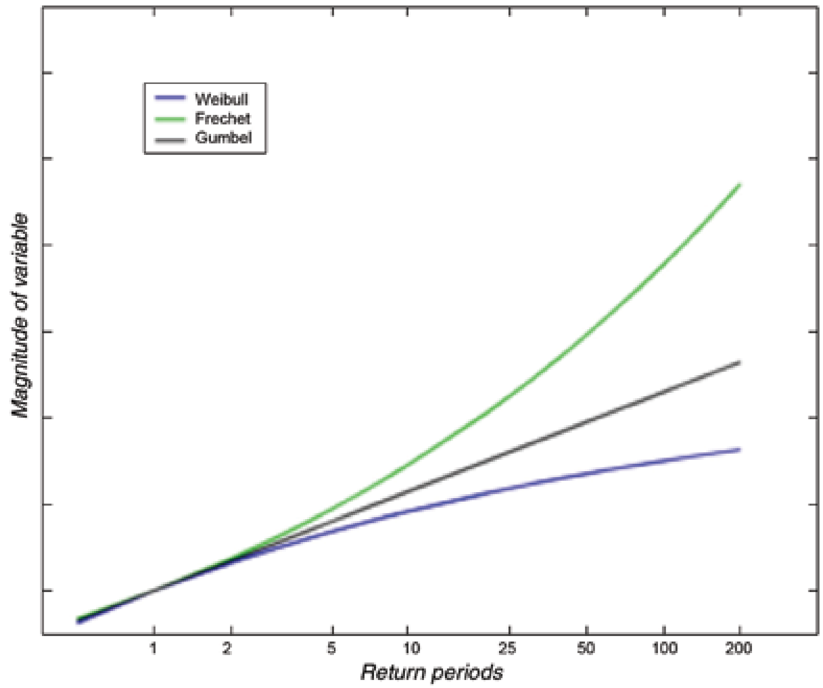
FIGURE 3.21
PARAMETER FOR THE GENERALIZED EXTREME DISTRIBUTION FUNCTION FOR FLOOD LEVELS



Source: Prepared by the authors.
Note: Refers to a dimensionless parameter, as indicated in figure 3.22.

As can be seen in figure 3.22 et seq., flood level (FL) trends have climbed over the past 61 years due to increases in wave activity, mean sea levels and storm surges (see previous project documents for descriptions of how these agents have changed).

FIGURE 3.22
GENERALIZED EXTREME VALUE (GEV) DISTRIBUTION FOR SHAPE PARAMETERS



Source: Prepared by the authors.

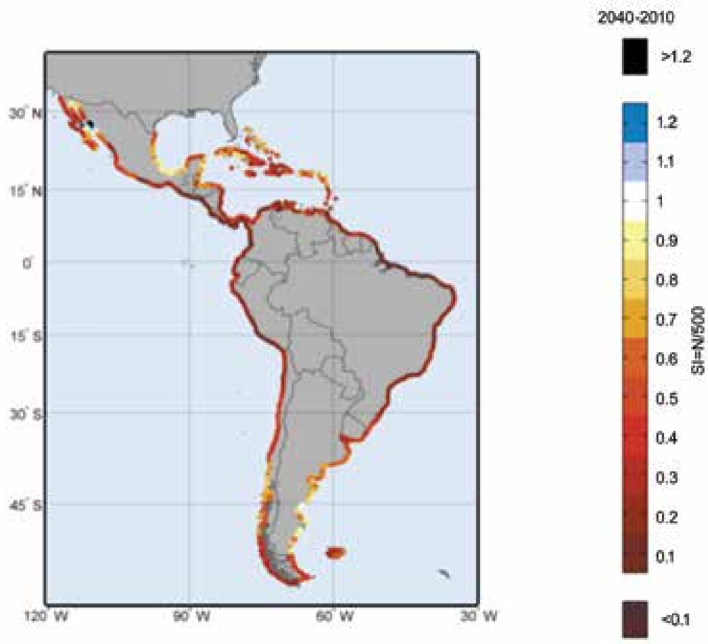
By analogy with the usual engineering practice for the design of infrastructure works, the recurrence interval of extreme values associated with a given return period (mean recurrence of an event of a specific intensity) —in this case, 500 years— has been analysed, and an index has been constructed in order to compare the future and current 500-year return periods for two time horizons: 2040 (figure 3.23) and 2070 (figure 3.24). In all cases, the index decreases, which signals an increased frequency of extreme flood events. In contrast to the results for extreme waves, which do not increase throughout the region as a whole, in this case, because of the joint action of the various factors relating to sea levels, there is a widespread increase in flooding in the region's coastal areas. Locations included in the 50-year return period (within the study period covered by the simulation) actually have recurrence intervals of less than 10 years in many cases (see table 3.12).

Unlike the situation with respect to rising sea levels (SLR), this type of coastal flooding does not increase gradually; instead, progressive but sustained changes in the overall dynamics increase the probability that this type of flooding will occur during storms. In this case, then, the effects are not deferred over time, and the measures that will need to be adopted differ from those associated with long-term trends and gradual developments. The foreseeable effects within the next few decades may manifest themselves in the form of events lasting a few hours or days that will be more intense than at present; in other words, the current types of extreme events may begin to occur more frequently.

The influence of such events on the population, land area and crops in each country has been analysed for floods based on current statistics under the various sea-level scenarios used in this study. Recurrence rates of 50 and 500 years have been used, since the first figure corresponds to the frequencies dealt with in simulations, while the second is the figure typically used for the return periods employed as a basis for the design of maritime structures.

FIGURE 3.23

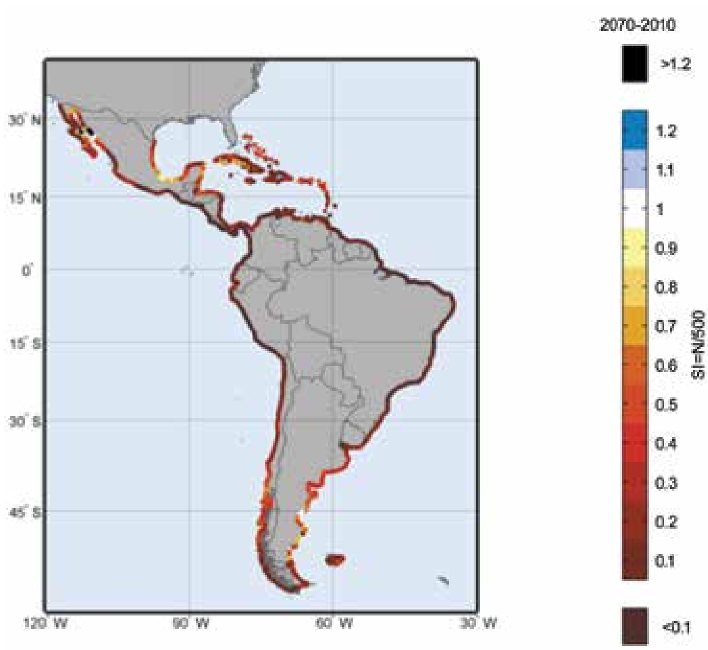
SAFETY INDEX FOR FLOOD LEVELS FOR A 500-YEAR RETURN PERIOD: 2040 TIME HORIZON (SCENARIO A)



Source: Prepared by the authors.

FIGURE 3.24

SAFETY MARGIN FOR FLOOD LEVELS HAVING A MEAN RETURN PERIOD OF 500 YEARS: 2070 TIME HORIZON (SCENARIO C)



Source: Prepared by the authors.

Table 3.12 shows the expected changes for the two return periods used here by 2040 and 2070. In the two cases, both for the case of recurrences covered in the simulation period (return period of 50 years) and for the case of the statistical extrapolation of extremes, flood events appear to become more frequent. For some locations, the frequency increases much more sharply than in others, but at most of the locations the rate of recurrence as of 2070 will be less than 10 years. This means that the most extreme value recorded in the past six decades will, on average, occur at least once a decade in the coming 60 years in many locations within the region.

TABLE 3.12
CHANGES IN RETURN PERIODS FOR FLOOD LEVELS (COASTAL FLOODING SERIES) AT VARIOUS LOCATIONS IN LATIN AMERICA AND THE CARIBBEAN

Study unit	50-year and 500-year return periods							
	Longitude	Latitude	2010	2040	2070	2010	2040	2070
Río de Janeiro (BRA)	-43.23	-22.99	50	12.22	3.89	500	83.11	18.78
Santos (BRA)	-46.24	-23.93	50	11.99	3.76	500	81.91	18.22
Montevideo (URY)	-56.00	-34.86	50	24.07	11.71	500	237.64	112.97
Concepción (CHL)	-73.09	-36.83	50	23.89	11.98	500	204.55	88.57
Valparaíso (CHL)	-71.63	-32.96	50	23.12	11.24	500	180.93	71.05
Arica (CHL)	-70.45	-18.38	50	17.52	6.92	500	131.65	40.70
Chorrillos (PER)	-77.04	-12.09	50	7.73	2.27	500	34.56	6.08
Talara (PER)	-81.26	-4.63	50	16.93	6.75	500	111.02	32.04
Machala (ECU)	-80.28	-3.40	50	29.82	18.04	500	269.96	148.40
La Libertad (ECU)	-80.78	-2.36	50	15.52	5.96	500	98.68	26.76
Bahía Solano (COL)	-77.38	6.05	50	12.39	4.32	500	65.01	14.90
Los Santos (PAN)	-80.26	7.34	50	13.91	5.01	500	78.61	19.13
San José (CRI)	-83.97	9.29	50	7.90	2.29	500	34.88	6.02
Managua (NIC)	-86.57	11.88	50	9.53	2.70	500	59.18	10.87
Acapulco (MEX)	-99.73	16.78	50	9.45	2.42	500	67.11	11.74
Ensenada (MEX)	-116.69	31.74	50	19.94	8.48	500	174.72	64.82
Cabo (MEX)	-109.85	22.98	50	30.18	17.81	500	333.41	218.64
Veracruz (MEX)	-96.02	19.05	50	45.25	40.89	500	448.38	401.60
Cancún (MEX)	-86.85	21.04	50	42.34	35.76	500	436.97	381.22
P. Plata (DOM)	-70.66	19.70	50	13.00	4.49	500	79.18	18.87
Bridgetown (BRB)	-59.56	13.20	50	19.30	8.54	500	131.26	43.48
Caracas (VEN)	-67.02	10.59	50	18.98	8.14	500	140.19	46.79
Georgetown (GUY)	-57.95	6.70	50	12.10	4.08	500	68.64	15.49
Fortaleza (BRA)	-38.49	-3.81	50	11.25	3.59	500	65.50	13.94
Maceio (BRA)	-35.60	-9.52	50	16.83	6.81	500	104.76	30.40
P. Segura (BRA)	-39.00	-16.28	50	11.68	3.74	500	70.05	15.19
P. Sta Cruz (ARG)	-68.26	-50.14	50	40.65	32.27	500	364.75	247.99
I. Taggart (CHL)	-75.58	-49.45	50	32.61	21.94	500	269.10	153.42

Source: Prepared by the authors.

Table 3.13 gives the surface areas for the different flood levels associated with the various scenarios. These values are for the differential increase relative to the current situation; in other words, they represent the impact of floods having a mean recurrence interval of 50 years minus the existing value. The results here are at least one order of magnitude greater than they are for sea level rise (the order in which the values are given in these tables is the same as the order used for flooding caused by sea level rise): approximately 3,500 km2 for Mexico in scenario E (table 3.8) versus over 15,000 km2 (table 3.13); in both cases, Mexico is the hardest-hit country.

El Niño has less of an impact in this case than in the computations for flooding caused by sea level rise because it plays no more than a small part in the combined effect of all the relevant factors. Consequently, the results for the F scenarios are similar to the others.

TABLE 3.13
INCREASE IN AFFECTED SURFACE AREA FOR EACH FLOOD LEVEL: 500-YEAR RETURN PERIODS MEASURED FROM 2010
(Square kilometres)

		Scenario									
ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Reference year: 2010
484	MEX	411	564	899	2 677	5 579	355	5 987	29	5 610	11 867
76	BRA	421	582	944	2 630	6 341	97	6 519	0	6 341	6 663
192	CUB	99	137	222	664	1 470	51	1 544	0	1 470	1 206
32	ARG	133	185	298	821	1 570	20	1 590	1	1 571	7 382
44	BHS	54	75	119	519	1 190	10	1 218	0	1 190	1 294
170	COL	42	57	92	263	755	21	861	0	755	644
862	VEN	31	42	67	180	379	2	381	0	379	475
340	HND	17	29	54	170	471	6	496	0	471	237
740	SUR	83	114	186	518	1 017	0	1 017	6	1 022	842
558	NIC	26	36	57	151	466	3	476	0	466	418
328	GUY	89	122	195	522	1 016	0	1 016	9	1 024	974
152	CHL	45	62	98	267	537	6	544	0	537	1 300
604	PER	18	25	39	181	362	73	447	0	362	1 597
218	ECU	10	14	22	157	322	75	401	0	322	442
591	PAN	16	21	34	127	263	22	287	0	263	288
84	BLZ	23	30	46	118	242	2	244	0	242	357
214	DOM	6	9	14	40	86	4	91	0	86	93
858	URY	12	17	27	79	165	4	169	0	165	791
254	GUF	6	8	13	34	75	0	76	0	75	200
320	GTM	1	1	1	5	16	2	24	0	16	6
188	CRI	2	3	4	16	40	5	47	0	40	51
332	HTI	2	3	4	18	59	1	64	0	59	24
222	SLV	1	1	1	5	12	2	17	0	12	10
630	PRI	7	10	17	48	102	3	106	0	102	159
388	JAM	3	4	7	20	45	2	48	0	45	76
796	TCA	8	10	17	46	129	2	134	0	129	55
780	TTO	0	0	0	2	20	0	20	0	20	3
136	CYM	0	0	0	2	5	0	5	0	5	6
530	ANT	2	3	5	12	19	0	19	0	19	11
28	ATG	1	1	1	4	10	0	11	0	10	11
312	GLP	1	1	2	4	8	0	9	0	8	9
474	MTQ	0	0	0	0	0	0	0	0	0	0

Table 3.13 (concluded)

		Scenario									
ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Reference year: 2010
660	AIA	1	1	1	4	8	0	8	0	8	16
92	VGB	1	1	2	4	9	0	9	0	9	13
850	VIR	0	0	0	1	2	0	2	0	2	2
533	ABW	0	0	0	1	2	0	2	0	2	1
662	LCA	0	0	0	0	1	0	1	0	1	1
659	KNA	0	0	0	1	2	0	2	0	2	1
52	BRB	0	0	0	0	0	0	0	0	0	0
308	GRD	0	0	0	0	0	0	0	0	0	0
212	DMA	0	0	0	0	0	0	0	0	0	0
670	VCT	0	0	0	0	0	0	0	0	0	0
500	MSR	0	0	0	0	0	0	0	0	0	0

Source: Prepared by the authors.

Figure 3.25 shows the surface area that would be flooded under present conditions using a 50-year return period. Values below 5 km2 have not been included. The reader will see that the eastern coast bears much more of an impact than the western coast does. While the southern Chilean coast is subject to high flood levels, it is barely affected at all because the configuration of the coast, with its high elevations, greatly reduces its exposure.

Figure 3.26 shows the surface area that would be flooded with respect to the present under scenarios C (2040) and E (1-m sea level rise) using the same extreme flooding statistic. Here again, the consequences, assuming a sea level rise of 1 m, are significant, while, with the observed changes, the foreseeable impact is of differential values relative to the present.

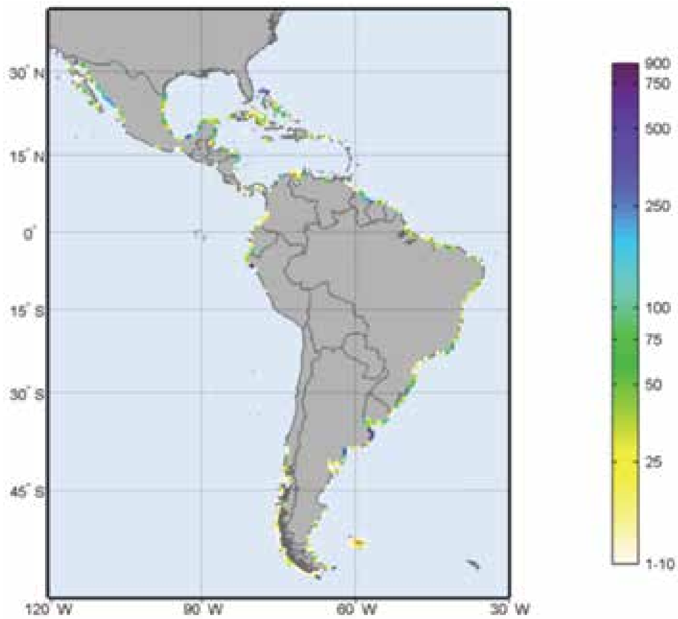
The impacted locations are the same in both cases, since, in a scenario of a sea level rise of 1 m, the flooding of the most low-lying areas caused by smaller (about 30 cm) rises is simply accentuated. In addition, under the scenario of a rise of 1 m, other areas along the western coast and in Central America are affected and flooding increases along the region's eastern coast. The main point to be brought out here is that the locations where the largest land areas would be flooded are the sites of large urban centres, and this is especially true of island countries.

A comparison of the results for the two different return periods shows that they are quite similar. This is because the distribution of the extreme floods is bounded by very extreme values, which attenuates the corresponding intensities. In this case, an increase in sea level has a greater relative impact on temporary flooding because it exposes larger areas to the impact of sporadic extreme flooding.

FIGURE 3.25

SURFACE AREAS AFFECTED BY COASTAL FLOODING: 50-YEAR RETURN PERIODS MEASURED FROM 2010

(Square kilometres)



Source: Prepared by the authors.

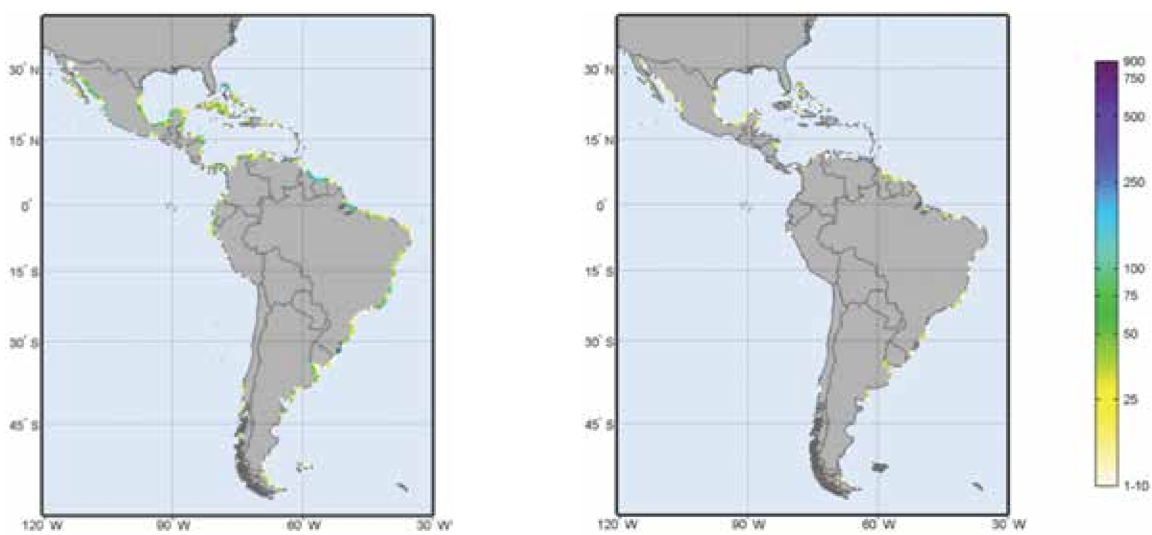
FIGURE 3.26

SURFACE AREAS AFFECTED BY COASTAL FLOODING: 50-YEAR RETURN PERIODS MEASURED FROM 2010 (SCENARIOS C AND E)

(Square kilometres)

a) Scenario E: sea level rise of 1 m

b) Scenario C: extrapolation of statistical trends to 2070



Source: Prepared by the authors.

Tables 3.14 and 3.15 show the percentages, by scenario and by country, of the population that would be affected by flooding with return periods of 50 and 500 years. The results for each scenario are given as percentages relative to the population in 2010 impacted by floods having the corresponding return period in each case; this is shown in the far-right column as the percentage of the population living in coastal areas (at elevations of up to 10 m). Scenarios F2 and G2 reflect the effect of El Niño and La Niña events given a 1-m rise in sea levels, and the population covered in scenario E has therefore been deducted.

When compared to the equivalent situation for a rise in sea levels (see table 3.7), countries such as the Dominican Republic, Haiti and Suriname are less affected by these extreme events than would be indicated by their position in the country ranking. Countries with the largest numbers of persons affected include Brazil, Mexico and Argentina. For Argentina, under scenario E, the impact of flooding would be 70% greater than it would be at present. The impact in most of the other countries would increase by less than 30%, but, in Suriname and Guyana, the increase would be approximately 80% relative to the foreseeable present impact. Generally speaking, around 25% of the population living in coastal areas on the mainland at elevations of between 0 m and 10 m would be affected by flooding (50-year return periods), while the figure for island countries is on the order of 45%. These figures will change significantly for many countries in the coming decades, however. In some, such as Panama and Haiti, the impact of El Niño events at an elevation of 1 m (scenario F2) may be less than at present. In other cases, however, such as that of Guatemala, the impacted population would increase (from 2.4% to 7% for a 50-year return period).

