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Sea-Level Rise and Storm Surges

A Comparative Analysis of Impacts in Developing Countries

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Abstract

An increase in sea surface temperature is evident at all latitudes and in all oceans. The current understanding is that ocean warming plays a major role in intensified cyclone activity and heightened storm surges. The vulnerability of coastlines to intensified storm surges can be ascertained by overlaying Geographic Information System information with data on land, population density, agriculture, urban extent, major cities, wetlands, and gross domestic product for inundation zones likely to experience more intense storms and a 1 meter sea-level rise. The results show severe impacts are likely to be limited to a relatively small number of countries and a cluster of large cities at the low end of the international income distribution.

This paper—a product of the Environment and Energy Team, Development Research Group—is part of a larger effort in the department to understand potential impacts of climate change. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at sdasgupta@worldbank.org.

Produced by the Research Support Team

Sea-Level Rise and Storm Surges: A Comparative Analysis of Impacts in Developing Countries

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I. Introduction

An increase in sea surface temperature is strongly evident at all latitudes and in all oceans. The scientific evidence indicates that increased surface temperature will intensify cyclone activity and heighten storm surges.[1] These surges[2] will, in turn, create more damaging flood conditions in coastal zones and adjoining low-lying areas. The destructive impact will generally be greater when storm surges are accompanied by strong winds and large onshore waves. The historical evidence highlights the danger associated with storm surges.

During the past 200 years, 2.6 million people may have drowned during surge events (Nicholls 2003). More recently tropical cyclone Sidr[3] in Bangladesh (November 2007) and cyclone Nargis[4] in the Irrawady delta of Myanmar (May 2008) provide examples of devastating storm-surge impacts in developing countries.

Recent scientific studies suggest that increases in the frequency and intensity of tropical cyclones in the last 35 years can be attributed in part to global climate change (Emanuel 2005; Webster et al. 2005; Bengtsson, Rogers, and Roeckner 2006). Others have challenged this conclusion, citing problems with data reliability, regional variability, and appropriate measurement of sea-surface temperature and other climate variables (e.g., Landsea et al. 2006). Although the science is not yet conclusive (IWTC 2006: Pielke et al. 2005), the International Workshop on Tropical Cyclones (IWTC) has recently noted that “[i]f the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase” and “[i]t is likely

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[1] A sea-surface temperature of 28° C is considered an important threshold for the development of major hurricanes of categories 3, 4 and 5 (Michaels, Knappenberger, and Davis 2005; Knutson and Tuleya 2004).

[2] *Storm surge* refers to the temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions: low atmospheric pressure and/or strong winds (IPCC AR4 2007).

[3] According to Bangladesh Disaster Management Information Centre (report dated Nov 26, 2007) 3,243 people were reported to have died and the livelihoods of 7 millions of people were affected by Sidr (http://www.reliefweb.int/rw/RWB.NSF/db900SID/EDIS-79BQ9Z?OpenDocument).

[4] In Mayanmar, 100,000 people were reported to have died and the livelihoods of 1.5 million people were affected by Nargis (http://www.dartmouth.edu/%7Efloods/Archives/2008sum.htm)

that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm. Model studies and theory project a 3-5% increase in wind-speed per degree Celsius increase of tropical sea surface temperatures."

The Intergovernmental Panel on Climate Change (IPCC 2007) cites a trend since the mid-1970s toward longer duration and greater intensity of storms, and a strong correlation with the upward trend in tropical sea surface temperature. In addition, it notes that hurricanes/cyclones are occurring in places where they have never been experienced before.[5] Overall, using a range of model projections, the report asserts a probability greater than 66% that continued sea-surface warming will lead to tropical cyclones that are more intense, with higher peak wind speeds and heavier precipitation (IPCC 2007; see also Woodworth and Blackman 2004; Woth, Weisse, and von Storch 2006; and Emanuel et al. 2008).[6]

The consensus among projections by the global scientific community points to the need for greater disaster preparedness in countries vulnerable to storm surges. Fortunately, significant adaptation has already occurred, and many lives have been saved by improved disaster forecasting, and evacuation and emergency shelter procedures (Shultz, Russell, and Espinel 2005; Keim 2006). At the same time, as recent disasters in Bangladesh and Myanmar have demonstrated, storm-surge losses remain huge in many areas. Such losses could be further reduced by allocating resources to increased disaster resilience, especially given the expected intensification of storms and storm surges along particularly vulnerable coastlines. However, setting a new course requires better understanding of expected changes in storm surge patterns in the future.

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[5] The first recorded tropical cyclone in the South Atlantic occurred in March 2004 off the coast of Brazil.

[6] Cyclones get their power from rising moisture which releases heat during condensation. As a result, cyclones depend on warm sea temperatures and the difference between temperatures at the ocean and in the upper atmosphere. If global warming increases temperatures at the earth's surface but not the upper atmosphere, it is likely to provide tropical cyclones with more power (Emmanuel et al. 2008).

Research to date has been confined to relatively limited sets of impacts[7] and locations.[8] In this paper, we broaden the assessment to 84 coastal developing countries in five regions.[9] We consider the potential impact of a large (1-in-100-year) storm surge by contemporary standards, and then compare it with intensification which is expected to occur in this century. In modeling the future climate, we take account of changes in sea-level rise (SLR), geological uplift and subsidence along the world's coastlines. Our analysis includes impact indicators for the following: affected territory, population, economic activity (GDP), agricultural land, wetlands, major cities and other urban areas. As far as we know, this is the first such exercise for developing countries.

Our analysis is based on the best available data for estimating the relative vulnerability of various coastal segments to increased storm surge. However, several gaps in the data limit our analysis. First and foremost, the absence of a global database on shoreline protection has prevented us from incorporating the effect of existing man-made protection measures (e.g., sea dikes) and natural underwater coastal protective features (e.g., mangroves) on exposure estimates. Second, lack of sub-national data on impact indicators has prevented us from including small islands in our analysis. Third, in the absence of reliable spatially disaggregated projections of population and socioeconomic conditions for 84 developing countries included in this analysis, we have assessed the impacts of storm surges using existing populations, socioeconomic conditions and patterns of land use. Human activity is generally increasing more rapidly in coastal areas, so our estimates are undoubtedly conservative on this score. On the other hand, we also have not attempted to estimate the countervailing effects of planned adaptation measures related to infrastructure (e.g., coastal embankments) and coastal-zone management (e.g., land-use planning, regulations, relocation). Fourth, among the 84 developing countries included in this analysis, we restrict our analysis to coastal segments where historical storm surges have been documented. Fifth, we did not assess the relative likelihoods of alternative storm surge scenarios. Following Nicholls et al. 2007, we assume a

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[7] For example, Nicholls et al. (2007) assess the impacts of climate extremes on port cities of the world.

[8] For example, the impacts of storm surges have been assessed for Copenhagen (Hallegatte et al., 2008); Southern Australia (McInnes et al. 2008); and the Irish Sea (Wang et al. 2008).

[9] We have employed the five World Bank regions: East Asia & Pacific, Middle East & North Africa, Latin America & Caribbean, South Asia, Sub-Saharan Africa.

homogeneous future increase of 10% in extreme water levels during tropical storms. In all likelihood, some regions of the world may experience a smaller increase and others a larger increase. Better local modeling of the impact of climate change on storm intensities will further fine tune future forecasts.

In the next section, we describe the methodology and data sources used to estimate the impact of storm surges in developing countries. Results are presented in Section III first at the global level, and then for each of the five regions. The above 6 indicators are further presented individually for each country comprising each of the five regions. Section IV concludes.