TABLE 3.14

VARIATION IN SIZE OF AFFECTED POPULATION UNDER EACH FLOOD-LEVEL SCENARIO: 50-YEAR RETURN PERIODS MEASURED FROM 2010

(Percentages of the population in coastal areas)

		Scenario									
ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Impacted coastal population in 2010 (up to 10 m)
76	BRA	1.69	2.32	3.69	10.33	21.91	0.43	0.53	0.00	0.00	25.09
484	MEX	2.56	3.52	5.64	14.02	25.47	1.09	1.31	0.16	0.09	25.35
32	ARG	4.12	6.61	12.01	33.97	69.47	1.13	2.47	0.01	0.01	14.07
192	CUB	0.36	0.50	0.82	2.65	6.43	0.19	0.32	0.00	0.00	27.66
862	VEN	3.31	4.41	6.78	14.79	22.84	0.08	0.10	0.09	0.02	24.29
170	COL	1.60	2.16	3.38	8.97	18.62	0.37	1.59	0.00	0.00	24.05
630	PRI	3.02	4.29	6.84	18.57	37.92	1.10	1.33	0.00	0.00	28.71
604	PER	0.15	0.21	0.34	2.37	5.44	0.76	1.27	0.00	0.00	34.06
214	DOM	0.94	1.30	1.97	4.88	9.25	0.62	0.42	0.00	0.00	10.58
332	HTI	2.52	2.91	3.70	5.57	14.99	2.11	1.11	0.00	0.00	15.70
218	ECU	0.91	1.24	1.98	15.16	28.84	7.48	8.23	0.00	0.00	25.63
152	CHL	0.21	0.30	0.52	1.81	3.92	0.07	0.11	0.00	0.00	35.50
328	GUY	5.93	8.15	13.35	39.14	81.54	0.00	0.00	0.64	0.81	21.58
858	URY	0.56	0.78	1.20	3.23	6.93	0.17	0.27	0.00	0.00	40.47
740	SUR	6.29	8.63	13.80	41.49	89.00	0.00	0.00	0.45	0.51	13.93
591	PAN	5.16	6.96	10.89	35.63	71.83	6.70	3.78	0.00	0.00	14.25
44	BHS	1.19	1.64	2.64	7.45	16.13	0.13	0.21	0.00	0.00	12.68
388	JAM	0.84	1.16	1.85	5.15	14.15	0.51	1.04	0.00	0.00	20.65
340	HND	1.42	1.96	3.26	10.35	26.02	1.25	3.46	0.00	0.00	7.58

Table 3.14 (concluded)

		Scenario									
ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Impacted coastal population in 2010 (up to 10 m)
222	SLV	0.22	0.30	0.48	2.00	4.60	0.87	2.94	0.00	0.00	12.72
780	TTO	0.03	0.04	0.06	0.33	11.21	0.00	0.00	0.00	0.05	11.14
320	GTM	0.60	0.84	1.34	5.62	12.90	2.42	6.97	0.00	0.00	6.19
558	NIC	0.22	0.30	0.48	1.54	12.88	0.32	3.72	0.00	0.00	15.17
84	BLZ	1.91	2.63	4.06	10.66	27.22	0.19	0.36	0.00	0.00	18.98
188	CRI	0.56	0.76	1.22	3.99	9.69	0.94	1.47	0.00	0.00	16.80
312	GLP	0.12	0.17	0.32	1.07	2.38	0.04	0.07	0.00	0.00	25.42
254	GUF	0.27	0.36	0.57	1.51	7.83	0.01	0.04	0.00	0.00	24.96
474	MTQ	9.90	13.61	15.24	15.36	15.55	2.21	0.01	0.00	0.00	29.51
850	VIR	0.10	0.13	0.21	0.47	0.95	0.04	0.03	0.00	0.00	43.25
660	AIA	0.32	0.45	0.71	2.58	5.55	0.14	0.21	0.00	0.00	47.12
136	CYM	0.15	0.21	0.33	1.21	4.74	0.09	0.34	0.00	0.00	16.92
530	ANT	0.94	1.30	2.07	5.48	9.17	0.00	0.00	0.02	0.01	24.39
533	ABW	0.35	0.49	0.77	2.03	5.54	0.06	0.13	0.00	0.00	34.73
28	ATG	0.78	1.08	1.78	4.93	9.94	0.31	0.33	0.00	0.00	34.88
52	BRB	0.23	0.32	0.51	0.88	0.88	0.00	0.00	0.00	0.00	42.03
92	VGB	0.04	0.09	0.20	0.68	1.44	0.00	0.05	0.00	0.00	46.99
662	LCA	0.24	0.33	0.51	1.02	1.02	0.02	0.00	0.00	0.00	34.26
796	TCA	1.52	2.12	3.38	9.36	21.69	0.52	0.97	0.00	0.00	21.54
212	DMA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.90
308	GRD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.58
659	KNA	0.00	0.00	0.00	0.00	1.79	0.00	0.14	0.00	0.00	40.46
670	VCT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.63
500	MSR	0.00	0.00	0.00	0.00	1.73	0.00	0.00	0.00	0.00	46.39

Source: Prepared by the authors.

TABLE 3.15
VARIATION IN SIZE OF AFFECTED POPULATION UNDER EACH FLOOD-LEVEL SCENARIO: 500-YEAR RETURN PERIODS MEASURED FROM 2010

(Percentages of the population in coastal areas)

		Scenario									
ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Impacted coastal population in 2010 (up to 10 m)
76	BRA	1.76	2.45	3.98	10.44	21.54	0.42	0.53	0.00	0.00	26.48
484	MEX	1.55	2.14	3.41	10.02	21.25	0.97	1.27	0.08	0.09	28.60
32	ARG	4.17	5.77	9.32	25.35	43.26	1.77	1.17	0.01	0.01	19.66
192	CUB	0.46	0.64	1.05	3.34	8.04	0.24	0.39	0.00	0.00	28.15
862	VEN	2.81	3.82	6.01	12.39	20.48	0.06	0.10	0.05	0.02	25.23
170	COL	1.47	2.02	3.22	8.59	19.46	0.31	1.55	0.00	0.00	24.47
630	PRI	2.68	3.69	5.90	16.58	31.92	1.10	0.91	0.00	0.00	31.91

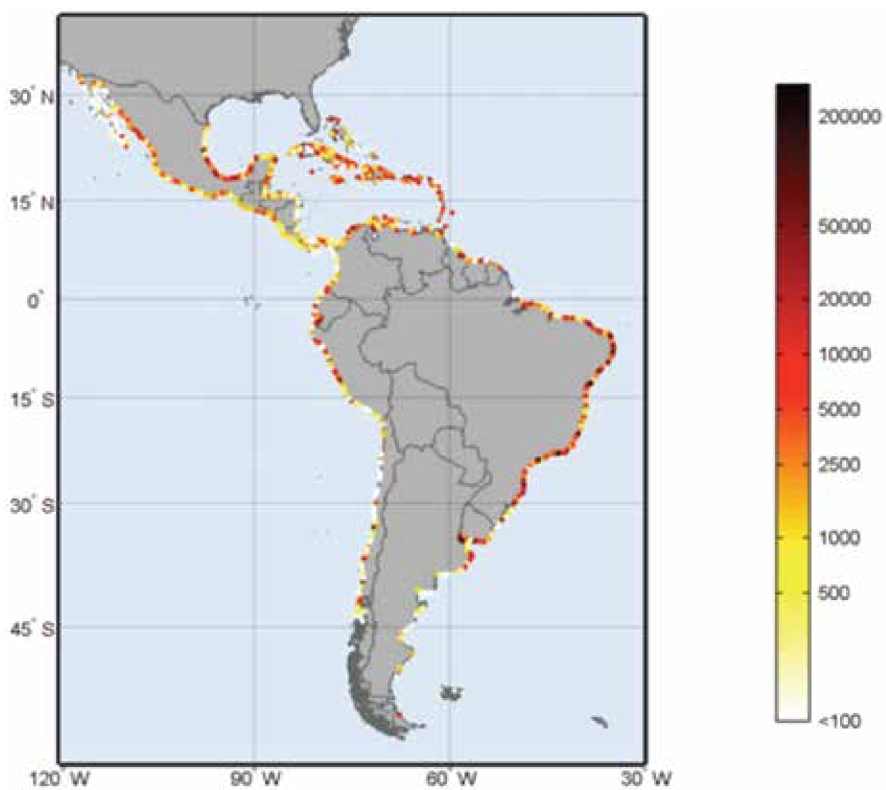
Table 3.15 (concluded)

ISO code	Country	A	B	C	D	E	F1	F2	G1	G2	Impacted coastal population in 2010 (up to 10 m)
		Scenario									
604	PER	0.16	0.23	0.37	2.63	5.71	0.88	1.31	0.00	0.00	34.19
214	DOM	0.78	1.05	1.65	4.44	8.43	0.53	0.46	0.00	0.00	10.83
332	HTI	1.00	1.37	1.79	5.14	15.09	0.69	1.32	0.00	0.00	16.12
218	ECU	0.87	1.20	1.91	13.85	28.60	7.23	7.98	0.00	0.00	26.42
152	CHL	0.31	0.43	0.67	1.90	4.05	0.11	0.11	0.00	0.00	35.86
328	GUY	5.80	8.23	13.60	38.11	78.33	0.00	0.00	0.61	0.76	22.92
858	URY	0.76	1.05	1.68	5.17	11.50	0.26	0.33	0.00	0.00	42.54
740	SUR	5.65	7.78	13.44	40.54	81.90	0.00	0.00	0.38	0.44	15.54
591	PAN	4.84	6.57	10.36	35.08	67.72	6.32	3.66	0.00	0.00	14.80
44	BHS	1.19	1.64	2.63	7.64	19.20	0.14	0.37	0.00	0.00	13.49
388	JAM	0.82	1.13	1.81	6.07	15.77	0.50	1.02	0.00	0.00	21.09
340	HND	1.59	2.27	3.83	12.14	31.90	1.35	4.31	0.00	0.00	8.01
222	SLV	0.22	0.30	0.48	1.99	5.72	0.87	2.92	0.00	0.00	12.78
780	TTO	0.03	0.04	0.06	1.13	13.48	0.00	0.00	0.00	0.05	11.14
320	GTM	0.61	0.84	1.34	5.54	16.08	2.38	6.83	0.00	0.00	6.28
558	NIC	0.22	0.30	0.48	1.53	17.87	0.32	3.72	0.00	0.00	15.22
84	BLZ	1.81	2.50	3.99	10.89	30.04	0.19	0.34	0.00	0.00	19.95
188	CRI	0.55	0.76	1.21	3.97	10.11	0.93	1.46	0.00	0.00	16.92
312	GLP	0.22	0.30	0.48	1.30	2.77	0.07	0.32	0.00	0.00	25.56
254	GUF	0.26	0.36	0.57	1.51	9.93	0.01	0.04	0.00	0.00	25.06
474	MTQ	2.39	2.40	2.42	2.53	2.70	1.96	0.01	0.00	0.00	33.21
850	VIR	0.02	0.05	0.11	0.42	0.91	0.00	0.05	0.00	0.00	43.40
660	AIA	0.49	0.66	1.06	2.91	5.52	0.21	0.16	0.00	0.00	48.16
136	CYM	0.15	0.21	0.32	2.46	5.97	0.09	0.34	0.00	0.00	17.00
530	ANT	0.93	1.29	2.05	5.41	8.26	0.00	0.00	0.02	0.00	24.71
533	ABW	0.35	0.49	0.77	2.03	6.01	0.06	0.13	0.00	0.00	34.86
28	ATG	0.81	1.11	1.77	4.81	10.82	0.32	0.45	0.00	0.00	36.31
52	BRB	0.23	0.32	0.50	0.56	0.56	0.00	0.00	0.00	0.00	42.16
92	VGB	0.13	0.17	0.28	0.76	1.38	0.05	0.04	0.00	0.00	47.23
662	LCA	0.23	0.33	0.51	0.52	0.52	0.02	0.00	0.00	0.00	34.43
796	TCA	1.45	2.02	3.22	8.93	24.80	0.50	0.92	0.00	0.00	22.59
212	DMA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.90
308	GRD	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	45.58
659	KNA	0.00	0.00	0.00	0.90	2.97	0.00	0.14	0.00	0.00	40.46
670	VCT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	42.63
500	MSR	0.00	0.00	0.00	0.69	2.77	0.00	0.00	0.00	0.00	46.39

Source: Prepared by the authors.

Figure 3.27 shows the spatial distribution of the population affected by flooding having a mean recurrence interval of 50 years. The majority of the affected population is located along the eastern coast, especially in Brazil, even though there is less flooding in these areas than further south. This is clearly due to the fact that the population concentration along the eastern coast is greater. The cities along the River Plate would also be severely impacted, since this area displays the highest flood-level values (see figure 3.18).

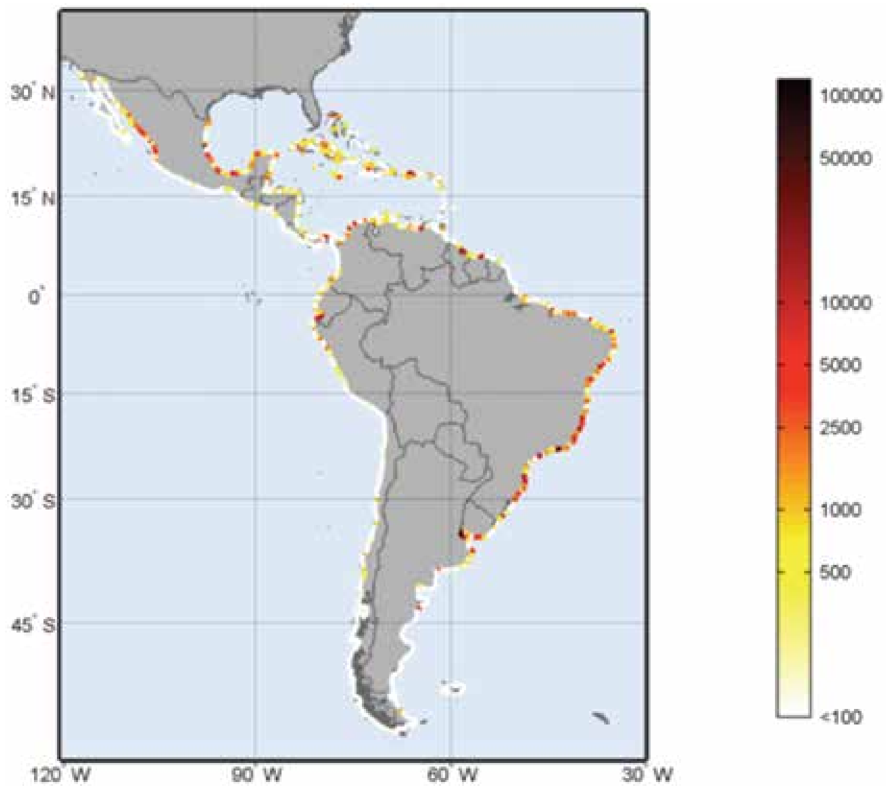
FIGURE 3.27
POPULATION AFFECTED BY FLOODING: 50-YEAR RETURN PERIODS MEASURED FROM 2010
(Number of persons)



Source: Prepared by the authors.
Note: Reference population corresponds to the year 2000.

Figure 3.28 depicts the difference in the size of the population that would be affected under scenario E (sea level rise of 1 m) and scenario C (extrapolation of statistical trends to 2070) by extreme coastal flooding. The possible impact of an increase in the size of the affected population along the eastern coast in the southern hemisphere and in major urban centres in the Caribbean, Mexico and Peru is noteworthy. The sharpest increases are in keeping with the major trends for the southern Atlantic coast (River Plate and southern Brazil), but Mexico would also be affected even though the trend figures are much lower. These results make it possible to pinpoint the coastal cities in the different countries that would be the hardest-hit (especially in northern Argentina, Uruguay and all along the coasts of Brazil).

FIGURE 3.28
DIFFERENCES BETWEEN THE POPULATION AFFECTED BY FLOODING UNDER SCENARIOS E AND C: 500-YEAR RETURN PERIODS
(Number of persons)



Source: Prepared by the authors.
Note: Reference population corresponds to the year 2000.

4.1.4 Hurricane flooding

This section will cover the results obtained for peak flood levels using a 54-year (hourly temporal resolution) hurricane database and the different pressure, wind, wave and storm surge models for various hurricane events that have been validated and then presented in the annexes to earlier project documents.

The objective of this analysis is to further define and supplement the statistical wave and storm surge maps constructed using numerical models prepared for the 61-year reanalysis of the data for the Atlantic and Pacific coasts. The maps used for this purpose depict the maximum potential waves and storm surges at these same locations during past hurricanes

This information is of crucial importance for two reasons. First, it provides an order of magnitude for the maximum wave and storm surge heights on record during high-energy events such as hurricanes. This, in turn, provides an avenue for determining the behaviour and limitations of the Global Ocean Waves (GOW) and Global Ocean Surges (GOS) reanalysis databases. Second, it serves as a basis for mapping past potential maximums; these maps can then be used as a first approximation, in the absence of other, more detailed information, for the design of coastal and harbour defence works along the Atlantic and Pacific coasts of North America (Mexico), Central America and South America.

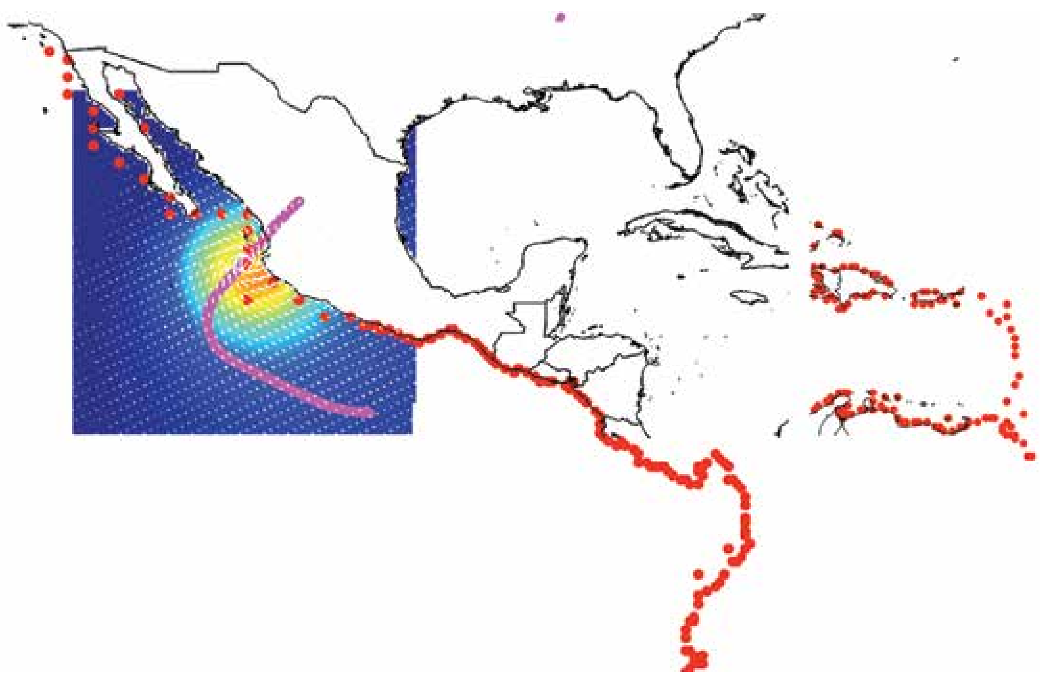
This kind of information does not provide a sufficient basis for determining trends in hurricane activity, as this would involve an extremely complex set of variables that would have to be studied in greater detail in order to arrive at reliable conclusions. Some of the more recent studies in this field are those of Bender and others (2010), Knutson (http://www.gfdl.noaa.gov/global-warming-and-hurricanes), Webster and others (2005), and Emanuel (2005).

Most global circulation models project an increase in the frequency of category 4 and category 5 tropical cyclones by the end of this century and a decrease in overall frequency. The greatest increase is expected to occur in the western Atlantic up to 20º N latitude (Bender and others, 2010).

In view of the scale of the impact of these phenomena in the region, they have been included in this risk assessment. While this study does not look at future changes in hurricane activity, scenario H does include the impacts of a hurricane (the maximum effect on record for each control point) should it reoccur (H1) and the impact of a hurricane under a climate change scenario involving a sea level rise of 1 m (H2).

In all, 369 control points for the Atlantic coast and 257 control points for the Pacific coast (see figure 3.29) have been used for this purpose.

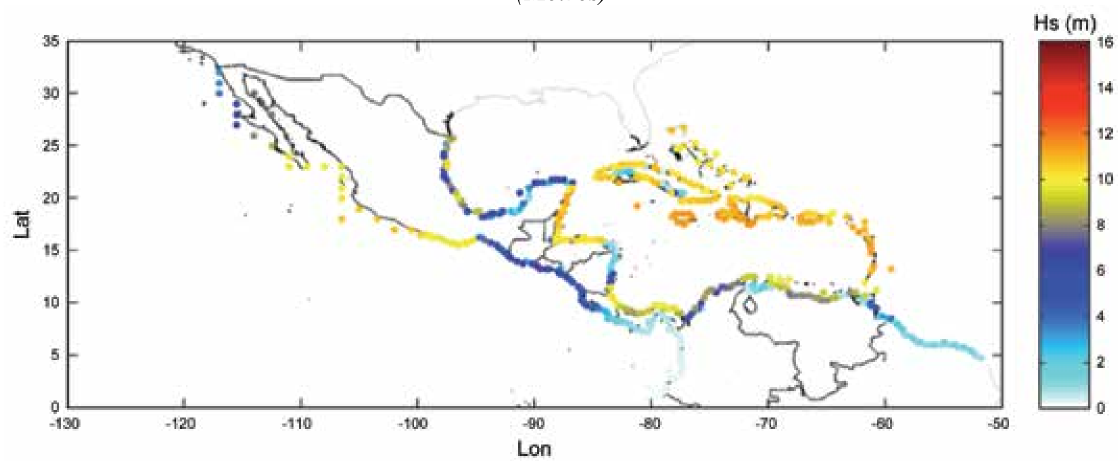
FIGURE 3.29
STUDY CONTROL POINTS AND WIND AND WAVE MAPS FOR HURRICANES KENNA (2001) AND KATRINA (2005)



Source: Prepared by the authors.
Note: The control points used in this study are marked in red.

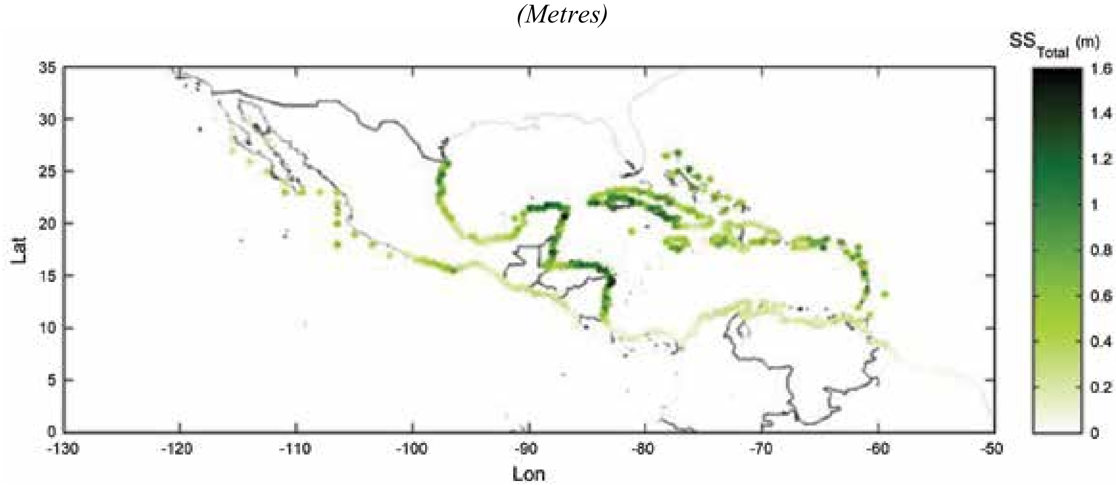
The annual maximum parameters (over a span of 54 years) have been obtained for pressure, wind velocity, significant wave height, peak period, wind-driven storm surges, pressure-driven storm surges and combined storm surges for each of the control points. Some of these parameters are shown below.

FIGURE 3.30
MAXIMUM SIGNIFICANT WAVE HEIGHTS: HURRICANES IN 1955-2009
(Metres)



Source: Prepared by the authors.
Note: Analysis for the study control points using hurricane data covering a time span of 54 years.

FIGURE 3.31
MAXIMUM COMBINED STORM SURGE HEIGHTS: HURRICANES IN 1955-2009
(Metres)



Source: Prepared by the authors.
Note: Analysis for the study control points using hurricane data covering a time span of 54 years. "Combined storm surges" refers to the linear sum of $SS_{pressure}$ +SS_{wind}.

4.1.5 The impact of coastal flooding: conclusions

Sea level rise

- There is no doubt about the fact that sea levels are trending upward at all locations in the region. The highest trend values are found along the Atlantic coast, with values of approximately 3 mm/year for the first study period for the northern coast of South America and the Caribbean coast. Values are lower for the Caribbean islands. Flooding may be greater in the region's deltas due to additional submergence effects.