II. Methodology and data sources

This section briefly discusses the methodology and data sources pertaining to the delineation of storm surge zones, and then discusses the methodology and data sources for the impact indicators used in this paper.

II.1 Storm surge zones

(i) Methodology

Recently released hydrologically conditioned version of SRTM data (part of the HydroSHEDS dataset) was used for elevation in this analysis. All 5ºx5º coastal tiles of hydrologically conditioned version of 90 m SRTM data were downloaded from http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php. Conditioning of the SRTM data refers to a series of processing steps that alter elevation values in order to produce a surface that drains to the coast (except in cases of known internal drainages). These steps include filtering, lowering of stream courses and adjacent pixels, and carving out barriers to stream flow. Despite known limitations, SRTM represents the best available high resolution global elevation model and, to our knowledge, there is no global dataset of shoreline protection.

In the calculation of storm surge (wave heights or extreme sea levels), the method outlined by Nicholls (2008) was primarily followed. In our slightly modified version, surges (for the two storm surge scenarios – with and without climate change) were calculated as follows:

Current storm surge = S100
Future storm surge = S100 + SLR + (UPLIFT * 100 yr) / 1000 + SUB + S100 * x
Where:
S100 = 1 in 100 year surge height (m);
SLR = 1 m;
UPLIFT = continental uplift/subsidence in mm/yr;
SUB = 0.5 m (applies to deltas only);

x = 0.1, or increase of 10%, applied only in coastal areas currently prone to cyclones or hurricanes.

Surges were calculated using data associated with the coastline. Vector coastline masks were extracted from SRTM version 2. Coastline attributes were downloaded from DIVA GIS database. Attributes used in this analysis are:

1. S100: 1-in-100-year surge height based on tidal levels, barometric pressures, wind speeds, sea-bed slopes and storm surge levels from monitoring stations;
2. DELTAID: coastline segments associated with river deltas;
3. UPLIFT: estimates of continental uplift/subsidence in mm/yr from Peltier (2000). This parameter includes a measure of natural subsidence (2 mm/yr) for deltas.

Surge (wave height) associated with current and future storms were then compared to the elevation value of inland pixels with respect to a coastline to delineate a potential inundation area for storm surges.

Each inland pixel could be associated with the nearest coastline segment, in a straight-line distance. However, in order to better capture the movement of water inland, in this analysis hydrological drainage basins have been used instead. The wave height calculated for the coastline segment closest to the basin outlet was applied to inland areas within that basin.

As a wave moves inland the height is diminished. The rate of decay depends largely on terrain and surface features, as well as factors specific to the storm generating the wave. In a case study on storm surges, Nicholls (2006) refers to a distance decay factor of 0.2-0.4 m per 1 km that can be applied to wave heights in relatively flat coastal plains. For this analysis, we used 0.3 m per 1 km distance from coastline to estimate the reduction in wave height applied to each inland cell.

The delineation of surge zones was then based on a simple comparison of the calculated wave height, taking into account distance decay, to the SRTM value. If the elevation value of any location is less than the wave height, then the location is part of the surge zone. Low-elevation "coastal zone" was delineated from inland pixels with less than 10m elevation- near the coastline, following McGranahan, Balk, and Anderson (2007).

All processing was done by 5º x 5º tile, using aml (ArcInfo Macro Language) for automation.

(ii) Datasets

The following datasets were used to delineate inundation areas:

1) Hydrosheds conditioned 90m DEM

Hydrologically conditioned version of 90 m SRTM data, conditioned to produce a surface that drains to the coast (except in cases of known internal drainages).

2) Hydroshed basins

The unofficial version of drainage basins derived from conditioned DEM in regional subsets downloaded from http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php.

3) SRTM coastline

Vector coastline mask derived by National Geospatial-Intelligence Agency during editing of SRTM version 2.

4) DIVA GIS database

A segmented linear representation of the coastline and a wide range of attributes associated with each segment from the DIVA GIS database -downloaded from http://diva.demis.nl/files/.