- The distributions of the population and of land elevations are major factors in the assessment of the impact of flooding along the region's coastlines. The distribution of the land areas that would be affected highlights the variable distribution of land elevations in the different countries' coastal areas (mainly slope gradients). In the first few metres of elevation in countries such as Honduras and Guyana, the percentage of land below the 1-m mark is much smaller than the percentage of the land area at higher elevations. On the other hand, in Peru, for example, the situation is just the opposite, since a large part of the total land area in coastal zones is below 1 m in elevation.
- The percentage of each country's total land area at each metre of elevation that would be impacted demonstrates how difficult a situation many island countries are in. A majority of the Caribbean island's territories are at less than 10 m in elevation. In these cases, the relative significance of coastal areas is much greater than in the case of countries with large territories such as Mexico, Brazil and Argentina. The Turks and Caicos, the Bahamas and the Cayman Islands are the most prone to impacts from flooding.
- Sea level rises of 0.5 and 1 m (IPCC Fourth Assessment Report (AR4) scenarios) would have a stronger impact than the impacts represented by the values obtained by extrapolating past statistical trends. As shown in figure 3.7 and figure 3.8, the extent of sea level rise is highly variable in spatial terms.
- As measured by the size of the affected population, a sea level rise of 1 m would have a major impact along the coasts of Brazil, where it would create major disruptions in large urban areas. The Caribbean islands, especially the more easterly ones, and large stretches of the Mexican coastline, especially in the east, would be seriously affected, as would a number of specific locations along the coasts of Peru and Ecuador and major population centres in Chile.
- When this situation is compared with what would occur in the presence of a sea level rise triggered by an El Niño event of the same magnitude as the strongest such event on record (1998), it can be seen that the western coast would clearly be more severely affected that the eastern coast and that the scale of the impact would be considerably less than the impact of a 1-m sea level rise.
- The examination of a scenario of a 1-m rise in sea level and the existing situation in terms of hurricanes yields a number of findings. The ratio between the affected land surface and population differs across countries. For Honduras, for example, the extent of the affected land area would increase nearly fourfold, whereas the size of the impacted population would remain roughly the same. The size of the impacted population in Mexico and Cuba would change only marginally, whereas the square metres of land area that would be flooded in these two countries would jump by a factor of 2.5 and a factor of 5, respectively. This does not hold true for all the countries or territories, however. For example, in Belize and Puerto Rico, the impacted population would nearly double. Jamaica and Haiti are other examples of this type of situation.
- When scenarios for current hurricane patterns that posit current sea levels and a 1-m rise in sea level are compared, the affected surface areas nearly double in all cases. Some of the countries where the impact of hurricanes will be much greater if sea levels rise by 1 m are Honduras, Panama, Belize, Costa Rica and the Bolivarian Republic of Venezuela. Other countries, such as the Cayman Islands, will see no significant change in the number of people impacted by hurricanes, however.
- The region's deltas are a special case, since these low-lying areas are subject to subsidence effects, in addition to sea level rises, and are particularly important in ecological and/or economic terms. The populations of the River Plate and Magdalena River deltas would be the most severely affected by a 1-m rise in sea levels; the largest land area that would be threatened is in the River Plate Delta.

- As far as infrastructure (roadways and railways) is concerned, the results indicate that a 1-m sea level rise would have a considerably greater effect than the impact generated by the gradual rise indicated by an extrapolation of current trends. Most of the stretches of roadway under 1 m of elevation that would be affected are located along the coasts of Brazil, Mexico and the Bolivarian Republic of Venezuela and on some of the Caribbean islands. Far fewer railroad tracks would be affected, although they play a relatively more important role in terms of infrastructure and transport networks. Nonetheless, the level of risk is significant only in the cases of Cuba, Mexico and Brazil and in the case of Puerto Rico under a scenario of sea level rise combined with hurricanes.
- For countries such as the Bolivarian Republic of Venezuela, Honduras, Panama and Costa Rica, the impact of a 1-m sea level rise would change considerably if combined with hurricane activity, whereas the impact would not be heightened substantially relative to the current situation in others, such as the Dominican Republic.

Flood levels (sea level extremes)

- Flood levels have been studied as a variable that defines sea levels in the presence of extreme events driven by a variety of factors. Flood levels have trended upward over the past 61 years due to increases in wave activity, mean sea levels and storm surges. The rate of change in the occurrence of extreme events that influence flood levels is the greatest (up to 1 cm/year) around the River Plate, which is also the geographic area with the highest flood levels. In the rest of the region, trends have been calculated at no more, generally speaking, than 0.5 cm/year.
- Seasonal changes can play an influential role by broadening the yearly range of variation. Seasonal variations are not very marked in the River Plate Delta, however, so trends for that area can be regarded as being virtually homogeneous for all months of the year.
- At over 4 m, the 50-year return period flood levels are the highest along the coasts of Chile, Argentina and Uruguay. In the Caribbean Sea, flood levels are around 1 m (in the absence of hurricanes).
- The index for future versus present return periods declines in all cases, signalling an increased frequency of extreme flooding events in the future. Unlike the situation with extreme waves, which do not increase in all locations in the region, in this case, because of the combined influence of the various components affecting sea levels, the increase in flooding is found across all of the region's coasts.
- The results for extreme flooding point to a much larger loss of land surface than the results obtained for rising sea levels, thus underlining the significance of sporadic flood events.
- In terms of the number of people affected, the values are particularly high for Brazil, Mexico and Argentina; in the latter case, the flooding associated with a 1-m rise in sea levels would add another 70% to the impact as measured for the present time. In the other countries, the impact increases by at least 25% over current levels except in Suriname and Guyana, where the jump amounts to over 80%.
- The extent of the impact is likely to change a great deal in many countries in coming decades. In some countries, such as Panama and Haiti, El Niño events may actually cause less damage if sea levels rise by 1 m than they do now. In others, however, such as Guatemala, the size of the impacted population is expected to expand (from 2.4% to 7% for events with 50-year return periods).

- The greatest impacts on the population will be seen along the eastern coast in the southern hemisphere, with specific impact areas in coastal cities in northern Argentina, Uruguay and Brazil and in metropolitan areas in the Caribbean, Mexico and Peru.

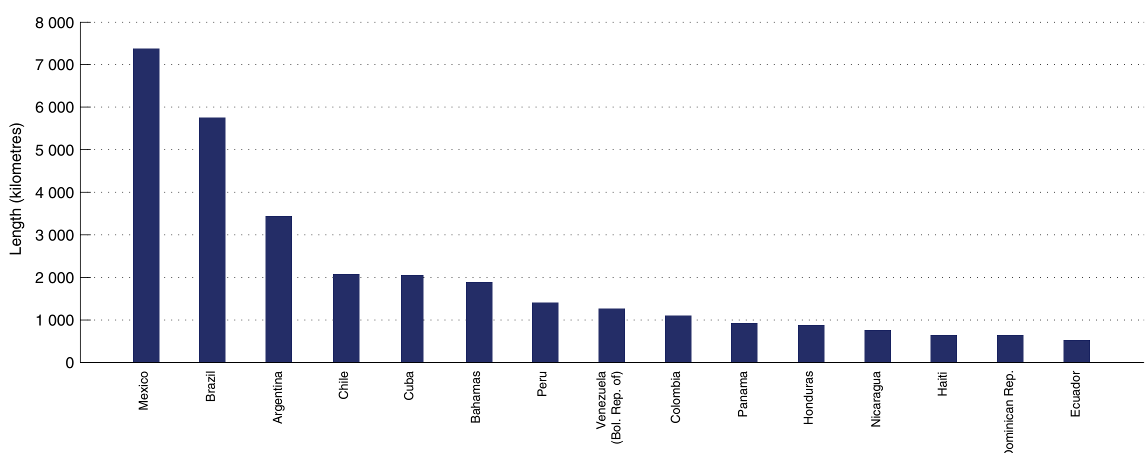
4.2 Erosion of beaches

4.2.1 Some characteristics of beaches in Latin America and the Caribbean

Beaches in the Latin American and Caribbean region vary greatly, with fine- to coarse-grained sand in structures from small enclosed coves to stretches of sands virtually unbroken for hundreds of kilometres, and barrier beaches which separate the open sea from intertidal lakes. Such diversity precludes analysing each type of beach in detail, so the examination here is based on certain hypotheses adopted to simplify the approach. First of all, both the grain diameter and equilibrium profile (Dean's profile) have been assumed to be homogeneous, regardless of tide regime and local dynamics. These hypotheses would be unsuitable for analysing beaches on a local scale, for which a more detailed description would be needed, with respect to both the dynamic conditions and the fixed characteristics of each beach under study. For an overall evaluation, however, these hypotheses are entirely acceptable. They are, in effect, an order of magnitude estimate and, most importantly, they offer a means of comparing how shifts in the causal agents would affect different areas in the region under equal conditions.

In terms of beach variability between countries, first by looking at length (see figure 3.32), Mexico has the longest beach coastline, followed by Brazil, Argentina, Chile and Cuba.

FIGURE 3.32
TOTAL LENGTH OF BEACHES IN LATIN AMERICA AND THE CARIBBEAN, BY COUNTRY
(Kilometres)



Source: Prepared by the authors.
Note: List of 15 countries with greatest length of beaches in the region.

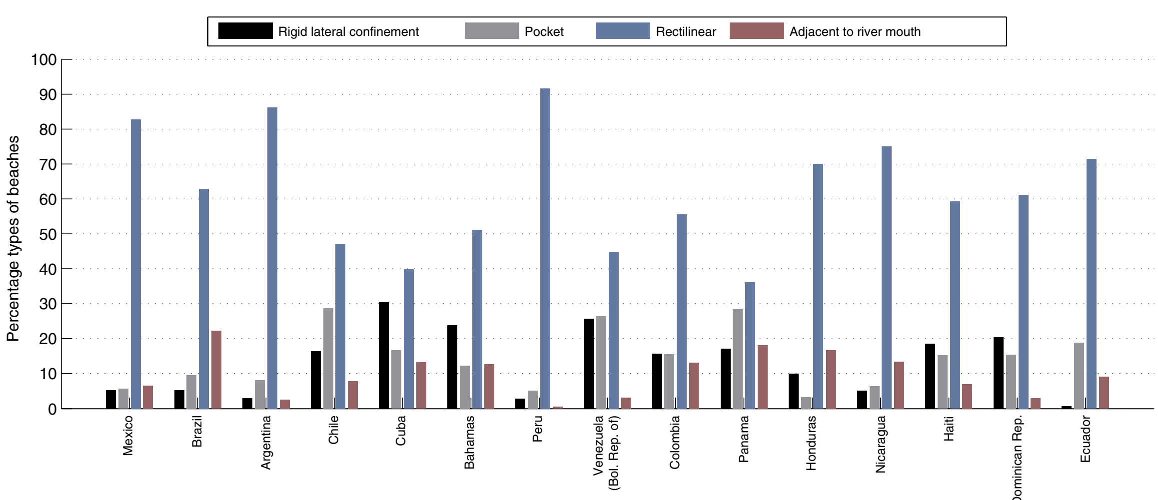
A study of coastal erosion must necessarily establish the configuration of the coast. This is shown in figures 3.33 to 3.38. In coastal countries in Latin America and the Caribbean, part of the coastal area is urbanized within the first few metres from the coastline. Here, it is much more difficult to move back in the event of coastal erosion than on coasts whose beaches have no anthropogenic influence, where the coastline can recede naturally with the dune system moving inland. Accordingly, for the present purposes, the length of consolidated urbanized coast, the length of beach and the length of stretches in which both occur together (urban beaches) were determined for each 5-km unit under consideration in Latin America and the Caribbean. Figure 3.34 and figure 3.35 show this data ordered by length of beach and length of urban front, respectively, distinguishing length of beaches, length of city immediately adjacent to the coast, and shoreline with both beach and urban front. This information is very useful for analysing coastline vulnerability and erosion-related risk. From the point of view of total beach length, which is particularly important inasmuch as it represents each country's degree of exposure, Mexico, Brazil and Argentina have the longest beach coastline, as noted above. Of these three countries, however, Brazil has by far the longest urban seafront. What is more, most of the country's built-up maritime front coincides with beaches: frequently, then, beaches act as defence works vis-à-vis marine dynamics, protecting the buildings behind them. Here, beaches serve a defensive as well as a recreational purpose. The country with the longest length of built-up coastline (on the immediate seafront) in percentage terms is Barbados, followed by Aruba, Anguilla, Jamaica and Uruguay. In these cases, the length of urbanized seafront is on the same order as the total length of beach; however, there are differences in the extent of shared seafront, which suggests that in some areas of the coast buildings are protected from dynamics by other means (presumably elevated zones such as cliffs). However, in all cases, most of the urbanized coast coincides with beaches, as shown in figure 3.35.

It may be concluded from these two figures that analysis of coastal erosion in the Latin American and Caribbean region must be twofold, because some countries have extensive beach coastlines with no immediately adjacent urban activities, while others have a length of built-up immediate seafront comparable with their total beach length (most of it coinciding with urbanized areas). The study must therefore look at this functional duality by analysing both the function of beaches as an ecological and tourism resource (recreational use) and their function as maritime defence works (defensive use).

FIGURE 3.33

TYPES OF BEACH DISTINGUISHED IN THE STUDY, BY COUNTRY

(Percentages)



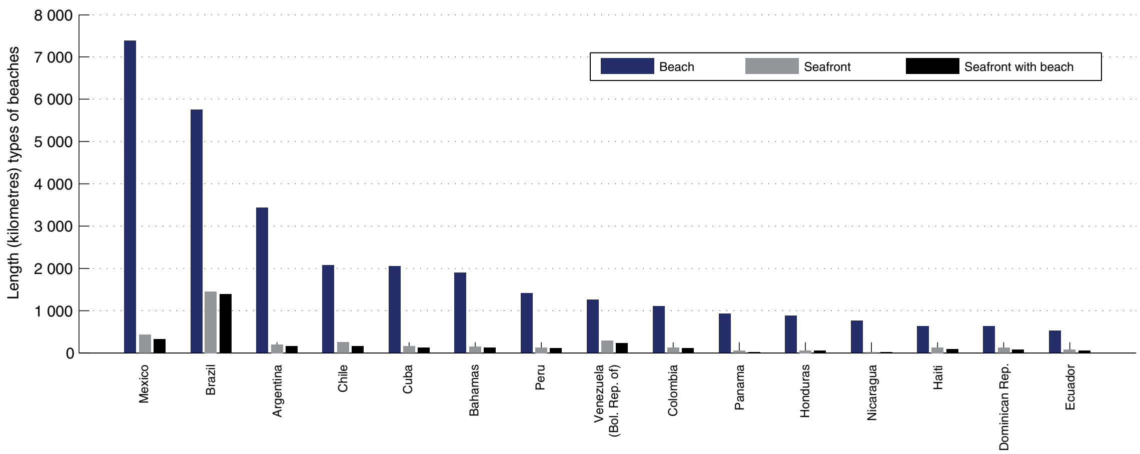
Source: Prepared by the authors.

Note: The 15 countries are shown in descending order to total beach length.

FIGURE 3.34

LENGTH OF COAST, ORDERED BY LENGTH OF BEACH, DISTINGUISHING BETWEEN BEACH LENGH AND SEAFRONT LENGTH

(Kilometres)



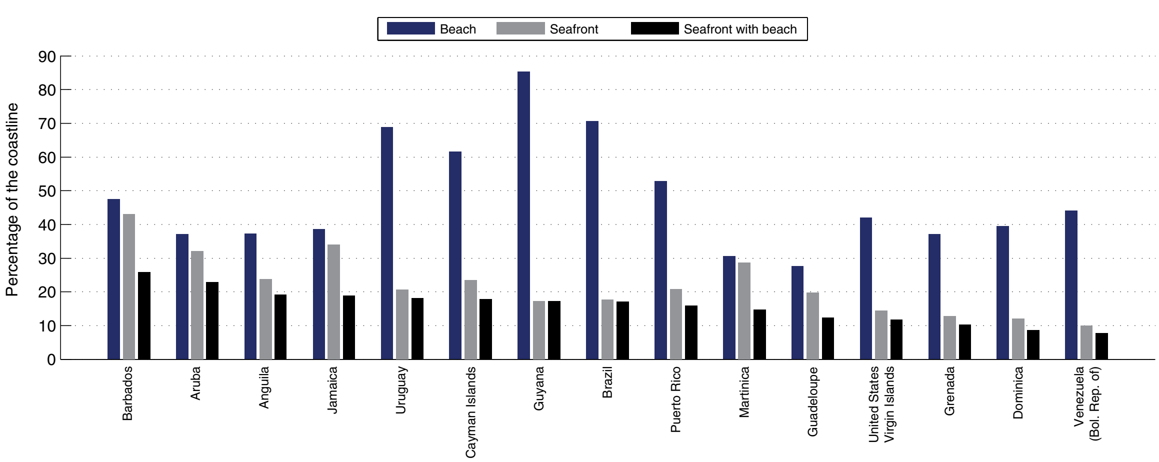
Source: Prepared by the authors.

Note: The 15 countries are shown in descending order to total beach length.

FIGURE 3.35

LENGTH OF COAST, ORDERED BY LENGTH OF SEAFRONT, DISTINGUISHING BETWEEN BEACH LENGH AND SEAFRONT LENGTH

(Percentage of total coastline)

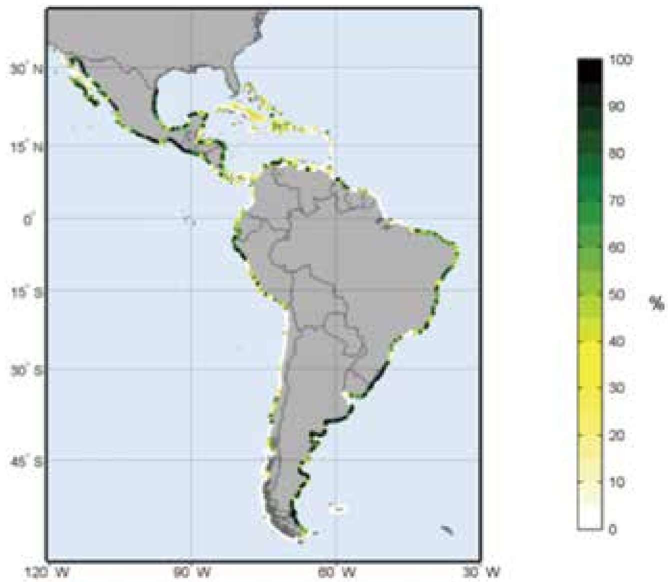


Source: Prepared by the authors.

Note: The 15 countries are shown in descending order of seafront length as a percentage of total coastline length.

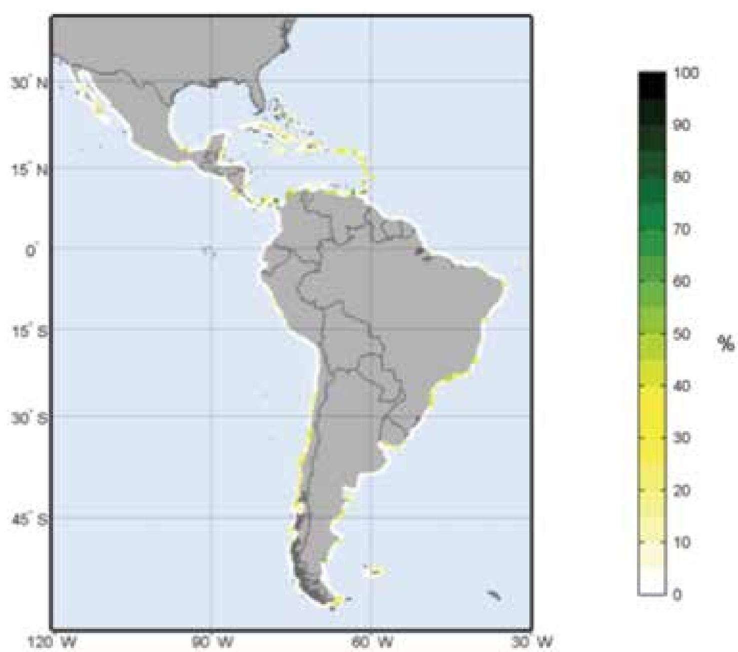
As was seen in earlier documents, large stretches of the region's beaches are vulnerable to the joint action of sea level rise and wave dynamics (see figure 3.36). Several conclusions may be drawn regarding beaches in Latin America and the Caribbean from analysis of figures 3.36 and 3.37: one is that the region has a much greater extent of rectilinear beaches than pocket beaches, especially on the continent.

FIGURE 3.36
COASTLINE WITH RECTILINEAR BEACHES, IN 50-KILOMETRE UNITS
(Percentages)



Source: Prepared by the authors.
Note: Rectilinear beaches are those with no rigid lateral confinement in the 5-km study units.

FIGURE 3.37
COAST WITH POCKET BEACHES IN 50-KILOMETRE UNITS
(Percentages)



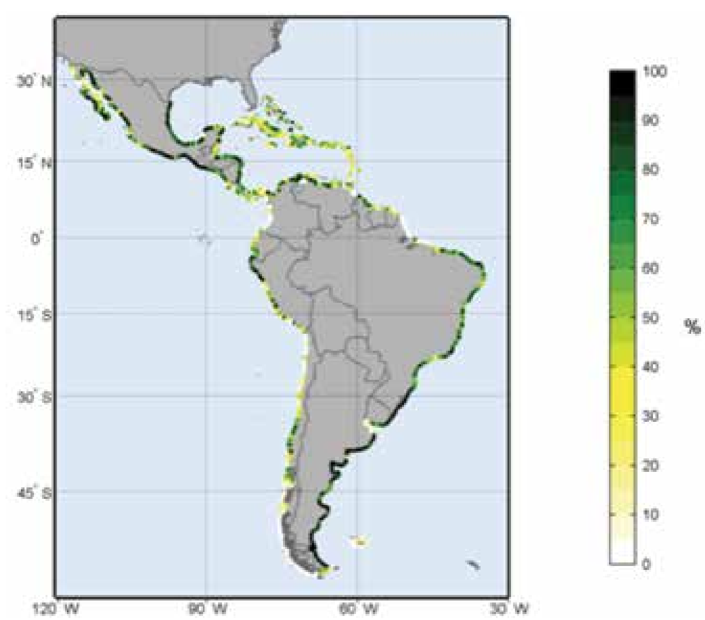
Source: Prepared by the authors.
Note: Pocket beaches are those with rigid confinement on both sides within a single 5-km study unit.

For the present analysis, information was drawn from satellite images, classifying beaches by four types. One of these types is rectilinear: beaches which, in a 5-km study unit, have no rigid internal boundary. These beaches are assumed to be suitable for analysis using the formula posited (see equation 3.7) although this is not strictly the case because sediment transport can occur on scales of hundreds of kilometres, far more than the spatial range of the 5-km study units.

Another type of beaches analysed are those with lateral confinements within the 5-km study unit; in this work these will be termed "pocket beaches". In pocket beaches, sediment transport longitudinally to the coast is limited by the lateral boundaries, so that the form the beach takes reflects sediment transport phenomena occurring within the study unit. This peculiarity makes these beaches suitable for analysis using the method described, because their planform behaviour can a priori be addressed independently of their profile behaviour. For this reason, as will be discussed in a later section, the analysis for pocket beaches must look at both foreseeable Bruun Rule changes and planform variation in response to swings in the dominant wave direction (the direction of the mean energy flow). For pocket beaches, the latter very often has a much stronger impact than the former.

Rectilinear beaches are the dominant type and make up much of the shoreline on Mexico's coasts, especially in the Gulf of Mexico, and also from the south of Brazil to the southern tip of the continent, as well as other isolated areas throughout the Latin American and Caribbean region. Pocket beaches dominate the coasts of Chile, southern Brazil and the Caribbean islands. Although they can all be analysed as confined in a study unit, in Chile boundaries are rigid —normally consisting of cliffs and high rocky escarpments— whereas in the Caribbean boundaries are usually much less pronounced land features making up changes in the direction of the coast.

FIGURE 3.38
COAST WITH BEACHES HAVING NO ADJACENT RIVER MOUTH EFFECT IN 50-KILOMETRE UNITS
(Percentages)



Source: Prepared by the authors.

4.2.2 Beach erosion and dynamic equilibrium

The joint action of the various marine dynamics on beach sediments transports sand, and thus produces bed variation. The study of this set of actions and responses —usually termed coastline processes— must necessarily be approximate, owing to its complexity and the scale of the study subject. Existing approaches are based on two hypotheses. The first refers to the three-dimensional nature of shoreline processes and admits separate analysis of cross-shore processes (beach profile) and longshore processes (beach planform). The second hypothesis refers to the temporal and spatial scale of coastline processes, and the need to use specific formulations for the chosen study scale.

All the hydrodynamic and sedimentary processes occurring on a beach are, to a greater or lesser extent, three-dimensional processes. We are prevented from analysing them in their full complexity, however, by limitations in the tools and formulations available, and even in our own understanding of these processes. The first and most important working hypothesis in the study of beach stability is thus the orthogonality of longshore and cross-shore movements.

Under the orthogonality hypothesis, any sediment movement on a beach, for example that occurring during a storm, can be studied by examining longshore and cross-shore sediment movements, which are assumed to be independent of each other. The orthogonality hypothesis thus allows us to analyse beach stability by studying on a separate basis:

- Beach profile stability (cross-shore)
- Beach planform stability (longshore)

Generally speaking, the orthogonality hypothesis comes sufficiently close to the reality, especially on open beaches with extreme morphodynamic states (reflective and dissipative). On beaches with intermediate morphodynamic states, or pocket beaches with strong planform curvature, planform-profile interaction is quite powerful, however. In this case, the separate analysis of profile and planform should be treated with caution.

Beach erosion occurs as a response to changes in wave conditions. Inasmuch as climate change affects wave behaviour, beach planforms and profiles change shape to reach a dynamic equilibrium with respect to the new hydrodynamic conditions. This morphodynamic response produces areas of erosion and sedimentation, or accretion, in both planform and profile.

At this point, it is necessary to distinguish between beach profile and planform in erosion-sedimentation process, because the variables governing equilibrium are different in each case. One hypothesis commonly used in coastal engineering is to assume beach profile and planform to be independent, so that the long-term equilibrium position of any given beach —that is, without considering short-term seasonal variations (see first supplementary document containing a methodological guide)— can be defined by an equilibrium profile and an equilibrium planform. Under this approach, erosion can be addressed by studying long-term profile erosion, on the one hand, and changes to the planform, on the other. For the first, the variables determining recession of the equilibrium profile, known as profile erosion, are significant wave height exceeded 12 hours per year (HS12) and mean sea level. The planform, however, is positioned at right angles to wave direction, so that changes in this direction cause the beach to rotate, advancing in one area and receding in another as a result of planform erosion.

Given the distinction between profile and planform, for the purposes of studying erosion beaches are classified by morphodynamic characteristics in the study units. Beaches are thus classified as:

- **Rectilinear beaches:** Those which have no lateral boundaries within the study unit; thus, planform movement occurs on a larger scale than the study unit (5 km), because sediment could be transported to adjacent units.

- **Pocket beaches:** Those which are confined on both sides, that is, planform movement can be assessed approximately by the hypothesis of orthogonality of planform shape and wave direction. In this case, sediment transport to or from flanking units does not occur.

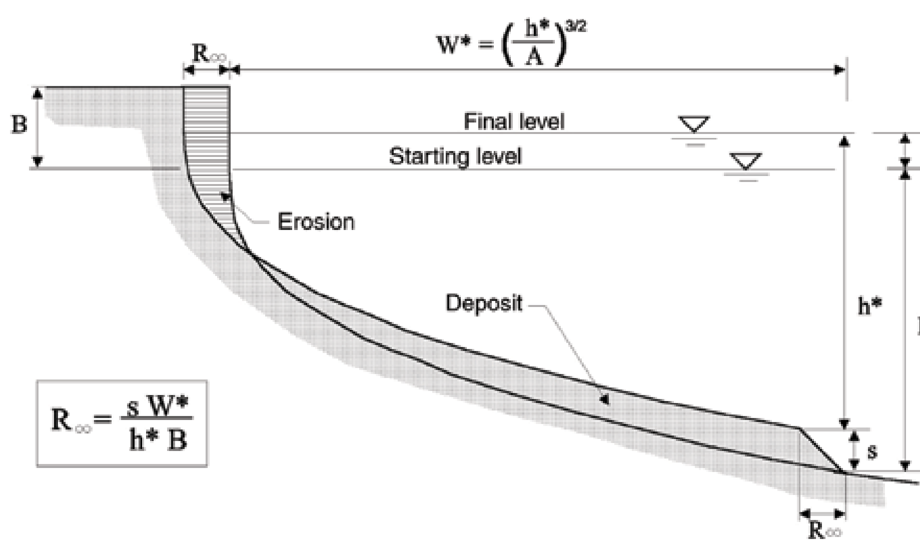
The following sections will discuss the annual rate of beach profile recession for each of the causal agents, as well as the probability of exceeding certain erosion thresholds in the study years.

4.2.3 Equilibrium profile erosion owing to sea level rise

The study of beach erosion is complex and specific to each beach. Among other factors, it depends on the physical characteristics of the sediment, local wave conditions, coastal bathymetry and the orientation and configuration of the shoreline. Beaches also show a marked seasonal variability: their form is not fixed over time but shifts as a function of variation in a range of constantly changing factors. Nevertheless, they have a mean state, known also as dynamic equilibrium, with respect to which seasonal variations occur.

For the equilibrium profile, Dean's profile is widely applied as the equilibrium shape of a beach perpendicular to the coastline. Profile changes are usually studied using the Bruun Rule, which estimates erosion occurring as a result of changes in sea level and closure depth. This determines the order of magnitude of long-term erosion caused by climate change in the absence of other sources of morphodynamic alterations (Zhang and others, 2004).

FIGURE 3.39
REPRESENTATION OF THE BRUUN RULE, SHOWING BEACH EQUILIBRIUM PROFILE AND RECESSION (R) CAUSED BY SEA LEVEL RISE (S)



Source: Ocean and Coastal Engineering Group, University of Cantabria.

For more details on the formulas used, see first auxiliary document containing a methodological guide.

The response of the different types of beaches to sea level rise, including when caused by climate change, can be quantified using the Bruun Rule, which establishes that mean sea level rise, $\Delta\eta$, will cause beach profile recession.

On the basis of the formulation proposed by Dean (1977) and in a number of existing studies on beach profile shape, it may be stated that beach profile is defined by the rate of fall of the sand grains making up the beach, which is a function of the mean grain diameter D50 and the density of the sediment. The profile shape is taken to be independent of the parameters defining wave incidence on the beach.

Taking the hypothesis that the shape of the equilibrium profile formed at the new sea level is identical to that existing before the sea level rise and that the volume of beach sand must be kept constant, and assuming that the equilibrium profile shape is determined by Dean's formulation (1977), and that the beach's closure depth is given by Birkemeier's formulation (1985), we obtain:

$$RE = \frac{\Delta\eta \cdot W*}{h* + B} = \Delta\eta \frac{(1.57\, H_{S12})^{1.5}}{(0.51\, w^{0.44})^{1.5}\,(1.57\, H_{S12}) + B} \qquad (3.6)$$

where:

$W*$ = profile length (m), as a function of the mean sediment diameter, parameterized by the sediment rate of fall (w)

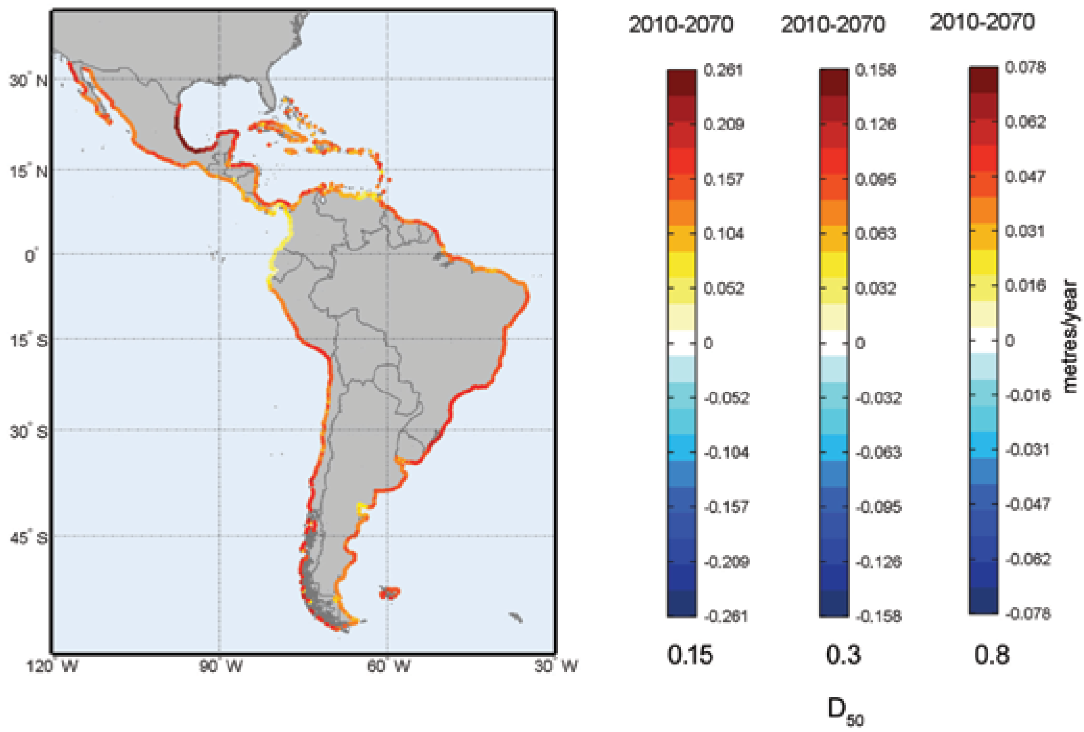
$h*$ = closure depth (m)

w = grain rate of fall (m/s)

On the basis of equation (3.6), it may be observed that beach profile recession is proportional to the variation in mean sea level, so that the larger the rise in this mean level, the greater the recession of a given beach. Recession is also a function of the wave height exceeded for 12 hours per year, of the rate of fall of grain w —that is, the size of mean grain D_{50} making up the beach— and of the height of the beach berm, B.

It may be concluded from the many studies conducted of beach profiles that the key physical parameter in equilibrium profile shape is the representative size of sediment (D_{50}); the effects of wave height and the other parameters are in fact negligible. Given the huge spatial scale of this study and the lack of information on the spatial distribution of sediments on the beaches of Latin America and the Caribbean, the calculation was performed for three different diameters in order to obtain a measure of upper and lower levels of erosion as a function of sand diameter. Geologically, sand may be defined as material composed of particles varying in diameter between 0.063 mm and 2 mm. Beach sand may be considered to vary between 0.15 mm and 0.8 mm in diameter, with 0.3 mm taken as a representative average value. Because sediment size exerts such a great influence in shaping beach profile, the study looked at beach profile recession for all three diameters (figure 3.40) —the maximum, minimum and mean for beach sand— although the graphs from figure 3.41 onwards show the calculations for the 0.3 mm diameter as a representative value for comparative purposes within the region. The results for the 0.15 mm diameter may be used for areas of very fine-grain beach sand and, conversely, the findings for the 0.8 mm diameter may be adopted for beaches of coarse sand verging on gravel.

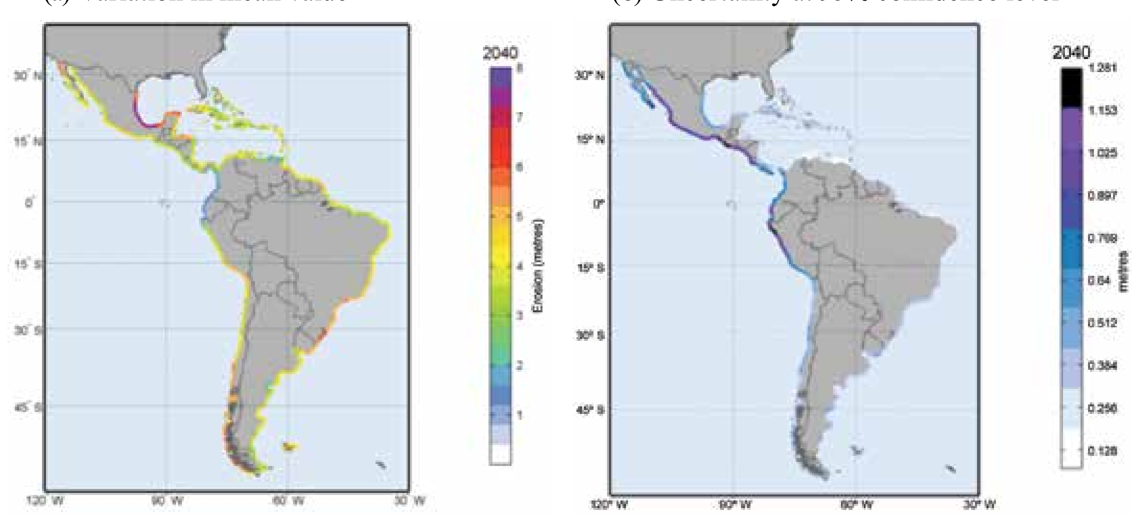
FIGURE 3.40
MEAN TREND IN BEACH EROSION FROM CHANGES IN EQUILIBRIUM PROFILE BETWEEN 2010 AND 2070
(Metres/year)



Source: Prepared by the authors.

FIGURE 3.41
BEACH EROSION FROM CHANGES IN EQUILIBRIUM PROFILE, IN 2040
(Metres)

(a) Variation in mean value (b) Uncertainty at 95% confidence level



Source: Prepared by the authors.

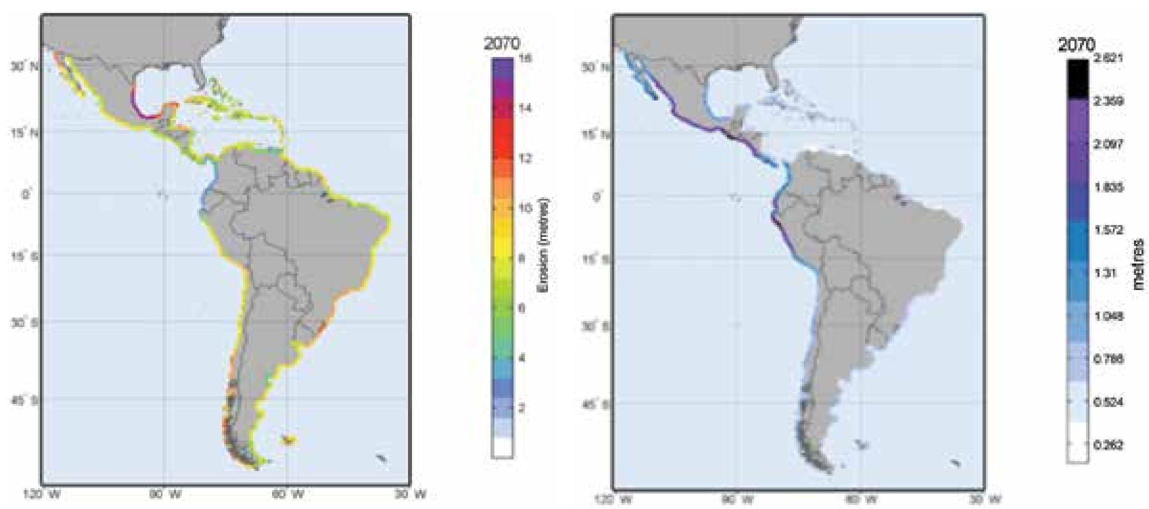
On the basis of trends calculated for sea level rise and variation in significant wave height over 12 hours per year (H_{S12}), which is related to closure depth, the change in the two variables is included in the erosion formulation, in order to determine the erosion trend directly from the profile erosion time series from 1948 onwards.

The results obtained show a stronger effect on the Atlantic and Caribbean coasts (see figure 3.40), with rates of annual recession of around 0.16 m for the mean representative diameter (0.3 mm), and varying from 0.3 to 0.26 m per year for the other two sediment sizes considered. It merits pointing out that positive erosion rates (recession) are found for the region overall, owing to the combined effect of (generalized) sea level rise and increase in H_{S12} (in some areas H_{S12} decreases, albeit slightly, see earlier documents). High rates of erosion are also found on the coasts of southern Brazil and southern Chile.

On average, the beaches in the Gulf of Mexico may be expected to show recession of around 8 m by 2040 and up to 16 m by 2070, with an uncertainly level of around 1 m and 1.5 m, respectively. Smaller recessions may be expected in the rest of the region, except for the south of Brazil and the north of Uruguay, where the figures are around 5.5 m and 11 m, with uncertainties of less than 1 m.

FIGURE 3.42
VARIATION IN BEACH EROSION FROM CHANGES IN EQUILIBRIUM PROFILE, IN 2070
(Metres)

(a) Variation in mean value (b) Uncertainty at 95% confidence level



Source: Prepared by the authors.

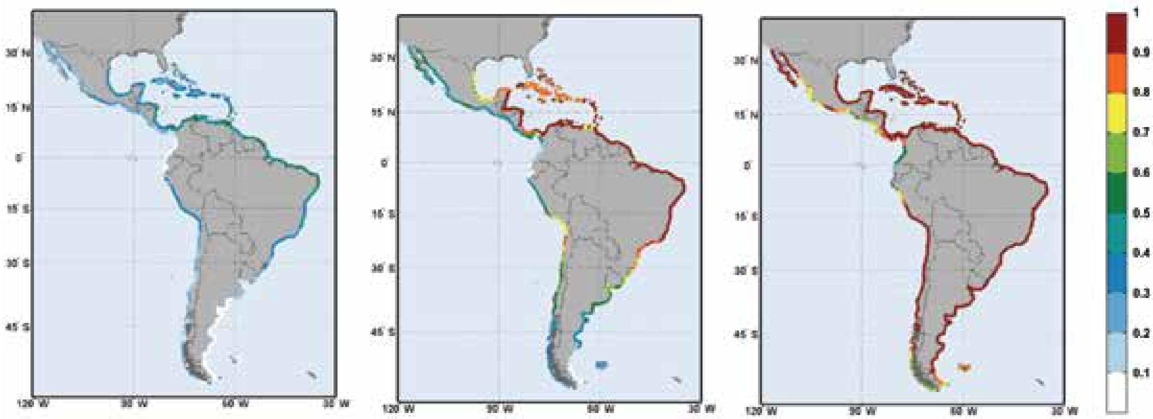
Under these hypotheses, the worst affected areas will be the northern Caribbean and the coastlines to the south of Brazil down to the River Plate. Erosion is, in any case, generalized throughout the region, especially in the event of sea level rise.

The foregoing results more or less fulfil the approximate rule that shoreline recession will be 50 times the magnitude of sea level rise (although this factor depends grain size, berm height and wave conditions, and although the analysis included coastal wave variability —H_{S12}— that rule is largely borne out). These increases are directly conditioned by extrapolation of the rate of sea level rise which, as seen in earlier documents, is gradual and will likely amount to around 0.3 m by 2070. The situation would be very different in the event of sea level rises of 1 m or more.

FIGURE 3.43

LIKELIHOOD OF EROSION EXCEEDING 5 METRES IN 2040, 2050 AND 2070

a) 2040 b) 2050 c) 2070



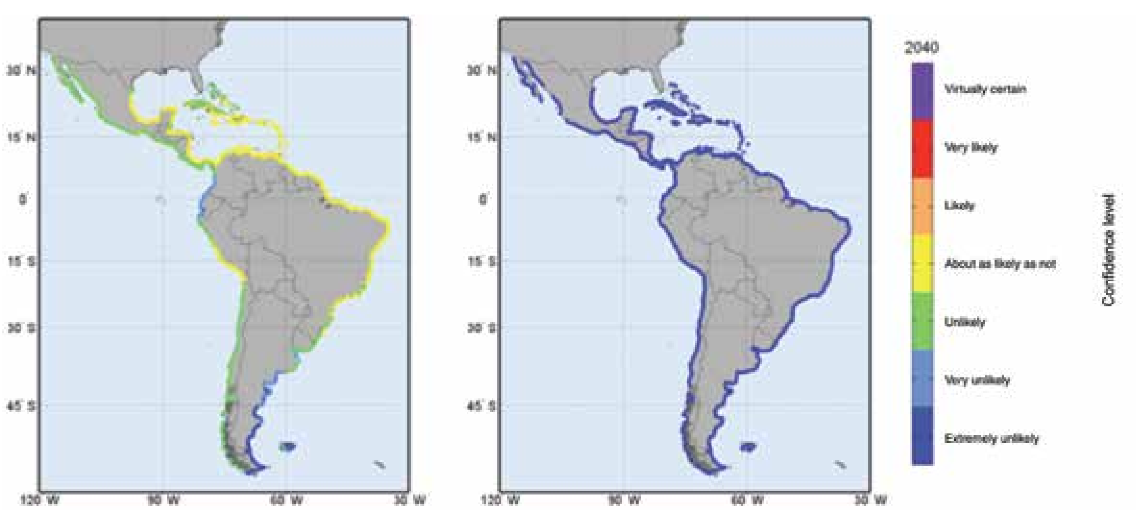
Source: Prepared by the authors.

Figure 3.44 shows the confidence level (IPCC scale) of 5-m and 10-m thresholds of erosion from sea level rise being exceeded. While changes of between 5 m and 10 m are *about as likely as not* (33% to 66% probability), changes of more than 10 m from sea level rise may be considered *exceptionally unlikely.*

FIGURE 3.44

CONFIDENCE LEVEL OF 5-METRE AND 10-METRE THRESHOLDS OF EROSION FROM SEA LEVEL RISE BEING EXCEEDED IN 2040

(a) Profile erosion > 5 m (b) Profile erosion > 10 m



Source: Prepared by the authors.
Note: The confidence level used is the IPCC scale and the probabilities shown on the legend are as follows: >0.99, virtually certain; 0.9-0.99, very likely; 0.66-0.9, likely; 0.33-0.66, about as likely as not; 0.1-0.33, unlikely; 0.01-0.1, very unlikely; <0.01, exceptionally unlikely.

For a sea level rise of 1 m or even 2 m, the results are very different in magnitude —figures 3.45 and 3.46— because recession would be around 20 m, 40 m and 60 m for the different diameters of sediment considered in the study. The results are much larger for a 2-m sea level rise. In these cases, the variability of the results depends exclusively on the wave conditions in each area of the region.

FIGURE 3.45
MEAN EROSION ON BEACHES HAVING VARIOUS GRAIN DIAMETERS WITH A SEA LEVEL RISE OF 1 METRE
(Metres)

(a) 1m D_{50} = 0.15 mm (b) 1m D_{50} = 0.3 mm (c) 1m D_{50} = 0.8 mm

Source: Prepared by the authors.

FIGURE 3.46
MEAN EROSION ON BEACHES HAVING VARIOUS GRAIN DIAMETERS WITH A SEA LEVEL RISE OF 2 METRES
(Metres)

(a) 2m D_{50} = 0.15 mm (b) 2m D_{50} = 0.3 mm (c) 2m D_{50} = 0.8 mm

Source: Prepared by the authors.

Table 3.16 shows results for erosion that may be expected for several locations in the region in the first five scenarios (statistical trends and rise between 0.5 m and 1 m). In the event of sea level rise greater than under scenario AR4, the order of magnitude of the impacts on beaches would be 50 m recession, generally speaking.