II.2 Indicators of impacts

(i) Methodology

Estimates for each indicator were calculated by overlaying the inundation zone with the appropriate exposure surface dataset (land area, GDP, population, urban extent, agriculture extent, and wetland).[10] Exposure surface data were collected from various public sources. Unless otherwise indicated, latitude and longitude are specified in decimal degrees. The horizontal datum used is the World Geodetic System 1984. For area calculation, grids representing cell area in square kilometers were created at different resolutions, using length of a degree of latitude and longitude at cell center.

For the exposure surfaces, two GIS models were built for calculating the exposed value. Since the units for GDP and population are in millions of U.S. dollars and number of people, respectively, the exposure was calculated by multiplying the exposure surface

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[10] The delineated surge zones and coastal zone are at a resolution of 3 arc seconds (approximately 90 m). The resolution of indicator datasets ranges from 9 arc seconds to 30 arc seconds. Due to this difference in resolution, a surge zone area may occupy only a portion of a single cell in an indicator dataset. In this case, the surge zone is allocated only a proportion of the indicator cell value.

with the inundation zone and then summing to a country total. Exposure indicators, such as land surface, urban extent, agriculture extent and wetlands were measured in square kilometers.

For exposure indicators such as land area, population and GDP, which have measured country "coastal zone" totals available, the exposed value is adjusted to reflect its real value by using the following formula:

$$V_{adj} = \frac{CT_{mea}}{CT_{cal}} \cdot V_{cal}$$

where:

V_{adj} : Exposed value adjusted;

V_{cal} : Exposed value calculated from exposure grid surfaces;

CT_{mea} : Country "coastal zone" total obtained based on statistics;
CT_{cal} : Country "coastal zone" total calculated from exposure grid surface.

Due to the relatively high resolution of some of these datasets, summary statistics are derived tile by tile, and a master table of countries is updated as each tile is processed. In the update, new values are added to existing values so that values in the final country table represent the sum of all tiles in which a country falls.

All processing, once again, was done by 5º x 5º tile, using aml (ArcInfo Macro Language) for automation. Output is in the form of a database table. Further manipulations are done in MS Excel.

(ii) Datasets

Summary statistics were calculated for each zone using the following datasets;

5) GRUMP 2005 (pre-release) gridded population dataset

A global gridded population dataset of approximately 1 km resolution produced by the Center for Earth Science Information Network (CIESIN) at Columbia University. Sub-national urban and rural population are allocated to grid cells using an urban extents mask and most recent census data adjusted to reflect U.N. projections for 2005. Data for the year 2005 were provided by ftp upon special request. The GRUMP alpha version for the year 2000 is available for download at: http://sedac.ciesin.columbia.edu/gpw/global.jsp.

6) 2005 gridded GDP surface

A global gridded dataset in which shares of GDP, in 2000 USD, are allocated to 1 km grid cells, using GRUMP 2005 population data, urban/rural extents mask, and, where available, regional accounts data for countries. Regional shares of GDP were standardized using 2005 estimated GDP in 2000 USD and allocated to cells on a rural or urban per capita basis. Data are not currently available for download.

7) Globcover 2.1

A global land cover dataset of approximately 300 m resolution produced by the European Space Agency (ESA). *Globcover* 2.1 was based on imagery acquired between December 2004 and June 2006 by ENVISAT's Medium Resolution Imaging Spectrometer (MERIS). The 22 general land cover categories derived by automatic and regionally specific classification include four agricultural classes which are used in this analysis. Data are available for download at: http://www.esa.int/due/ionia/globcover.

Note that the Globcover database covers three different types of agricultural land use indicator. A first indicator includes areas which most of the coverage is rainfed/irrigated/post-flooding cropland. A second indicator includes areas for which 50-70% is made of mosaic cropland and the rest is made of grassland, shrubland, and forest. A third indicator includes areas for which 20-50% is made of mosaic cropland and the rest is made of grassland, shrubland, and forest. For purpose of identifying impacted agricultural extent, in this research we have retained solely the agricultural land identified as rainfed/irrigated/post-flooding cropland (the first indicator above). As a result, our calculations are likely to underestimate the impacts on agricultural extent.