TABLE 3.16
LIKELY MEAN EROSION FOR VARIOUS LOCATIONS IN LATIN AMERICA AND THE CARIBBEAN
(Metres)

(Calculation for a standard beach with D_{50}=0.3mm and berm height of 1 m)							
	Longitude	Latitude	A	B	C	D	E
			2040	2050	2070	0.5 m	1 m
Río de Janeiro (BRA)	-43.23	-22.99	4.64	6.18	9.28	24.62	49.24
Santos (BRA)	-46.24	-23.93	4.26	5.67	8.51	14.78	29.56
Montevideo (URY)	-56.00	-34.86	4.65	6.20	9.30	21.17	42.34
Concepción (CHL)	-73.09	-36.83	3.58	4.78	7.17	18.18	36.36
Valparaíso (CHL)	-71.63	-32.96	4.04	5.39	8.08	17.49	34.99
Arica (CHL)	-70.45	-18.38	4.85	6.47	9.70	20.41	40.83
Chorrillos (PER)	-77.04	-12.09	5.20	6.93	10.39	23.95	47.89
Talara (PER)	-81.26	-4.63	4.18	5.57	8.35	20.53	41.06
Machala (ECU)	-80.28	-3.40	3.99	5.31	7.97	19.84	39.69
La Libertad (ECU)	-80.78	-2.36	3.92	5.22	7.83	17.08	34.16
Bahía Solano (COL)	-77.38	6.05	3.97	5.30	7.94	18.79	37.59
Los Santos (PAN)	-80.26	7.34	3.92	5.22	7.84	20.60	41.20
San Jose (CRI)	-83.97	9.29	5.09	6.79	10.18	21.00	42.00
Acapulco (MEX)	-99.73	16.78	4.64	6.19	9.29	19.28	38.55
Ensenada (MEX)	-116.69	31.74	5.75	7.66	11.49	17.40	34.80
Cabo (MEX)	-109.85	22.98	3.86	5.14	7.72	28.24	56.49
Veracruz (MEX)	-96.02	19.05	3.47	4.63	6.94	25.20	50.40
Cancún (MEX)	-86.85	21.04	4.54	6.06	9.08	28.80	57.60
Caracas (VEN)	-67.02	10.59	1.62	2.16	3.25	17.35	34.71
Georgetown (GUY)	-57.95	6.70	1.55	2.07	3.11	14.84	29.68
Fortaleza (BRA)	-38.49	-3.81	4.89	6.51	9.77	18.48	36.96
Maceio (BRA)	-35.60	-9.52	7.55	10.07	15.10	30.90	61.80
P.Segura (BRA)	-39.00	-16.28	5.95	7.93	11.90	24.73	49.47
P.Sta Cruz (ARG)	-68.26	-50.14	4.21	5.61	8.41	18.87	37.74
I. Taggart (CHL)	-75.58	-49.45	2.74	3.65	5.47	27.95	55.90

Source: Prepared by the authors.

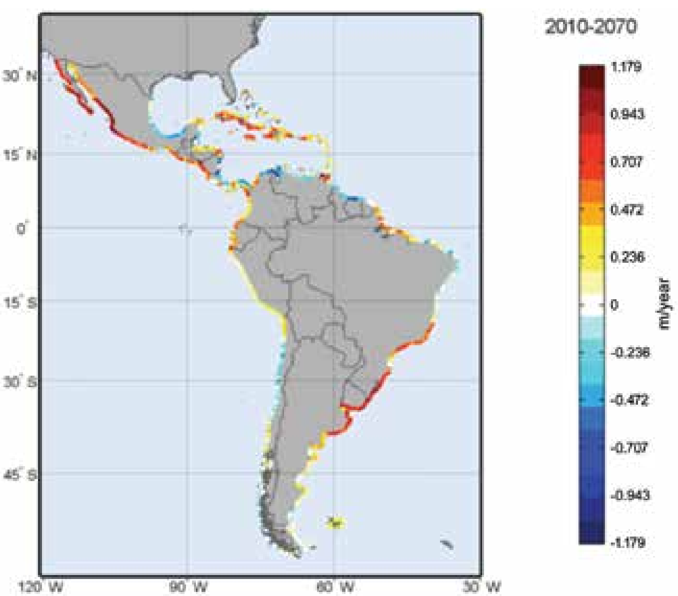
4.2.4 Equilibrium profile erosion owing to wave height increase

For analysis of the effect of climate change on beaches, it is important to bear in mind the interrelation between profile and planform. This is very important in pocket beaches with maximum sand load, in which lateral boundaries, such as seawalls and headlands, limit the maximum expansion of the embayed beach. The annual mean value of the cut off depth (given in previous sections as h^*), which affects the area within which sediment is transported, depends on the wave height exceeded for 12 hours per year (H_{S12}), the occurrence of storms and their duration. If climate change were to cause a variation in any of these parameters such that the depth of the beach cross-section were reduced, the beach's lateral boundaries would allow the beach to lengthen: assuming availability of sediment in the open sea that could be transported to the beach by wave incidence asymmetry, the beach's cross-shore length would increase. Conversely, if the closure depth were increased, the lateral boundaries would be unable to contain any extension to the existing dry beach, which would therefore be eroded. That recession —or advance, as the case may be— can be estimated using Dean's profile (1977), since the profile shape will not change as long as the grain diameter remains unchanged. All that will change is the seaward limit of the beach profile.

Recession (erosion rate, ER) is given by the difference between the cross-shore length of the future active profile and its existing length (see details in first auxiliary document containing a methodological guide), which is closely related to wave variation —which, as seen in the first project document (on climate variability, dynamics and trends), is changing. The formulation shows that the larger the significant wave height breaking on the beach and the smaller the diameter of the sediment making up the beach, the larger the recession. In other words, the effect of increasing the cut off depth is generalized beach recession, providing that the beach has reached its maximum sand load. Moreover, the recession effect will be greater in dissipative beaches.

As may be observed in figure 3.47, the pattern of change is homothetic to changes in H_{S12} wave heights. Wave height increase produces much greater foreseeable changes than patterns in sea level change do. Nevertheless, the study of this factor is more delicate than the Brunn role for profile change, because it depends hugely on the specific local characteristics of each stretch of beach and on sediment transport in general. Even so, the analysis serves as a warning and as a diagnostic of possible changes to identify areas most prone to erosion from wave pattern changes.

FIGURE 3.47
MEAN EROSION RATE IN BEACHES WITH REFERENCE TO PROFILE ALTERATION FROM CHANGES IN CLOSURE DEPTH BETWEEN 2010 AND 2070
(Metres /year)



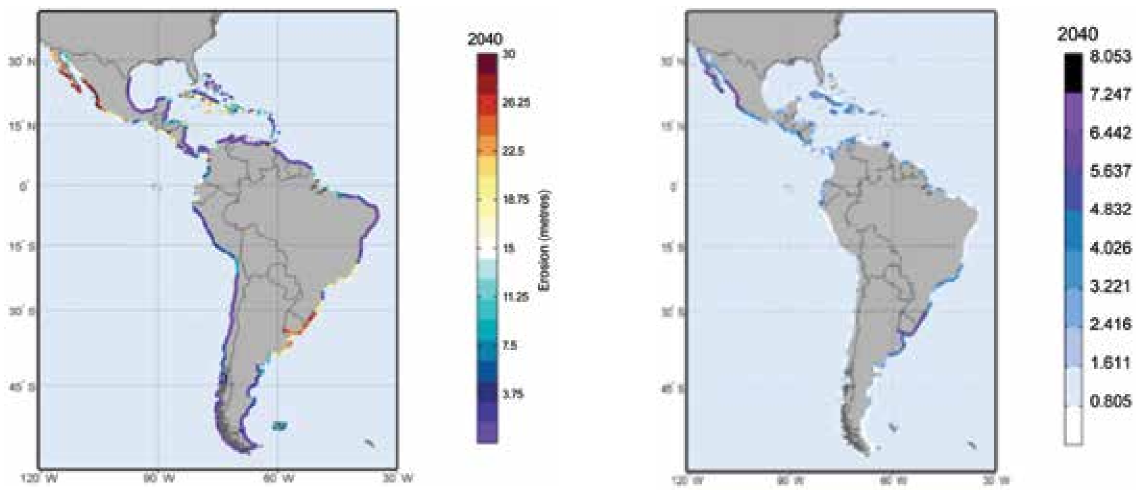
Source: Prepared by the authors.
Note: The erosion rate is analysed for a representative grain diameter of 0.8 mm.

Extrapolation of these changes gives erosion values of over 25 m on the coasts of southern Brazil, Uruguay and western Mexico. In certain parts of the Caribbean islands the recession could be between 10 m and 20 m (see figure 3.48).

Figure 3.49 shows the IPCC confidence level of 5 m and 10 m thresholds of erosion from wave height changes being exceeded. By contrast with the pattern in relation to sea level rise (figure 3.44), much of the region is *about as likely as not* (33% to 66% probability) to experience beach erosion in the range of 5–10 m. However, changes of over 10 m are *likely* in several parts of Central America and the west of Mexico and *very likely* on the southern coasts of the Caribbean islands.

FIGURE 3.48
MEAN EROSION (AND UNCERTAINTY) FROM CHANGES IN CLOSURE DEPTH OF BEACH PROFILE BY 2040 UNDER SCENARIO A
(Metres)

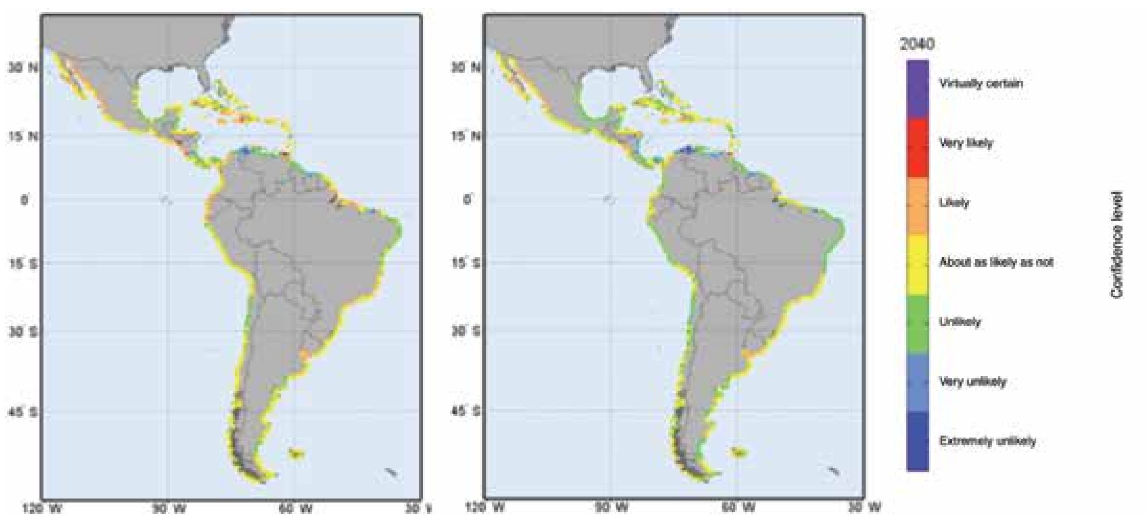
(a) Mean erosion (b) Uncertainty at 95% confidence level



Source: Prepared by the authors.
Note: The results shown are for a homogeneous grain diameter.

FIGURE 3.49
IPCC CONFIDENCE LEVEL OF 5-METRE AND 10-METRE THRESHOLDS OF EROSION FROM CHANGES IN CLOSURE DEPTH OF BEACH PROFILE BEING EXCEEDED

(a) Profile > 5 m (b) Profile > 10 m



Source: Prepared by the authors.
Note: The probability legend is as follows: >0.99, virtually certain; 0.9-0.99, very likely; 0.66-0.9, likely; 0.33-0.66, about as likely as not; 0.1-0.33, unlikely; 0.01-0.1, very unlikely; <0.01, exceptionally unlikely.

4.2.5 Beach erosion owing to changes in equilibrium planform

Long-term analysis of beach planform shape is based on two hypotheses: orthogonality of profile and planform (this means that the analysis of the two parts can be separated for the study) and the different time scale of profile and planform processes. Because of the different time scale of the processes, studies of planform shape assume that the beach profile is always in its equilibrium position. The long-term evolution of a beach's planform shape is therefore studied using a constant profile shape.

The analysis of beach planform equilibrium over the long term distinguishes between the following two situations:

- Beaches in static equilibrium (nil longshore transport)
- Beaches in dynamic equilibrium or non-equilibrium (non-nil longshore transport)

Variability of wave conditions in shorter time periods (years or even months) defines the shape of a beach planform at a given moment in time but, in the long run, this variability oscillates around an average or long-term position which can be considered to be its equilibrium shape.

The beach therefore has a modal equilibrium position, with oscillations around that mean position. The oscillations are usually weak unless wave direction varies markedly by season. In any case, analysis of the effects of climate change on beach planform shape is concerned with the long term, that is, with the impacts on the annual mean position.

The planform shape of these beaches is governed by mean energy flow direction associated with wave incidence on the beach. If this parameter is altered, the beach will rotate to bring the planform shape back into parallel with the wave fronts and perpendicular to mean energy flow direction. Depending on whether the beach is carrying its maximum sand load, such a rotation can bring about advance or erosion in the future.

This section examines the recession or advance that will occur in rectilinear beaches in static equilibrium and not carrying maximum sand load, in response to a hypothetical change in the wave direction. For this purpose, it is assumed that the lateral bounds of the beach are capable of containing it, however much it advances in the future and that no sand is imported from the open sea or from areas adjacent to the beach.

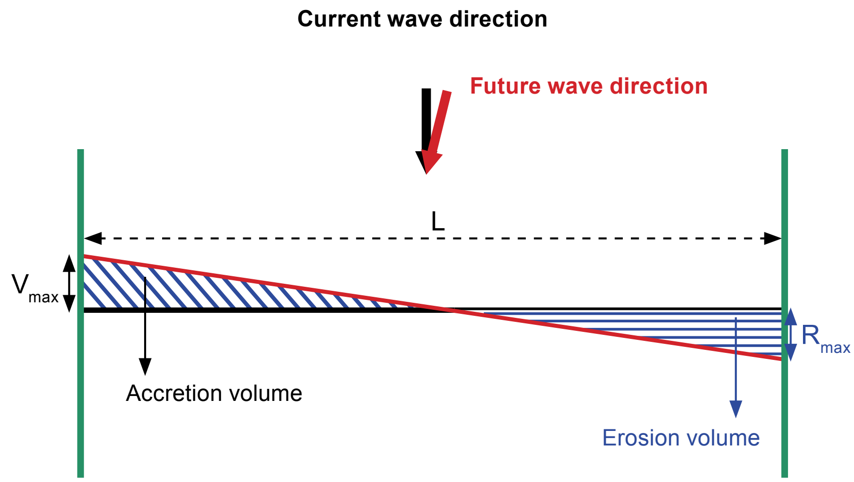
If climate change impacts should produce a variation in mean energy flow direction, the beach will change its orientation. This change will be accompanied by an advance and recession of the beach, such that the volume of sand eroded is equivalent to the volume accreted on the beachfront (see figure 3.50).

The maximum recession and advance will occur at the edges of the beach and their extent will depend on the variation in wave direction and the length of the beach, approximately (see project document dealing with theoretical effects for a detailed explanation of this), on the basis of the equation:

$$ER_{max} = \frac{L}{2} tg\,(\Delta\beta) \qquad (3.7)$$

Figure 3.51 shows the rate of change obtained for beach planform rotation. As may be seen, the largest changes are likely to occur on the southern coasts of Brazil (over 1 m/year), the Caribbean coasts (especially eastern Cuba and the easterly islands), part of the coast of Chile and the north-east coast of Mexico; in the last case again at rates of over 1 m of erosion per year on average. Extrapolation of these results to 2040 (study scenario A) gives erosion values of up to 40 m.

FIGURE 3.50
EFFECT OF CHANGE IN WAVE DIRECTION ON RECTILINEAR BEACHES IN STATIC EQUILIBRIUM WITHOUT MAXIMUM SEDIMENT LOAD



Source: Prepared by the authors.

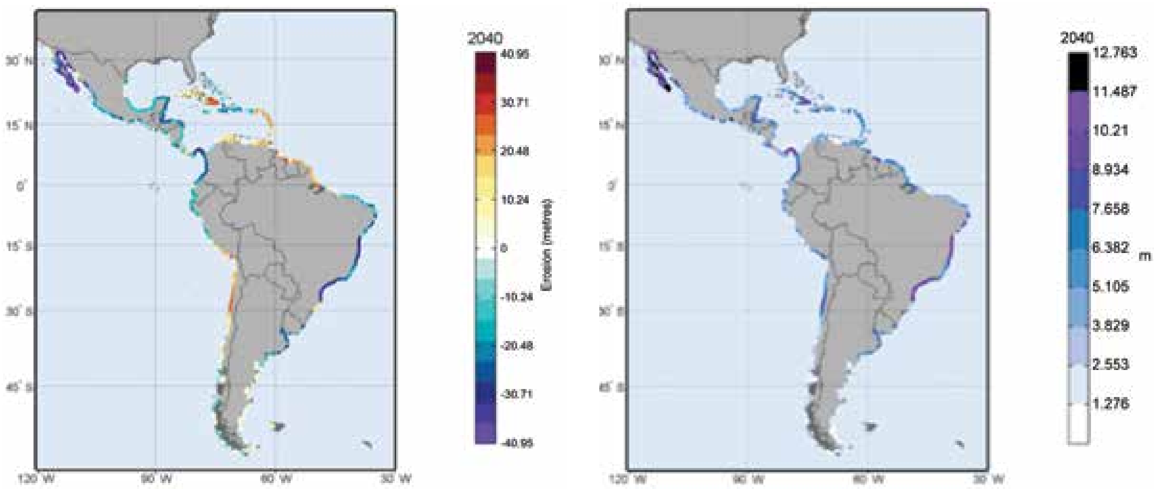
FIGURE 3.51
MEAN EROSION TREND IN BEACHES FROM CHANGES IN EQUILIBRIUM PLANFORM BETWEEN 2010 AND 2070
(Metres/year)

Source: Prepared by the authors.

If these results are compared with the areas having most pocket beaches (see figure 3.37) —and therefore those most susceptible to this type of erosion— it is found that some areas of Brazil, the eastern Caribbean coasts and Chile, as well as a small part of Mexico, appear likely to suffer the worst impacts.

FIGURE 3.52
BEACH EROSION IN 2040 FROM CHANGES IN EQUILIBRIUM PLANFORM
(Metres)

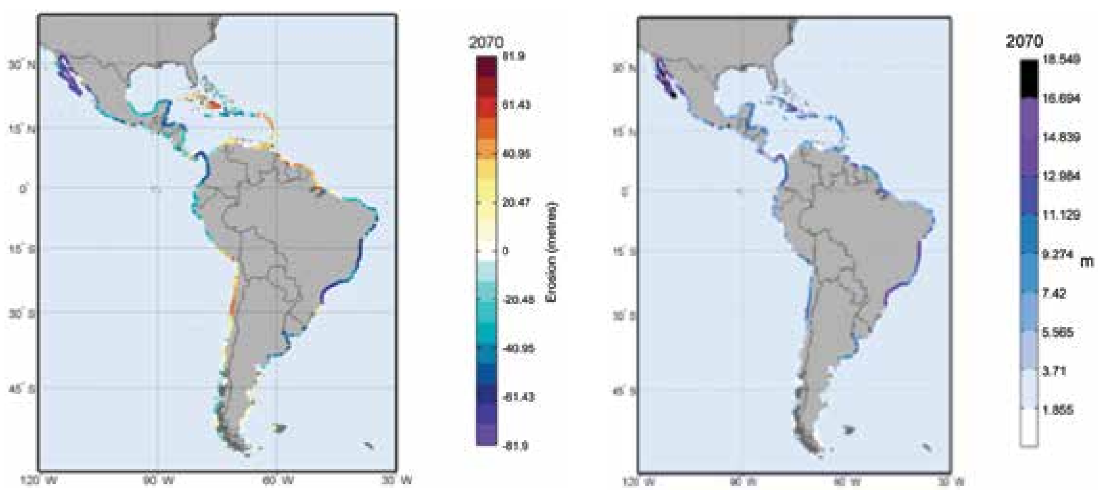
(a) Mean variation (b) Uncertainty at 95% confidence level



Source: Prepared by the authors.

FIGURE 3.53
BEACH EROSION IN 2070 FROM CHANGES IN EQUILIBRIUM PLANFORM
(Metres)

(a) Mean variation (b) Uncertainty at 95% confidence level



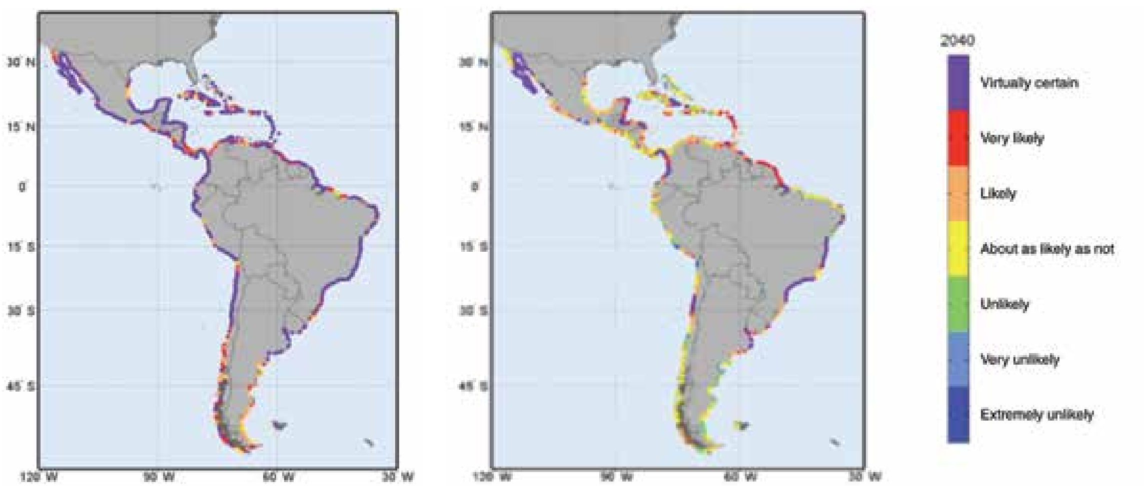
Source: Prepared by the authors.

Figure 3.54 shows the IPCC confidence level regarding erosion exceeding 10 m and 25 m as a result of changes in wave direction and the resulting beach rotation by 2040. As may be seen, the changes are greater than those resulting from changes in sea level and wave heights: in this case on the order of tens of metres. Although changes of over 10 m of are *virtually certain* for all beaches prone to rotation in the region, changes of over 25 m are *very likely* for the eastern coasts of Central America, the Caribbean islands and parts of Chile and Uruguay. Changes exceeding this magnitude are also *likely* for large stretches of the Pacific and Caribbean coasts.

This type of erosion occurs only in a specific type of beach, but its foreseeable order of magnitude is much larger than that occurring from sea level rise, according to earlier results. In other types of beaches, the effect of changes in wave direction will alter the sediment transport regime, with implications for coastline erosion, but these implications cannot be evaluated using the formulation in this section, because they are determined by local conditions and take place on a much larger spatial scale.

FIGURE 3.54
CONFIDENCE LEVEL REGARDING EROSION EXCEEDING 10-METRE AND 25-METRE THRESHOLDS IN 2040 AS A RESULT OF CHANGES IN INCIDENT WAVE DIRECTION

(a) Planform erosion > 10 m (b) Planform erosion > 25 m



Source: Prepared by the authors.
Note: The confidence level used is the IPCC scale and the probabilities shown are as follows: >0.99, virtually certain; 0.9-0.99, very likely; 0.66-0.9, likely; 0.33-0.66, about as likely as not; 0.1-0.33, unlikely; 0.01-0.1, very unlikely; <0.01, exceptionally unlikely.

4.2.6 Potential sediment transport

Variations in sediment transport can be generated by:

- Variations in wave height at breaking
- Variations in breaker depth
- Variations in the incident angle of breaking waves

The volume of solid material transported per unit of time can be obtained using the CERC solid transport formula (see first auxiliary document containing a methodological guide) for a more detailed description), as a function of *wave obliqueness*:

$$Q = \frac{K}{(\rho_s - \rho)\, g\lambda} \frac{1}{16} \rho g^{3/2} H_b^{5/2} \gamma^{-1/2} \, sen 2\alpha_b \qquad (3.8)$$

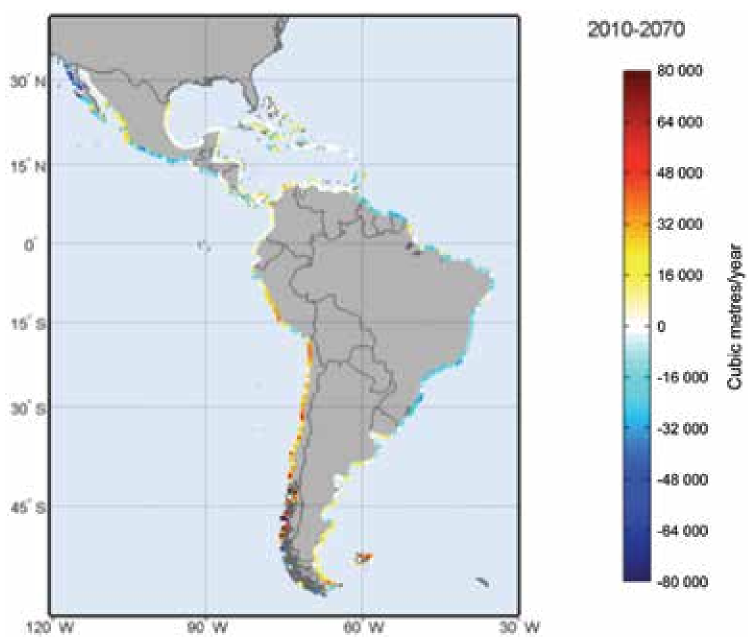
This equation includes the terms for littoral transport from *wave obliqueness* only.

Of the three parameters above whose variation can induce changes in sediment transport, the first two are related by the breaker index:

$$h_b = \frac{H_b}{\gamma} \qquad (3.9)$$

The rate of change obtained is shown below (see figure 3.55). The results show major changes in potential transport for the coasts of Brazil, Guyana, Suriname, French Guiana and the north of Mexico. Positive transport rates were obtained for Peru and Chile, which indicates that wave incidence (especially associated with high energy events) tends to transport sediment southwards. The expected impact of sediment transport is particularly important in areas where high potential transport rates coincide with significant availability of sediment (see figure 3.36), as on the coasts of Brazil, the Caribbean islands, Mexico, Costa Rica and the north of Peru.

FIGURE 3.55
TRENDS REGARDING CHANGE IN POTENTIAL SEDIMENT TRANSPORT
(Cubic metres/year)



Source: Prepared by the authors.
Note: The plus sign denotes a southerly direction.

4.2.7 General conclusions regarding impacts on beaches in the region

The analysis on the possible effect of climate change on beach morphology in Latin America and the Caribbean resulted in the following main findings:

- A rise in average sea level generates a sand deficit in the active beach profile, which is balanced out by erosion of the upper profile, leading to beach recession. The smaller the mean diameter of the sediment making up the beach and the smaller the beach's berm height, the larger the recession.

- The variation in significant wave height that is exceeded for 12 hours per year, HS12, alters cut off depth, so that if H_{S12} increases then so will h*. Increased closure depth can also lead to future erosion in beaches that have reached their maximum sand load.
- Wave direction, or mean energy flow, is the parameter that governs the shape of a beach's equilibrium planform and its variation will cause the beach to advance or recede.
- For beaches subject to littoral sediment transport, potential transport can be changed by variations in wave direction. The position of the coastline will only vary, however, when the potential sediment transport gradient is altered.

For the study of coastal erosion it is vital to determine the configuration of the coast and the type of beach, since the processes that shape erosion vary from one situation to another.

Analysis of coastal erosion in the Latin American and Caribbean region must be twofold, because some countries have extensive beach coastlines with no immediately adjacent urban development, while others have a length of built-up immediate seafront comparable with their total beach length (most of it coinciding with urbanized areas). The study must therefore look at this duality by analysing both the function of beaches as an ecological and tourism resource (recreational use) and their function as maritime defence works (defensive use).

With respect to typology, rectilinear beaches are the dominant type and make up much of the shoreline on Mexico's coasts, especially in the Gulf of Mexico, and also from the south of Brazil to the south of the continent, as well as other isolated areas throughout the Latin American and Caribbean region. Pocket beaches dominate the coasts of Chile, southern Brazil and the Caribbean islands.

The study examined the impact of sea level change and of the intensity and direction of wave incidence on beach profile and planform:

Equilibrium profile erosion owing to sea level rise

- The results obtained show a stronger effect on the Atlantic and Caribbean coasts, with rates of annual recession of around 0.16 m for the mean representative diameter (0.3 mm) of sand, and varying from 0.3 to 0.26 m per year for the other two sediment sizes considered. Importantly, positive erosion rates are found for the region overall, owing to the combined effect of (generalized) sea level rise and increases in significant wave height. High rates of erosion are also found for the coasts of southern Brazil and southern Chile. On average, the beaches in the Gulf of Mexico may be expected to show recession of around 8 m by 2040 and up to 16 m by 2070, with a low uncertainty level (around 1.5 m). Smaller recessions may be expected in the rest of the region, except for the south of Brazil and the north of Uruguay, where the figures are around 5.5 m and 11 m, with uncertainties of less than 1 m.
- Under these hypotheses, the worst affected areas will be the northern Caribbean and the coastlines to the south of Brazil down to the River Plate. Erosion is, in any case, generalized throughout the region, especially in the event of sea level rise.
- Erosion values of between 5 m and 10 m resulting from sea level rise are *about as likely as not* (33% to 66% probability). Changes of more than 10 m from sea level rise may be considered *exceptionally unlikely* in the region generally speaking.
- For a sea level rise of 1 m or even 2 m, the results are very different because recession would be around 20 m, 40 m and 60 m for the different diameters of sediment considered in the study. The results are much larger for a 2-m sea level rise. For a sea level rise occurring evenly throughout the region, the variability of the results depends exclusively on the different wave conditions in each area.

Equilibrium profile erosion owing to wave height increase

- Changes in wave height (H_{S12}) can cause erosion because they alter beach profile, and the foreseeable changes from this cause are much greater than from sea level change (exceeding 1 m/year). Nevertheless, the study of this factor is more delicate, because it depends hugely on the specific local characteristics of each stretch of beach and on sediment transport in general. Even so, the analysis serves as a warning and as a diagnostic of possible changes to identify areas most prone to erosion from wave pattern changes.
- Extrapolation of these changes gives erosion values of over 25 ± 8 m by 2040 on the coasts of southern Brazil, Uruguay and western Mexico. In certain parts of the Caribbean islands the mean recession could be between 8 m and 10 m, in general, with uncertainties of around 5 m.
- By contrast with the pattern in relation to sea level rise, the possibility of beach erosion exceeding 5 m or 10 m from wave height change is *about as likely as not* (33% to 66% probability). However, changes of over 10 m are *likely* in several parts of Central America and the west of Mexico and *very likely* on the southern coasts of the Caribbean islands.

Beach erosion owing to equilibrium planform change

- The largest changes from beach planform rotation are likely to occur on the southern coasts of Brazil (more than 1 m/year), the Caribbean coasts (especially eastern Cuba and the easterly islands), part of the coast of Chile and the north-east coast of Mexico; in the last case again at rates of over 1 m of erosion per year on average.
- Extrapolation of these results to 2040 gives erosion values of 30 ± 10 m on the coasts of Brazil, 20 ± 8 m on the tropical Atlantic coast, 10 to 20 ± 8 m on the tropical Pacific coast and 20 ± 8 m in the north of Chile.
- The IPCC confidence level regarding erosion exceeding 10 m and 25 m by 2040 owing to changes in wave direction and resulting planform rotation shows that the foreseeable impacts are greater than those resulting from changes in sea level and wave heights: in this case on the order of tens of metres. Although erosion of over 10 m is *virtually certain* for all beaches prone to rotation in the region, erosion of over 25 m is *very likely* for the eastern coasts of Central America, the Caribbean islands and parts of Chile and Uruguay. Erosion of over 25 m is also *likely* for large stretches of the Pacific and Caribbean coasts.
- If these results are compared with the areas having most pocket beaches —and therefore those most susceptible to this type of erosion— it is found that some areas of Brazil, the eastern Caribbean coasts and Chile, as well as a small part of Mexico, appear likely to suffer the worst impacts.

Sediment transport

- Both the angle of wave incidence and wave height at breaking are being affected by climate change. Accordingly, potential sediment transport (assuming *full sediment availability*) must be examined to quantify variations in net transport of littoral sediment. The results show major changes in potential sediment transport on the coasts of Brazil, Guyana, Suriname, French Guiana, the north of Mexico, Peru and Chile.
- The expected impact of sediment transport is particularly important for areas in which high potential transport rates coincide with significant availability of sediment, as occurs on the coasts of Brazil, the Caribbean islands, Mexico, Costa Rica and the north of Peru.

4.3 Impacts on ports

4.3.1 Impacts on port operationality

4.3.1.1 The concept of operationality

Port operationality is defined as the complementary value of the probability of an operations failure during the first period of analysis relative to all the major failure modes for failure thresholds (*General Procedure and Requirements in the Design of Harbor and Maritime Structures* (ROM 0.0) – Ministry of Development of Spain).

Various physical factors can make a port halt its operations, including wind, the overtopping of breakwaters, currents and internal port turbulence due to long-wavelength waves. Evaluating the threshold levels for all the different factors that can lead a port to halt operations is a complex exercise that must be tailored to each specific harbour. Given the scale of this study, an analysis of the situation in specific ports cannot be undertaken at a sufficient level of detail here. This analysis will therefore be limited to a consideration of off-shore wave activity.

It is possible to analyse situations in which a port ceases operations because of access problems created by prevailing wave conditions. Based on the dynamics in each location, it is also possible to compare current and future overflow values for a typical breakwater, averaged for all ports.

4.3.1.2 Stoppages due to navigation conditions

Using the maritime structure recommendations (*Recommendation for Design of the Maritime Configuration of Ports: Approach Channels and Harbour Basins* (ROM 3.1)) of the Ministry of Development of the Government of Spain as a frame of reference for the computation of general and conservative values, the maritime weather conditions defined as operational cut-off points are based on the desired level of service. In the absence of targeted studies, the following conditions (running perpendicular to the ship), which are the standard parameters for port access, are recommended:

- Absolute wind velocity $V10 \leq 10.00$ m/s (20 knots)
- Absolute current velocity $Vc \leq 0.50$ m/s (1 knot)
- Wave height $H_S \leq 3.00$ m

Longitudinal (relative to the ship) conditions regarded as threshold limits for the analysis of access routes under storm conditions are determined by means of statistical analyses of the desired service levels. In the absence of more specific inputs, the recommended standard operational thresholds are as follows:

- Absolute wind velocity $V10 \leq 16.00$ m/s (32 knots)
- Absolute current velocity $Vc \leq 2.00$ m/s (4 knots)
- Wave height $H_S \leq 5.00$ m

These recommendations also include guidelines for wave height limits for berthing operations (H_S from 2.5 m to 4.5 m, depending on the type of operation) and for mooring and buoy lines (H_S from 2.5 m to 4.5 m). Transversal weather conditions are the most restrictive ones for navigation (H_S=3 m), and this threshold value is therefore taken as the operational cut-off point. The scope of this study does not encompass in-port wave conditions, as this analysis is confined to port-access navigation conditions.

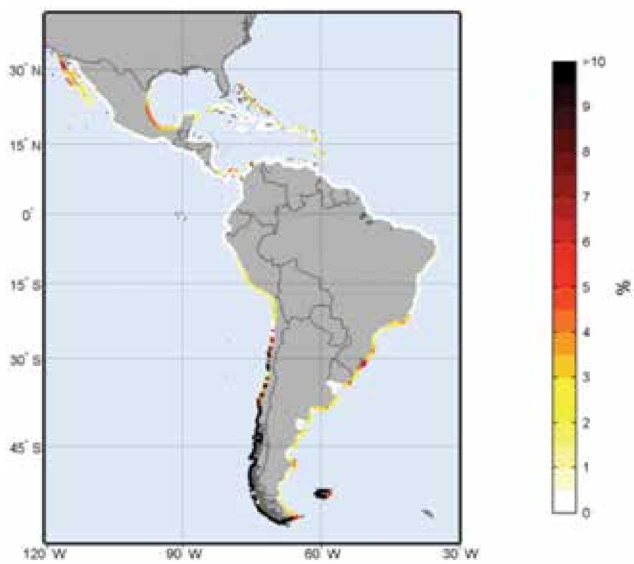
In order to determine the number of hours during which port access is closed off because of navigation conditions, the probability that significant wave height, per hour, will exceed the operational threshold has to be calculated:

$$\text{Number of hours/year} = \text{Prob}\ (H_S > 3) \cdot 8640 \qquad (3.10)$$

For purposes of comparison, and in line with ROM 3.1, the allowable mean length of time for the closure of port operations due to adverse weather conditions (exceeding the established operational thresholds) for general-purpose (international) ports are set at 200 hours/year and 20 hours/month.

Figure 3.56 et seq. give the probabilities for significant wave heights in excess of 3 m, trends in mean monthly wave conditions (mean monthly significant heights) and the values for two time horizons (see previous project documents).

FIGURE 3.56
HOURS PER YEAR WHEN SIGNIFICANT WAVE HEIGHTS EXCEED 3 METRES: RELATIVE TO 2010
(Percentages)



Source: Prepared by the authors.

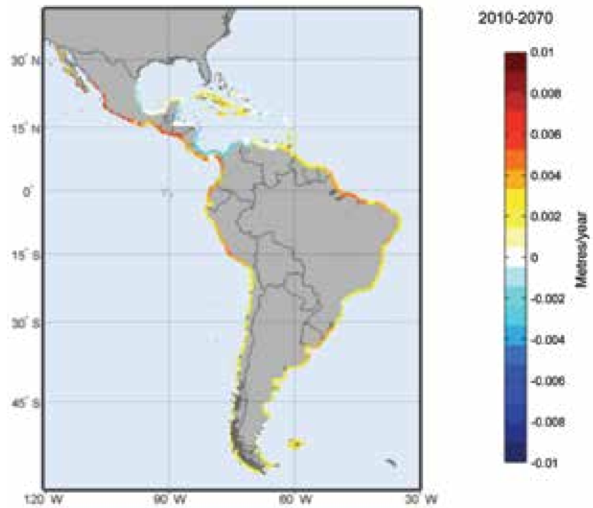
4.3.1.3 Operationality: navigation conditions

A port's exposure to operational failures is determined by the duration of wave conditions that act as constraints on the feasibility of continued port activity owing to navigation constraints for ships seeking to enter the port. The variable used here is the number of hours per month that significant wave heights exceed the threshold of Hu=3 m, in line with ROM 3.1 parameters (Ministry of Development, Government of Spain) (see figure 3.56). The economic cost of port closures is determined on the basis of the number of non-operational hours per year: $_N$.

While the reliability of port operations is gauged both for ports for which breakwater data (measured using Google-Earth —see the section on methodology) are available and for major ports in Latin America and the Caribbean for which ECLAC statistics are provided, operationality can be measured only for the latter because data on mercantile activity are not available for the other ports.

As discussed in the first project document, which deals with climate variability, dynamics and trends, changes in wave activity in the region have been identified. The implications of these changes for port operations depend on the spatial variations of these trends along the coasts of the region (see figure 3.57).

FIGURE 3.57
MEAN MONTHLY TRENDS IN SIGNIFICANT WAVE HEIGHTS: 2010 AND 2070
(Metres/year)



Source: Prepared by the authors.

An analysis of the probability of the occurrence of a significant wave height of over 3 m in the years covered by this study (see figure 3.58) indicates that, under mean conditions, the probability will increase as time goes by; in other words, navigation conditions for ships wishing to enter ports in the region will worsen.

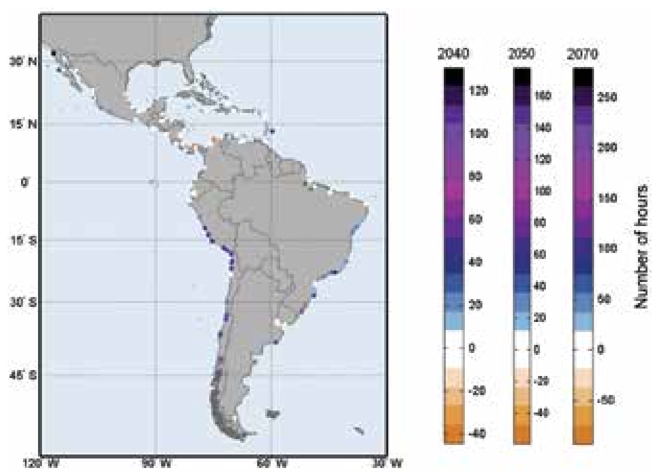
FIGURE 3.58
VARIATIONS IN THE PROBABILITY THAT SIGNIFICANT WAVE HEIGHTS WILL EXCEED 3 METRES (HOURLY SEA STATES): SCENARIOS A, B AND C
(Percentage probability)

(a) Scenario A (2040) (b) Scenario B (2050) (c) Scenario C (2070)

Source: Prepared by the authors.

This same result can be expressed in terms of the number of hours/year corresponding to those probability values. Figure 3.59 shows that probability as measured by the mean number of hours in which significant wave heights in the seas bordering the region's major ports (measured by tons of cargo and 20-foot equivalent units (TEUs) as ranked by ECLAC) would exceed the 3-m threshold. The results indicate that the most severely impacted ports will be those along the south-eastern and northern coasts of Mexico, along with the Brazilian ports that are most exposed to the open seas.

FIGURE 3.59
VARIATION IN THE MEAN NUMBER OF HOURS IN WHICH SIGNIFICANT WAVE HEIGHTS WILL EXCEED 3 METRES (HOURLY SEA STATES) FOR VARIOUS TIME HORIZONS



Source: Prepared by the authors.
Note: The results for the ports covered here are given in numbers of hours.

4.3.1.4 Operationality: overtopping of breakwaters

Another variable that should be taken into account when assessing port operationality is the overtopping of breakwaters that protect harbours.

In order to conduct this assessment, a hypothetical vertical breakwater of the standard type seen in Latin America and the Caribbean has been posited such that the differing effects of dynamics and trends can be compared on the basis of the same type of structure at different locations along the region's coasts.

The overtopping of a vertical structure can be described by the formula used in the supplementary project document that serves as a methodological handbook.

$$Q = \frac{q}{\sqrt{gH^3}} = 0.2 \exp\left(-b \frac{R_c}{H_s}\right) \qquad (3.11)$$

Where:

R_c represents the breakwater's freeboard, which is defined as the distance between the crest and the mean local waterline and is assumed here to measure 3 m. (This variable will, in actual fact, be different at different locations, depending on how strong the waves typically are, but a standard measurement has been used here for comparative purposes. The fact remains that this standard measurement will be an underestimate in areas with stronger and bigger waves and an overestimate in areas with less wave action.) The b=4.3 parameter represents a vertical breakwater without a parapet.

The overtopping variable may change a great deal over time, since overtopping is caused by storms that vary greatly in terms of their severity and is determined in a non-linear fashion by significant wave heights; as a result, the time series for overtopping is highly discontinuous. Trends have been calculated on the basis of annual frequencies. The disturbance method can also be used to evaluate the effect of overtopping driven by changes in coastal dynamics. Using the formulas presented in the first supplementary project document (the methodological handbook), changes in overtopping can be described using the following expressions:

Change in overtopping due to variations in MSL:

$$\frac{\delta q}{q} = b\,\frac{\delta \eta}{H_s} \qquad (3.12)$$

Change in overtopping due to variations in wave activity:

$$\frac{\delta q}{q} = b\,\frac{R_c}{H_s}\,\frac{\delta H}{H_s} + \frac{3}{2}\,\frac{\delta H}{H_s} \qquad (3.13)$$

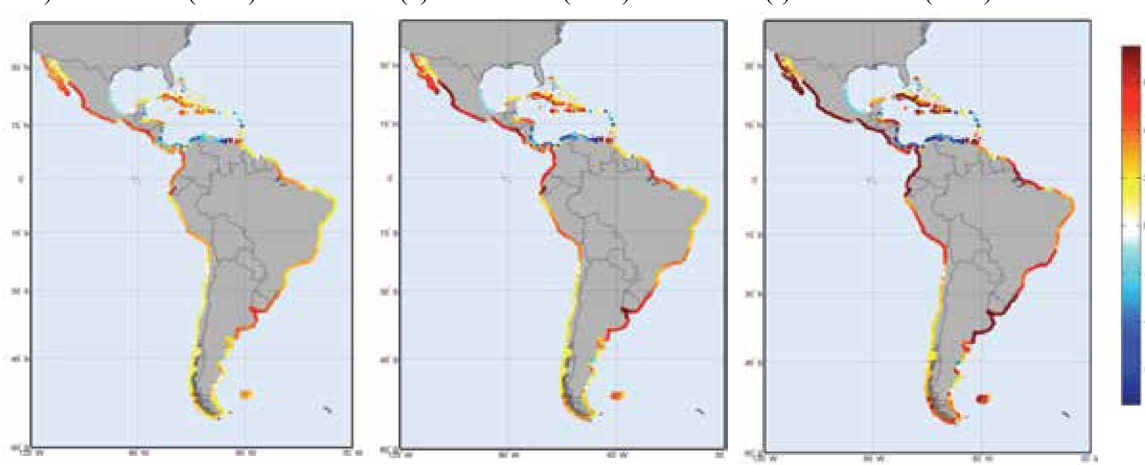
To calculate changes in overtopping due to variations in MSL, the MSL trends for the various types of dynamics covered in the study have been used along with the spatial variability in wave height along the coasts of Latin America and the Caribbean.

Given the lack of information about the type of structure in each port, the overtopping calculations are based on two typical types of breakwaters for purposes of cross-territorial comparison. Using the same type of approach as was employed in assessing port operationality based on navigation conditions, the percentage of total time corresponding to work stoppages due to breakwater overtopping will be measured.

Figure 3.60 shows the percentage values for increases in overtopping relative to current overtopping levels due to variations in wave activity for scenarios A, B and C (2040, 2050 and 2070 time horizons, respectively) and due to variations in mean sea levels.

FIGURE 3.60
VARIATION IN OVERTOPPING OF A TYPICAL BREAKWATER DUE TO VARIATIONS IN WAVE ACTIVITY: SCENARIOS A, B AND C
(Percentages)

a) Scenario A (2040) (b) Scenario B (2050) (c) Scenario C (2070)

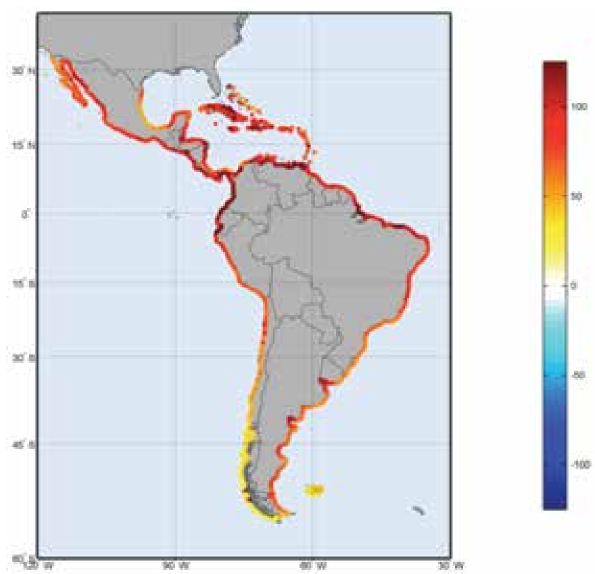


Source: Prepared by the authors.

As indicated by the results of the impact assessment for breakwater overtopping caused by changes in wave activity, the greatest changes are expected to be observed along the western coast from Ecuador northward, the northern coast of Argentina, the Uruguayan coast and the southern and northern coasts of Brazil. Weaker effects are projected for some of the Caribbean islands, southern Peru and northern Chile.