8) GLWD-3

A global gridded dataset of wetland areas of approximately 1 km resolution, developed by the World Wildlife Fund in partnership with Center for Environmental Systems Research, University of Kassel, Germany. In the dataset wetlands are differentiated by type, but for the purposes of this analysis all wetlands are considered equal. Data are available for download at: http://www.worldwildlife.org/science/data/item1877.html.

9) GRUMP urban area

A global gridded dataset of urban extents compiled by the CIESIN GRUMP project from built-up areas polygons (DCW) and the NOAA-NGDC Nighttime Lights dataset derived from satellite imagery. Nighttime Lights is a dataset of visible light detected by the DMSP-OLS system. It is known to somewhat exaggerate the extent of lit areas due to spatial resolution and other characteristics of the sensor. A revised version of the GRUMP alpha urban extents dataset was provided by ftp upon request, but is not currently publicly available.

10) City Polygons from Urban Risk Index

A subset of urban extent polygons from the GRUMP urban extents layer was linked to the urban population growth dataset compiled by Henderson 2002. Decision rules describing point-to-polygon linking are described in detail in the dataset documentation. In general, a polygon was assigned to a city based on the city affiliation of the center of the polygon. In cases of merging urban extents, thiessen polygons were created to divide urban extents from one another.

A summary of the various datasets used in this analysis is presented in Table 1.

Table 1. Summary of data sources

Dimension	Dataset Name	Unit	Resolution	Source(s)
Coastline	SRTM v2 Surface Water Body Data			NASA
Elevation	Hydrosheds conditioned SRTM 90m DEM	Km^2	90m	http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php.
Watersheds	Hydrosheds Drainage Basins	Km^2		http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php.
Coastline Attributes	DIVA GIS database			http://diva.demis.nl/files/
Population	GRUMP 2005 (pre-release) gridded population dataset	Population counts	1km	CIESIN
GDP	2005 GDP Surface	Million USD	1km	World Bank , 2008
Agricultural Land	Globcover 2.1	Km^2	300m	http://www.esa.int/due/ionia/globcover
Urban areas	Grump, revised	Km^2	1km	CIESIN
Wetlands	GLWD-3	Km^2	1km	http://www.worldwildlife.org/science/data/item1877.html
Cities	City Polygons with Population Time Series			Urban Risk Index*

*Urban extents from GRUMP (alpha) (http://sedac.ciesin.org/gpw/) joined with World Cities Data (J. Vernon Henderson 2002).
http://www.econ.brown.edu/faculty/henderson/worldcities.html

III. Results

This section first presents global results across regions. Then it examines country results for each of the following five regions: Sub-Saharan Africa, East Asia, Latin America & Caribbean, Middle East & North Africa, and South Asia, and presents a summary of results by most impacted countries for each indicator used in this paper.

III.1 Global results

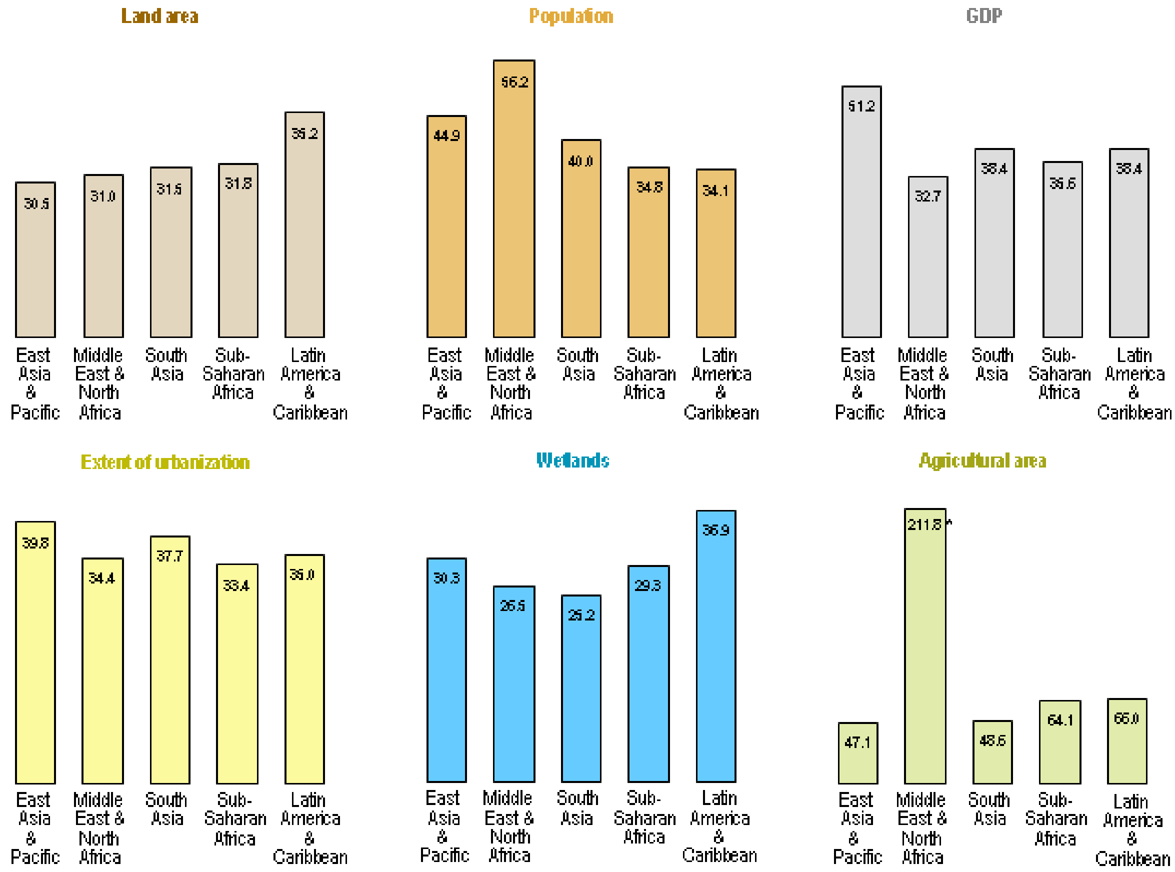
As shown in Table 2, the impacts of SLR and the intensification of storm surges will significantly increase over time compared to existing 1-in-100-year storm surges. At present, approximately 19.5% (391,812 km^2) of the combined coastal territory of 84 countries considered in this analysis is vulnerable to inundation from a 1-in-a-100-year storm surge. A 10% future intensification of storm surges will increase the potential inundation zone to 25.7% (517,255 km^2) of coastal territory, taking into account sea-level rise. This translates to a potential inundation for an additional population of 52 million; 29,164 km^2 of agricultural area; 14,991 km^2 of urban area; 9% of coastal GDP and 29.9% of wetlands.

Table 2: **Impacts of intensification of storm surges across indicators at the global level**

	Current Storm Surge	With Intensification
Coastal Land Area (Total= 2,012,753 km^2)		
Exposed area	391,812	517,255
% of total coastal area	19.5	25.7
Coastal Population (Total= 707,891,627)		
Exposed population	122,066,082	174,073,563
% of total coastal population	17.2	24.6
Coastal GDP (Total =1,375,030 million USD)		
Exposed GDP (USD)	268,685	390,794
% of total coastal GDP	19.5	28.4
Coastal Urban area (Total=206,254 km^2)		
Exposed area	40,189	55,180
% of total coastal urban area	19.5	26.8
Coastal Agricultural area (Total = 505,265 km^2)		
Exposed area	59,336	88,500
% of total coastal agricultural area	11.7	17.5
Coastal Wetlands Area (Total = 663,930 km^2)		
Exposed area	152,767	198,508
% of total coastal wetlands area	23.0	29.9