Overtopping patterns will be affected by changes in sea level, as well as by changes in wave activity. Figure 3.61 depicts the impact on overtopping patterns, in percentage terms, of a sea level rise of 0.5 m (scenario D). As can be seen from the figure, spatial variability is determined by the different spatial distribution of wave activity in the region. The biggest increases (over 100%) can be expected to occur near the equator, since waves are generally small in this zone and an increase in sea levels would have a disproportionately strong effect in terms of total overtopping.

FIGURE 3.61
INCREASES IN VERTICAL BREAKWATER OVERTOPPING DUE TO A SEA LEVEL RISE OF 0.5 METRES
(Percentages)



Source: Prepared by the authors.
Note: As a benchmark, the 99th percentile of wave heights in the 1948-2008 time series has been used for each point.

4.3.2 Port reliability

The reliability of a maritime structure is defined as the complementary value of the combined probability of failure relative to all main failure modes associated with the ultimate limit states (ROM 0.0 – Ministry of Development of Spain). Given the scale at which this study is being conducted and the available data, the only failure mode that will be considered here is the failure that occurs when the design significant wave height is exceeded.

The design wave height is defined as the height for which the probability of exceedance is *1/T,* with T being the breakwater design return period. It is therefore a variable that can be arrived at by analysing the extreme values for the statistical population of significant wave heights. The return period can be related to the probability of failure and the useful life of the structure, which can be defined as the period of time encompassing a service life *V,* which generally corresponds to the period of time during which the structure fulfils the principal function that it was designed to perform, such that:

$$T = \frac{1}{1-(1-PFV)^{V}} \qquad (3.14)$$

Where *PFV* is the probability of failure during the structure's service life.

In order to assess the reliability of breakwaters, the length of their service life and the probability of failure during that time have to be determined as a basis for the calculation of the probability that the design limits will be exceeded in the future owing to trends in extreme wave heights that are being driven by climate change.

Following the maritime structure recommendations (ROM) of the Ministry of Development of the Government of Spain, the importance of a given section of breakwater or other harbour defence structure can be determined, along with the economic, social and environmental implications of its destruction or loss of operationality, by looking at the structure as a whole. These recommendations provide guidelines for the approach to be taken in adopting values for the various parameters that are used as standard professional practice in port engineering.

The overall status of a structure can be established using the following indices:

- Economic Repercussions Index (ERI)
- Social and Environmental Repercussions Index (SERI)

The Economic Repercussions Index (ERI) provides a quantitative measurement of the economic implications of rebuilding the structure and of the foreseeable stoppage or impairment of directly related economic activities in the event that the structure is destroyed or ceases to function.

Using the ERI, harbour defence structures can be grouped into three categories corresponding to the three subintervals Ri, (i=1, 2, 3):

- R1, structures having minor economic repercussions: ERI < 5
- R2, structures having mid-range economic repercussions: 5 < ERI < 20
- R3, structures having major economic repercussions: ERI > 20

Based on the ERI, the Ministry's recommendations set out the following service lives for harbour defence works:

TABLE 3.17
SERVICE LIFE OF A MARITIME STRUCTURE BASED ON THE ERI

ERI	<6	6-20	>20
Service life (years)	15	25	50

Source: *General Procedure and Requirements in the Design of Harbor and Maritime Structures* (ROM 0.0), Ministry of Development of the Government of Spain.

All port infrastructure can be assumed to have an ERI value > 20.

The Social and Environmental Repercussions Index (SERI) provides a qualitative estimate of the foreseeable social and environmental impact of the destruction or total loss of operationality of a maritime structure by measuring the possibility and scope of: (1) loss of human life; (2) damage to the environment and to historical and/or artistic heritage resources; and (3) societal distress. The assumption here is that failures can be said to occur only once directly related economic activities have become firmly established.

The SERI is the sum of three subindices:

$$\text{SERI} = \sum_{i=1}^{3} \text{SERI}_i \quad (3.15)$$

Where:

SERI1 is the subindex for the possibility and scope of the loss of human life

SERI2, is the subindex for damage to the environment and to historical and/or artistic heritage resources

SERI3, is the subindex for societal distress.

Using the SERI, harbour defence structures can be grouped into four categories corresponding to the four subintervals Si, (i=1, 2, 3, 4):

S1, structures having no significant social or environmental repercussions: SERI < 5

S2, structures having minor social and environmental repercussions: 5 < SERI < 20

S3, structures having major social and environmental repercussions: 20 < SERI < 30

S4, structures having highly significant social and environmental repercussions: SERI > 30

Based on the SERI, the Ministry's recommendations set out the probability of failure during a structure's service life.

TABLE 3.18
PROBABILTY OF FAILURE FOR A MARITIME STRUCTURE BASED ON THE SERI

SERI	<5	5-19	20-29	>29
Pf	0.20	0.10	0.01	0.0001
βf	0.84	1.28	2.32	3.71

Source: *General Procedure and Requirements in the Design of Harbor and Maritime Structures* (ROM 0.0), Ministry of Development of the Government of Spain.

A structure's ranking on the SERI will vary at each port depending on its characteristics and significance.

Using this format, a classification of the maritime structures of the different ports of the Latin American and Caribbean region can be developed on the basis of their service lives and probabilities of failure as a function of the social, economic and environmental importance of each type of port.

This classification is based on the available data provided by ECLAC (see the 2009 report on port activity in Latin America and the Caribbean), which were used to develop a system in 2010 for ranking port activity in the region using TEUs and tons of bulk cargo as units of measurement.

Using this approach, ports have been ranked based on indices for level I and level II ports as defined in the preceding classification.

TABLE 3.19
SERI VALUES FOR PORTS IN SOUTH AMERICA

	SERI 1	SERI 2	SERI 3	SERI
Level I	3-LOW	8-HIGH	5-INTERMEDIATE	16
Level II	0-REMOTE	4-INTERMEDIATE	0-LOW	4

Source: Prepared by the authors.

The ERI value for all ports is >20, since this type of infrastructure is associated with major economic repercussions. Based on the Ministry's recommendations, the following return periods have been calculated for ERI > 20 and the two SERI values.

TABLE 3.20
PROBABILITY OF FAILURE AND RETURN PERIODS FOR SELECTED PORTS

	SERI	Probability of failure in year 1 of service life	Return period (years)
Level I	5 – 10	0.1	~ 500
Level II	< 5	0.2	~ 250

Source: Prepared by the authors.

Based on the extreme wave height regime, the design wave height associated with each return period can be determined. It is assumed that the breakwater will be totally destroyed if this design limit is exceeded.

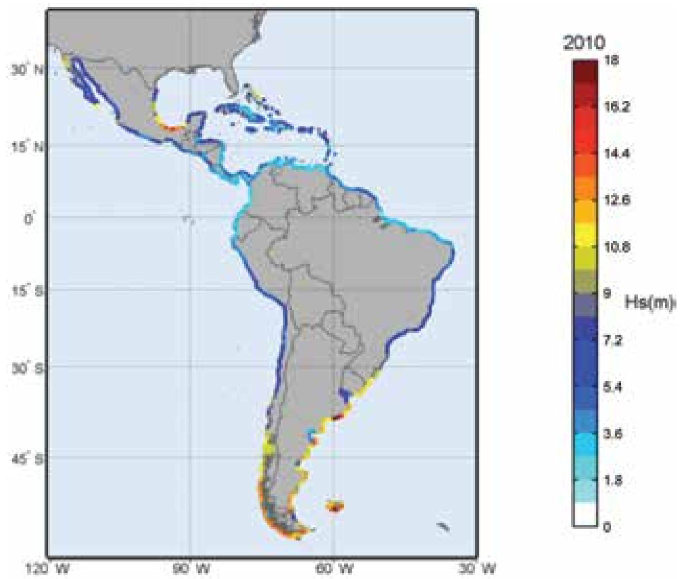
4.3.2.1 Impact of climate change on the design return period for maritime structures

As discussed in the first project document, which deals with climate variability, dynamics and trends, the pattern of the most extreme waves is also changing in Latin America and the Caribbean. And these extreme waves are the variables that determine how harbour defence structures are designed. Currently, the most extreme wind-generated waves occur along the southern portion of the continent and in the southern part of the Gulf of Mexico, with values of over 10 m for a mean recurrence interval of 500 years (see figure 3.62). The degree of spatial variability in the region is quite high, with these values ranging from less than 2 m in equatorial seas to over 12 m in the southernmost areas.

In addition to determining whether or not harbour defence works will continue to perform the function for which they were designed, it is extremely important to determine the structural response to different conditions when gauging a structure's stability. Stability can be analysed on the basis of variations in the heights for which a breakwater was designed. The design height is defined as the height for which the probability of exceedance is 1/T.

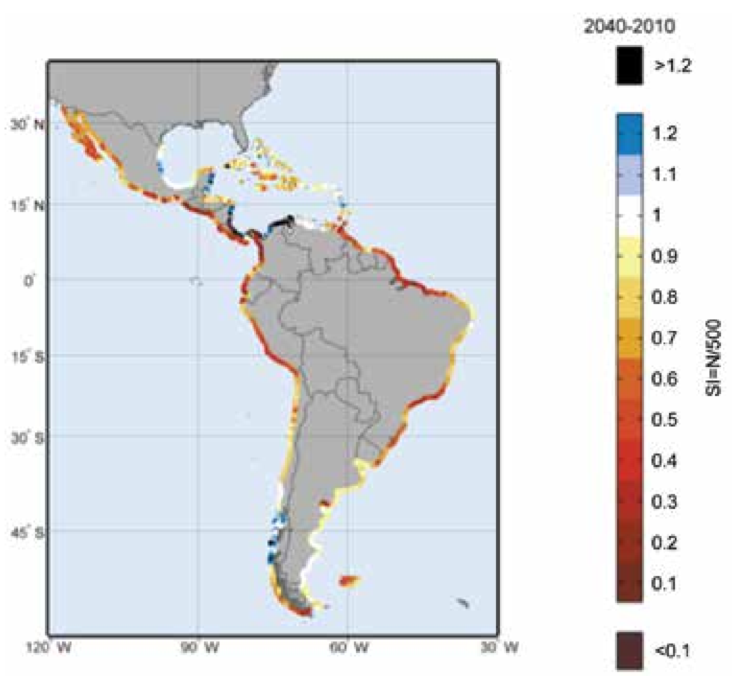
The degree of reliability in the design of maritime structures for a given return period (T) will change in the future. One simple way of gauging this effect is to derive the ratio between future and current wave recurrence and the current 500-year return period, i.e. N/500, where N is the current 500-year significant wave height return period (see figure 3.63 and figure 3.64). This ratio can be used as a maritime structural safety index.

FIGURE 3.62
EXTREME SIGNIFICANT WAVE HEIGHT REGIME IN 2010: 500-YEAR RETURN PERIOD
(Metres)



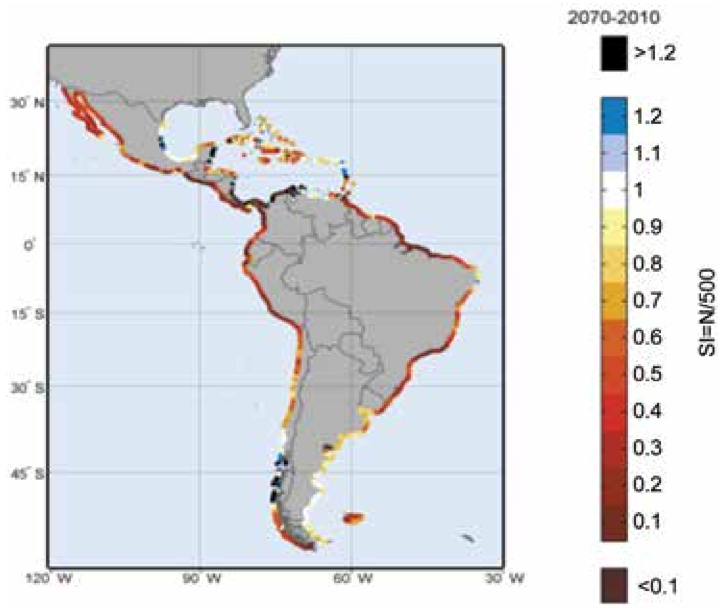
Source: Prepared by the authors.

FIGURE 3.63
MARITIME STRUCTURAL SAFETY INDEX FOR A MEAN RECURRENCE INTERVAL OF 500 YEARS: 2040 TIME HORIZON (SCENARIO A)



Source: Prepared by the authors.

FIGURE 3.64
MARITIME STRUCTURAL SAFETY INDEX FOR A MEAN RECURRENCE INTERVAL OF 500 YEARS: 2070 TIME HORIZON (SCENARIO C)



Source: Prepared by the authors.

The results indicate that the reliability of existing maritime structures and of those designed in the near future without factoring in the effects of long-term changes will be reduced by around 60% (in mean terms as of 2070) in a large part of the region (other than the inner portion of the Caribbean Sea, where tropical storms are the main design actions taken into account). Extreme wave heights are on the rise, and their effect on maritime structures therefore needs to be taken into account in the design of such structures and in the assessment of their current safety levels.

4.3.2.2 Effect of climate change on the required weight of materials used in rubble mound breakwaters

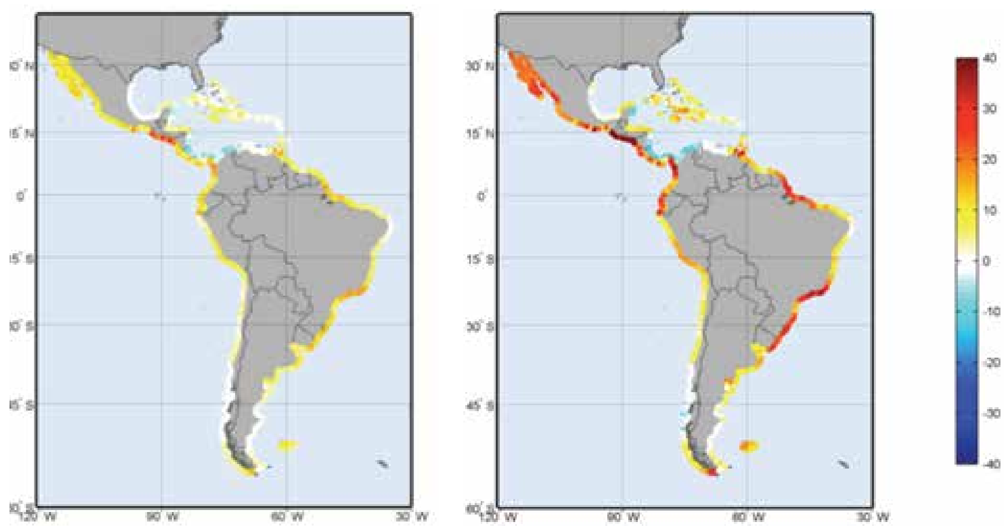
In order to study maritime structural responses to given changes in coastal dynamics, the relationship between breakwater stability and marine dynamics has to be examined. This relationship is determined by a given stability function, which depends on the type of breakwater concerned and the extent of the assumed failure or hazard (see the first supplementary project document (methodological handbook)). The weight of the materials making up a stable breakwater at the present time and the weight that will be required in the future to maintain that same degree of stability can be compared. The difference between the two is indicative of the future degree of instability of the breakwater and of the investments that should be undertaken to maintain its current level of stability.

Most of the experimental data currently available refer to breakwaters that have been tested in wave channels, with normal wave incidence. In addition, the breakwaters are usually tested on a horizontal platform or on a gentle slope, so the floor can be assumed to be horizontal. Consequently, in most testing formulas, the only incident wave parameters are the design wave height Hc, propagated up to the breakwater, and the design period T_c.

Figure 3.65 shows the difference in the weight of the revetment of harbour defence structures (for 2040 and 2070) that would be necessary to maintain the current level of stability of a hypothetical port at each location along the coast of Latin America and the Caribbean. For the most part, except in some areas of the Caribbean, the results indicate that any maritime structure is going to need to be shielded with heavier components in the future. The calculations have been made using the formula set out in the first supplementary project document (methodological handbook) for computing the relative increase in the size of the required components for a design wave height having a 500-year return period.

FIGURE 3.65
REDUCTION IN THE RELIABILITY OF MARITIME STRUCTURES WHEN ANALYSED IN TERMS OF REQUIRED CHANGES IN THE WEIGHT OF STRUCTURAL COMPONENTS: SCENARIOS A AND C
(Percentages)

(a) Variation in W_{50} in 2040 > 10 m (b) Variation in W_{50} in 2070



Source: Prepared by the authors.

The areas expected to sustain the largest reductions in the reliability of maritime structures are the same as those where wave extremes are expected to change the most: the coasts of Uruguay and of northern and southern Brazil, and the western coast running upward from northern Ecuador (especially the coasts of Guatemala and El Salvador and the western coast of Mexico). In the southern Caribbean, there will be gains in the reliability of maritime structures due to the foreseen reduction in the design wave height. Generally speaking, however, the ability of maritime structures to withstand the effects of climate change is expected to decline.

4.3.3 Impacts on maritime structures: general conclusions

Various indices and indicators have been used to assess the impacts of changes in wave activity and sea levels on the operationality and reliability of maritime structures. The main conclusions to be drawn from this analysis are as follows:

4.3.3.1 Operationality: navigation conditions

- Under mean conditions, the probability of adverse conditions for ships seeking to enter ports will be greater in the future.

- This will be reflected in the mean number of hours per year during which ports are closed. Figure 3.59 shows the mean number of hours during which there will be a sea state defined by a significant wave height of 3 m or more (by cargo measured in tons and TEUs based on the ECLAC ranking) for the region's major ports. These results indicate that the most severely affected ports will be those of the south-eastern and northern coasts of Mexico and the Brazilian ports that are most exposed to the open sea.

4.3.3.2 Operationality: overtopping of breakwaters

- As indicated by the results of the impact assessment for breakwater overtopping caused by changes in wave activity, the greatest changes are expected to be observed along the western coast from Ecuador northward, the northern coast of Argentina, the Uruguayan coast and the southern and northern coasts of Brazil. Weaker effects are projected for some of the Caribbean islands, southern Peru and northern Chile.
- Overtopping patterns will be affected by changes in sea level, as well as by changes in wave activity. Figure 3.61 depicts the impact on overtopping patterns, in percentage terms, of a sea level rise of 0.5 m (scenario D). Spatial variability is determined by the different spatial distribution of wave activity in the region. The biggest increases (over 100%) can be expected to occur near the equator, since waves are generally small in this zone and an increase in sea levels would have a disproportionately strong effect in terms of total overtopping.

4.3.3.3 The effect of climate change on the return periods of maritime structures

- The pattern of the most extreme waves is also changing in Latin America and the Caribbean, and these extreme waves are the variables that determine how harbour defence structures are designed. Currently, the most extreme wind-generated waves occur along the southern portion of the continent and in the southern part of the Gulf of Mexico, with values of over 10 m for a mean return period of 500 years. The degree of spatial variability in the region is quite high, with these values ranging from less than 2 m in equatorial seas to over 12 m in the southernmost areas.
- The results indicate that the reliability of existing maritime structures and of those designed in the near future without factoring in the effects of long-term changes will be reduced by around 60% (in mean terms as of 2070) in a large part of the region (other than the inner portion of the Caribbean Sea, where the most extreme design actions will primarily correspond to tropical storms).
- Extreme wave heights are on the rise, and their effect on maritime structures therefore needs to be taken into account in the design of such structures and in the assessment of their current safety levels.

4.3.3.4 Effect of climate change on the required weight of materials used in rubble mound breakwaters

- The areas expected to sustain the largest reductions in the reliability of maritime structures are the same as those where wave extremes are expected to change the most: the coasts of Uruguay and of northern and southern Brazil, and the western coast running upward from northern Ecuador (especially the coasts of Guatemala and El Salvador and the western coast of Mexico). In the southern Caribbean, there will be gains in the reliability of maritime structures due to the foreseen reduction in design wave heights. Safety factors will be subject to the effects of hurricanes in this area, however.

4.4 Impacts of changing sea surface temperature in terms of coral bleaching

Coral reefs are a unique habitat that is capable of supporting an abundance of biodiversity and density of life. One of the ways in which global warming may impact coral reefs is bleaching. Coral bleaching occurs when the coral is repeatedly or continuously exposed to temperatures outside its tolerance range. Coral can withstand such conditions for a time, but if the reefs continue to be stressed by high temperatures, they will die. The rise in sea surface temperature (SST) is a well-documented cause of coral bleaching. A prolonged increase in SST during the hotter summer months of even just 1ºC over the monthly mean can trigger a bleaching event (Glynn, 1996). Coral bleaching is occurring around the world, and coral mortality indices are high. Recovery rates vary across regions and are largely determined by the baseline condition of the reefs.

4.4.1 Possible changes in coral reefs as a result of global warming

Scientists have developed various global analyses of the risks posed by climate change to the planet's coral reefs. One such study is that of Donner and others (2005), which presents a global assessment of coral bleaching and the required rates of adaptation under climate change.

Recent studies have warned that climate change may increase the frequency of coral bleaching events and pose a long-term threat to the survival of coral reefs, which appear to be one of the ecosystems that are most vulnerable to climate change.

For this study on the impacts of climate change on the coastal areas of Latin America and the Caribbean, the method used in various global analyses has been downscaled for use at the regional level based on temperature data and trends calculated on a monthly basis. This impact analysis posits the possibility that the 1ºC coral-bleaching threshold may be exceeded. Given the hazards to which the coral reefs of the Caribbean (the most numerous in the region) are subject and based on observations of previous events and their consequences (Burke, L. and J. Maidens, 2005), the onset of bleaching may trigger the death of, if not all, a major portion of the existing reefs. Bleaching events are therefore assessed in terms of the potential damage that they may cause. Earlier project documents provide a more detailed introduction to coral reefs and climate change in the region.

Earlier studies on the status of the tropical coral reefs of the Caribbean and the hazards that they face include *Arrecifes en Peligro en el Caribe* (Burke, L. and J. Maidens, 2005), prepared by the World Resources Institute. The second project document (on the region's vulnerability to climate change) includes a description of this earlier study's main conclusions and the threats that it identifies. This description is intended to serve as a baseline and point of departure for this examination of the threats to the region's coral reefs posed by climate change.

A brief overview of the four region-wide hazards analysed in *Arrecifes en Peligro en el Caribe* (Burke, L. and J. Maidens, 2005) is provided here before proceeding to integrate these four components into an overall index:

- It is estimated that one third of the coral reefs in the Caribbean are threatened by coastal development.
- Sediments and pollution from land-based sources are threatening roughly one third of the Caribbean reefs.
- Marine sources of threats to the coral reefs are widespread throughout the Caribbean.
- Overfishing poses a threat to more than 60% of the Caribbean coral reefs.

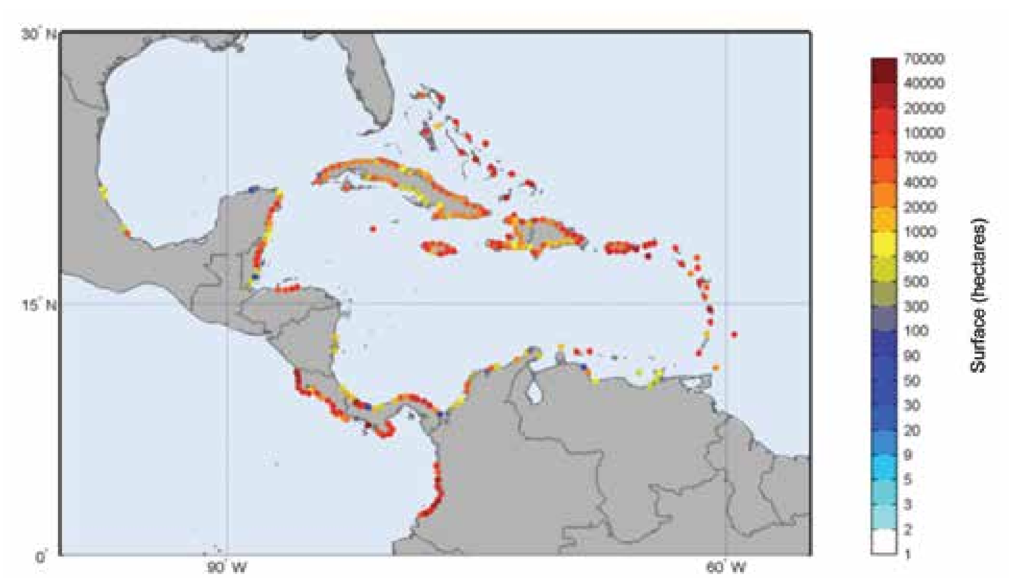
- Ineffective management of protected areas constitutes an additional threat to the Caribbean reefs.
- The coastal communities and national economies of the Caribbean islands are on the verge of sustaining considerable economic losses if current trends in the degradation of the subregion's coral reefs continue.
- Observed diseases and sea temperature increases are viewed as additional hazards for coral reefs throughout the Caribbean subregion, although they were not evaluated in quantitative terms by the project.
- This study focuses on coral bleaching caused by increases in sea surface temperatures.

4.4.2 Analysis of the impact of coral bleaching on a regional scale

In order to evaluate the risk that coral reefs will be destroyed by rising sea surface temperatures and an increased frequency of bleaching events, a similar approach to that used by Donner and others (2005) has been taken in the analysis of the situation in Latin America and the Caribbean.

Data provided by the World Resources Institute (WRI) has been used to determine where coral reefs are located within the 5-km study units used here. Figure 3.66 shows the units in which coral reefs are located according to this information source. As the reader will see, most of the reefs are found in the tropical waters of the Caribbean, while there are a few reefs off the coasts of Baja California, Brazil and northern Chile.

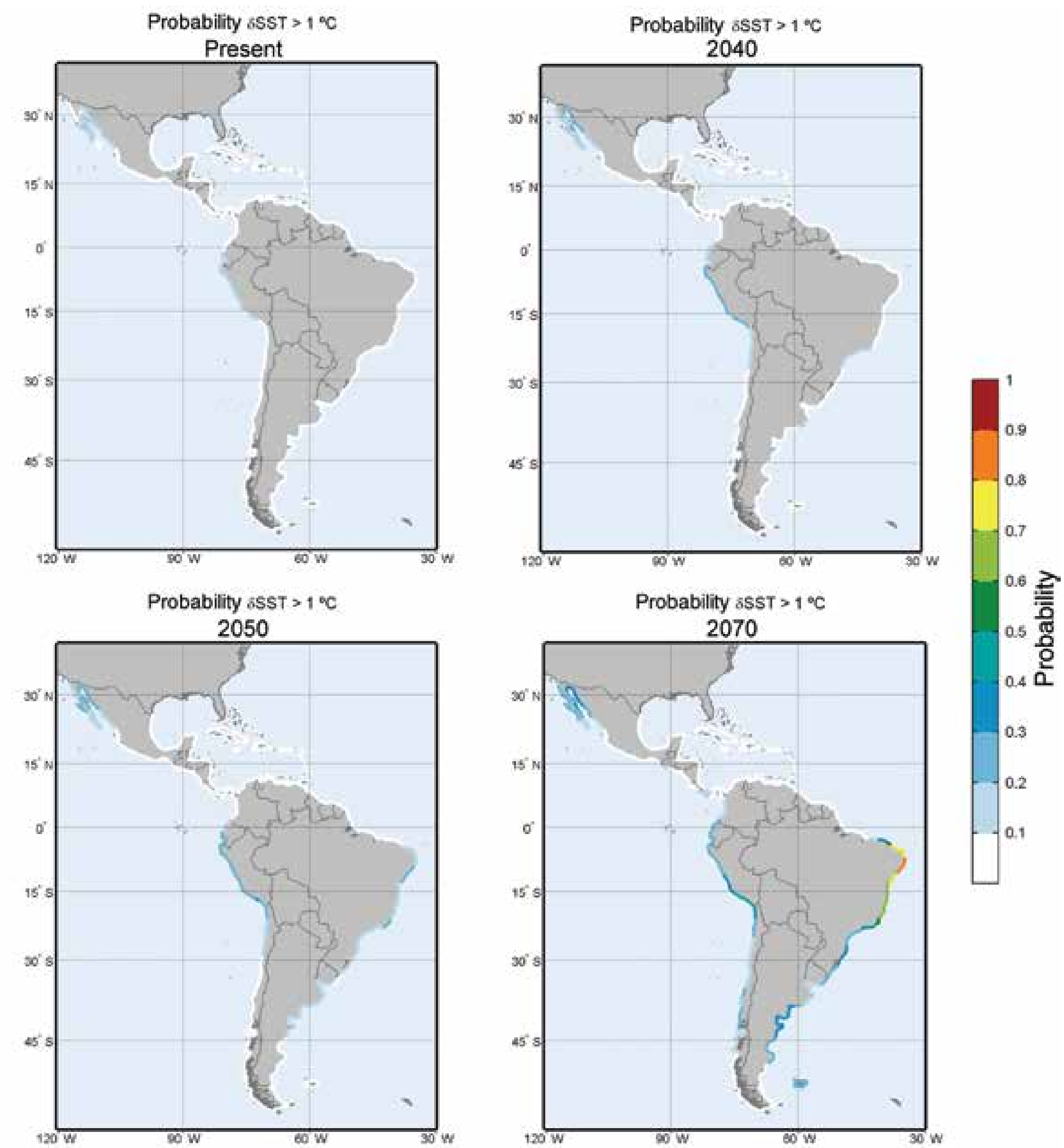
FIGURE 3.66
SURFACE AREA OF CORAL REEFS IN THE CARIBBEAN SEA AND THE CENTRAL PACIFIC
(Hectares)



Source: Prepared by the authors.

Using the approach developed by Donner and others (2005), it is possible to determine the impact on the reefs of an increase in sea surface temperature likely to exceed the critical threshold of 1ºC. Beyond that threshold, unless the coral are able to adapt to the higher temperatures, the reefs will be destroyed. Thus, using the terminology employed in this study, the impact that is being analysed is the probability that the variable SST will exceed 1ºC. This probability has been analysed in earlier studies for the whole of Latin America and the Caribbean. What is important here is to gauge this probability for the areas where coral reefs are actually located (i.e. the term of the product of the hazard (H) and exposure (E) (figure 3.66), multiplied by the probability of a future increase in SST greater than 1ºC (see the first project document, on climate variability, dynamics and trends). The results of this computation are shown in figure 3.67 for the present and for the three time horizons (2040, 2050 and 2070) for scenarios A, B and C.

FIGURE 3.67
MEAN PROBABILITY OF AN INCREASE IN SEA SURFACE TEMPERATURE IN EXCESS OF 1°C



Source: Prepared by the authors.

The results provide a basis for a number of conclusions. First, while the coral reefs off Brazil are not subject to variations in surface temperatures of over 1ºC now, there is a probability of more than 0.7 that they will be by 2070 (the end of the mean 2040-2070 period of analysis) because this is the area in which the greater mean SST rise is expected to occur. Second, it is probable that the current impacts being seen in the Caribbean will spread to islands where there are virtually no such impacts at present. Finally, for the Caribbean islands where the probability of exceeding the threshold value is currently below 0.1, the probability will rise to 0.2 by 2070.

4.4.3 Impacts in terms of coral bleaching: general conclusions

- The coral reefs off Brazil are not currently subject to variations in sea surface temperatures in excess of 1ºC, but the probability that mean surface temperatures will exceed this threshold by 2070 is 0.7.
- It is probable that the current impacts being seen in the Caribbean will spread to islands where virtually no such impacts are observed at present.
- Finally, for the Caribbean islands where the probability of exceeding the threshold value is currently below 0.1, that probability will rise to 0.2 by 2070.

5. Conclusions

Coastal flooding due to rising sea levels

- The steepest trends in rising sea levels during the first period under analysis are found along the Atlantic coast, with values of approximately 3mm/year along the northern coast of South America and the Caribbean coastline, while the values are lower for the Caribbean islands. In the deltas, flooding could be greater due to additional submergence.
- The distribution of the population and of land by metre of elevation is a major factor in the assessment of the impact of coastal flooding. The distribution of land by elevation varies greatly across countries owing to the differing configurations of the coastline (chiefly the slope or gradient). The amount of land located at less than 1 m of elevation in countries such as Honduras and Guyana is far smaller than the amount of land located at higher elevations. However, in Peru, for example, the situation is just the opposite, with a significant part of the total coastal land area being at less than 1 m in elevation.
- An examination of the percentage of land area located at each 1-m increment of elevation relative to the total land area of each country shows what a difficult position many island countries are in, since the vast majority of many of these islands' territories are at elevations of less than 10 m. In these cases, coastal areas account for a much larger percentage of total land area than they do in larger countries such as Mexico, Brazil or Argentina. Of all the Caribbean islands, the Turks and Caicos, the Bahamas and the Cayman Islands are the most vulnerable to the impacts of coastal flooding.
- Sea level rises of 0.5 and 1 m (IPCC Fourth Assessment Report (AR4) scenarios) would have a stronger impact than the values obtained by extrapolating past statistical trends. As shown in figure 3.7 and figure 3.8, the extent of sea level rise is highly variable in spatial terms.
- As measured by the size of the affected population, a sea level rise of 1 m would have a major impact along the coasts of Brazil, where it would create major disruptions in large urban areas. The Caribbean islands, especially the more easterly ones, and large stretches of the Mexican

coastline, especially in the east, would be seriously affected, as would a number of specific locations along the coasts of Peru and Ecuador and major population centres in Chile.

- When this situation is compared with what would occur in the presence of a sea level rise triggered by an El Niño event of the same magnitude as the strongest such event on record (1998), it can be seen that the western coast would clearly be more strongly affected that the eastern coast and that the scale of the impact would be considerably less than the impact of a 1-m sea level rise.
- The examination of a scenario of a 1-m rise in sea level combined with the existing situation in terms of hurricanes yields a number of findings. The ratio between the affected land surface and population differs across countries. For Honduras, for example, the extent of the affected land area would increase nearly fourfold, whereas the size of the impacted population would remain roughly the same. The size of the impacted population in Mexico and Cuba would change only marginally, whereas the square metres of land area that would be flooded would jump by a factor of 2.5 and a factor of 5, respectively. This does not hold true for all the countries or territories, however. For example, in Belize and Puerto Rico, the impacted population would nearly double. Jamaica and Haiti are other examples of this type of situation.
- When scenarios for current hurricane patterns that posit current sea levels and a 1-m rise in sea level are compared, the affected surface areas nearly double in all cases. Some of the countries where the impact of hurricanes would be much greater if sea levels rise by 1 m are Honduras, Panama, Belize, Costa Rica and the Bolivarian Republic of Venezuela. Other countries, such as the Cayman Islands, would see no significant change in the number of people who would be affected by hurricanes, however.
- The region's deltas are a special case, since these low-lying areas are subject to subsidence effects, in addition to sea level rises, and are particularly important in ecological and/or economic terms. The populations of the River Plate and Magdalena River deltas would be the most severely affected by a 1-m rise in sea levels; the largest land area that would be threatened is in the River Plate Delta.
- As far as infrastructure (roadways and railways) is concerned, the results indicate that a 1-m sea level rise would have a considerably greater impact than the impact generated by the gradual rise indicated by an extrapolation of current trends. Most of the stretches of roadway under 1 m of elevation that would be affected are located along the coasts of Brazil, Mexico and the Bolivarian Republic of Venezuela and on some of the Caribbean islands. Far fewer railroad tracks would be impacted, although they play a relatively more important role in terms of infrastructure and transport networks. Nonetheless, the level of risk is significant only in the cases of Cuba, Mexico and Brazil and in the case of Puerto Rico under a scenario of sea level rise combined with hurricanes.
- For countries such as the Bolivarian Republic of Venezuela, Honduras, Panama and Costa Rica, the impact of a 1-m sea level rise would change considerably if combined with hurricane activity, whereas the impact would not be heightened substantially relative to the current situation in others, such as the Dominican Republic.

Flood levels (sea level extremes)

- Flood levels have been studied as a variable that defines sea levels in the presence of extreme events driven by a variety of factors. Flood levels have trended upward over the past 61 years due to increases in wave activity, mean sea levels and storm surges. The rate of change in the occurrence of extreme events influencing flood levels is the greatest (up to 1 cm/year) around the River Plate, which is also the geographic area with the highest flood levels. In the rest of the region, trends have been calculated at no more, generally speaking, than 0.5 cm/year.

- Seasonal changes can play an influential role by broadening the yearly range of variation. Seasonal variations are not very marked in the River Plate Delta, however, so trends can be regarded as being virtually homogeneous for all months of the year.
- At over 4 m, the 50-year return period flood levels are the highest along the coasts of Chile, Argentina and Uruguay. In the Caribbean Sea, flood levels are around 1 m (in the absence of hurricanes).
- The index for future versus present return periods declines in all cases, signalling an increased frequency of extreme flooding events in the future. Unlike the situation with extreme waves, which do not increase in all locations in the region, in this case, because of the combined influence of the various components affecting sea levels, the increase in flooding is found across all of the region's coasts.
- The results for extreme flooding point to a much larger loss of land surface than the results obtained for rising sea levels, thus underlining the significance of sporadic flood events.
- In terms of the number of people affected, the values are particularly high for Brazil, Mexico and Argentina; in the latter case, the flooding associated with a 1-m rise in sea levels would add another 70% to the impact as measured for the present time. In the other countries, the impact increases by at least 25% over current levels except in Suriname and Guyana, where the jump amounts to over 80%.
- The extent of the impacts is likely to change a great deal in many countries in coming decades. In some countries, such as Panama and Haiti, El Niño events may actually cause less damage if sea levels rise by 1 m than they do now. In others, however, such as Guatemala, the size of the affected population is expected to expand (from 2.4% to 7% for events with 50-year return periods).
- The greatest impacts on the population will be seen along the eastern coast in the southern hemisphere, with specific impact areas in coastal cities in northern Argentina, Uruguay and Brazil and in metropolitan areas in the Caribbean, Mexico and Peru.

Beaches

General comments

- A study of coastal erosion must necessarily establish the configuration of the coast and the typology of its beaches, since the processes that shape erosion vary in each situation.
- Analysis of coastal erosion in the Latin American and Caribbean region must be twofold, because some countries have extensive beach coastlines with no immediately adjacent urban development, while others have a length of built-up immediate seafront comparable with their total beach length (most of it coinciding with urbanized areas). The study must therefore look at this duality by analysing both the function of beaches as an ecological and tourism resource (recreational use) and their function as maritime defence works (defensive use).
- With respect to typology, rectilinear beaches are the dominant type and make up much of the shoreline on Mexico's coasts, especially in the Gulf of Mexico, and also from the south

of Brazil to the south of the continent, as well as other isolated areas throughout the Latin American and Caribbean region. Pocket beaches dominate the coasts of Chile, southern Brazil and the Caribbean islands.

Equilibrium profile erosion owing to sea level rise

- The results obtained show a stronger effect on the Atlantic and Caribbean coasts, with rates of annual recession of around 0.16 m for the mean representative diameter (0.3 mm) of sand, and varying from 0.3 to 0.26 m per year for the other two sediment sizes considered. Importantly, positive erosion rates are found for the region overall, owing to the combined effect of (generalized) sea level rise and increases in significant wave height. High rates of erosion are also found for the coasts of southern Brazil and southern Chile. On average, the beaches in the Gulf of Mexico may be expected to show recession of around 8 m by 2040 and up to 16 m by 2070, with a low uncertainty level (around 1.5 m). Smaller recessions may be expected in the rest of the region, except for the south of Brazil and the north of Uruguay, where the figures are around 5.5 m and 11 m, with uncertainties of less than 1 m.
- Under these hypotheses, the worst affected areas will be the northern Caribbean and the coastlines to the south of Brazil down to the River Plate. Erosion is, in any case, generalized throughout the region, especially in the event of sea level rise.
- Erosion values of between 5 m and 10 m resulting from sea level rise are *about as likely as not* (33% to 66% probability). Changes of more than 10 m from sea level rise may be considered *exceptionally unlikely* in the region generally speaking.
- For a sea level rise of 1 m (or even 2 m), the results are very different because recession would be around 20 m, 40 m and 60 m for the different diameters of sediment considered in the study. The results are much larger for a 2-m sea level rise. For a sea level rise occurring evenly throughout the region, the variability of the results depends exclusively on the different wave conditions in each area.

Equilibrium profile erosion owing to wave height increase

- Changes in wave height (H_{S12}) can cause erosion because they alter beach profile, and the foreseeable changes from this cause are much greater than from sea level change (exceeding 1 m/year). Nevertheless, the study of this factor is more delicate, because it depends hugely on the specific local characteristics of each stretch of beach and on sediment transport in general. Even so, the analysis serves as a warning and as a diagnostic of possible changes to identify areas most prone to erosion from wave pattern changes.
- Extrapolation of these changes gives erosion values of over 25 ± 8 m by 2040 on the coasts of southern Brazil, Uruguay and western Mexico. In certain parts of the Caribbean islands the mean recession could be between 8 m and 10 m, in general, with uncertainties of around 5 m.
- By contrast with the pattern in relation to sea level rise, the possibility of beach erosion exceeding 5 m or 10 m from wave height change is *about as likely as not* (33% to 66% probability). However, changes of over 10 m are *likely* in several parts of Central America and the west of Mexico and *very likely* on the southern coasts of the Caribbean islands.

Beach erosion owing to equilibrium planform change

- The largest changes from beach planform rotation are likely to occur on the southern coasts of Brazil (more than 1 m/year), the Caribbean coasts (especially eastern Cuba and the easterly islands), part of the coast of Chile and the north-east coast of Mexico; in the last case again at rates of over 1 m of erosion per year on average.

- Extrapolation of these results to 2040 gives erosion values of 30 ± 10 m on the coasts of Brazil, 20 ± 8 m on the tropical Atlantic coast, 10 to 20 ± 8 m on the tropical Pacific coast and 20 ± 8 m in the north of Chile.
- The IPCC confidence level regarding erosion exceeding 10 m and 25 m by 2040 owing to changes in wave direction and resulting planform rotation shows that the foreseeable impacts are greater than those resulting from changes in sea level and wave heights: in this case on the order of tens of metres. Although erosion of over 10 m is *virtually certain* for all beaches prone to rotation in the region, erosion of over 25 m is *very likely* for the eastern coasts of Central America, the Caribbean islands and parts of Chile and Uruguay. Erosion of over 25 m is also *likely* for large stretches of the Pacific and Caribbean coasts.

If these results are compared with the areas having most pocket beaches —and therefore those most susceptible to this type of erosion— it is found that some areas of Brazil, the eastern Caribbean coasts and Chile, as well as a small part of Mexico, appear likely to suffer the worst impacts.

Sediment transport

- Both the angle of wave incidence and wave height at breaking are being affected by climate change. Accordingly, potential sediment transport (assuming *full sediment availability*) must be examined to quantify variations in net transport of littoral sediment. The results show major changes in potential sediment transport on the coasts of Brazil, Guyana, Suriname, French Guiana, the north of Mexico, Peru and Chile.
- The expected impact of sediment transport is particularly important for areas in which high potential transport rates coincide with significant availability of sediment, as occurs on the coasts of Brazil, the Caribbean islands, Mexico, Costa Rica and the north of Peru.

Ports

Operationality: navigation conditions

- An analysis of the probability of the occurrence of a significant wave height of over 3 m indicates that, under mean conditions, the probability will increase as time goes by.
- This same result can be expressed in terms of the number of hours/year corresponding to those probability values. Figure 3.59 shows that probability as measured by the mean number of hours in which significant wave heights in the seas bordering the region's major ports (measured by tons of cargo and 20-foot equivalent units (TEUs) as ranked by ECLAC) would exceed the 3-m threshold. The results indicate that the most severely impacted ports will be those along the south-eastern and northern coasts of Mexico, along with the Brazilian ports that are most exposed to the open seas.

Operationality: overtopping of breakwaters

- As indicated by the results of the impact assessment for breakwater overtopping caused by changes in wave activity, the greatest changes are expected to be observed along the western coast from Ecuador northward, the northern coast of Argentina, the Uruguayan coast and the southern and northern coasts of Brazil. Weaker effects are projected for some of the Caribbean islands, southern Peru and northern Chile.

- Overtopping patterns will be affected by changes in sea level, as well as by changes in wave activity. Figure 3.61 depicts the impact on overtopping patterns, in percentage terms, of a sea level rise of 0.5 m (scenario D). As can be seen from the figure, spatial variability is determined by the different spatial distribution of wave activity in the region. The biggest increases (over 100%) can be expected to occur near the equator, since waves are generally small in this zone and an increase in sea levels would have a disproportionately strong effect in terms of total overtopping.

Impact of climate change on the design return period for maritime structures

- The pattern of the most extreme waves is also changing in Latin America and the Caribbean, and these extreme waves are the variables that determine how harbour defence structures are designed. Currently, the most extreme wind-generated waves occur along the southern portion of the continent and in the southern part of the Gulf of Mexico, with values of over 10 m for a mean recurrence interval of 500 years. The degree of spatial variability in the region is quite high, with these values ranging from less than 2 m in equatorial seas to over 12 m in the southernmost areas.
- The results indicate that the reliability of existing maritime structures and of those designed in the near future without factoring in the effects of long-term changes will be reduced by around 60% (in mean terms as of 2070) in a large part of the region (other than the inner portion of the Caribbean Sea, where tropical storms are the main design actions to be taken into account).
- Extreme wave heights are on the rise, and their effect on maritime structures therefore needs to be taken into account in the design of such structures and in the assessment of their current safety levels.

Effect of climate change on the required weight of materials used in rubble mound breakwaters

- The areas expected to sustain the largest reductions in the reliability of maritime structures are the same as those where wave extremes are expected to change the most: the coasts of Uruguay and of northern and southern Brazil and the western coast running upward from northern Ecuador (especially the coasts of Guatemala and El Salvador and the western coast of Mexico). In the southern Caribbean, there will be gains in the reliability of maritime structures due to the foreseen reduction in the design wave height.

Coral reefs

- The coral reefs off Brazil are not currently subject to variations in sea surface temperatures in excess of 1ºC, but the probability that mean surface temperatures will exceed this threshold by 2070 amounts to 0.7.
- It is probable that the current impacts being seen in the Caribbean will spread to islands where virtually no such impacts are observed at present.
- Finally, for the Caribbean islands where the probability of exceeding the threshold value is currently below 0.1, that probability will rise to 0.2 by 2070.

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This document is the third in a series prepared in the framework of the Regional study on the impacts of climate change on the coast of Latin America and the Caribbean. A total of approximately 72,182 km of coastline is studied in four geographical areas: North America, Central America, South America and the Caribbean islands. The study covers analysis of changes detected in coastal dynamics, the influence of climate variability, coastal vulnerability in terms of factors ranging from the physical environment to the socioeconomic impacts, the physical coastal configuration and foreseeable impacts and risks for the future.

This third volume documents the analysis of climate change impacts on the region's coasts. It looks at the effects and probability of coastal flooding caused by sea level rise and extreme events, beach erosion from changes in wave patterns and sea level, the new conditions that may affect port operations and the safety of port defence works, and the possible impact of coral bleaching as a result of rising sea surface temperatures. This knowledge is vital for coastal and port engineering in the region, for analysing the vulnerability of human settlements in coastal areas and for the integrated management of coastal environments, among other uses.

The information provided in this third volume provides the basis for the analysis of climate change risks for the coasts of Latin America and the Caribbean, which are documented in the fourth volume.

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