These impacts are, however, far from uniformly distributed across the regions. Figure 1 presents the breakdown of the impacts for the five regions identified in the study, and presents the incremental impacts in the value of the various indicators relative to the impacts of existing storm surges. As Figure 1 shows, the Latin America & Caribbean region has the largest percentage increase in storm surge zone area (35.2%), but the coastal population impacts are largest for the Middle East & North Africa (56.2%), while coastal GDP impacts are most severe in East Asia (51.2%). Similar disparities characterize the impacts on urban areas, agricultural land, and wetlands.

Figure 1. Incremental impacts of storm surges
(as percentage of impacts of current storm surges)



[*] The large incremental impact of storm surges on "agricultural areas" in the Middle East and North Africa region arises mostly from anticipated impacts in Egypt (326%) and Algeria (143%).

Because GDP per capita is generally above average for coastal populations and cities, we estimate that storm surge intensification would cause additional GDP losses (above the current 1-in-100-year reference standard) of $84.9 billion in the East Asia & Pacific region, $12.7 billion in the Middle East & North Africa, $8.4 billion in South Asia, $14.4 billion in Latin America & the Caribbean and $1.8 billion in Sub-Saharan Africa.

The increase of impact on agricultural areas is significant for the Middle East & North Africa Region, mainly because Egyptian and Algerian cropland in surge zones would increase from the existing estimated 212 km^2 to approximately 900 km^2 with SLR and intensified storm surges.

III.2 Country specific results

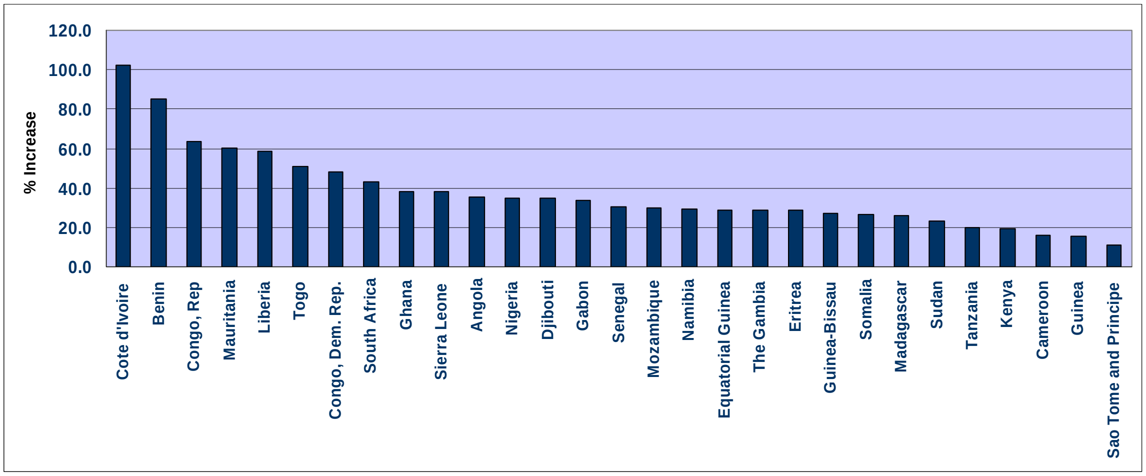
This subsection examines country specific results for each of the five regions. To facilitate the reading of these results, we follow a similar structure of presentation for all regions, recognizing that readers may examine results for specific regions of interest, as opposed to specific indicators across all regions. For comparative absolute values of storm surge impacts, see Appendix Figure A1-A5 starting on page 39.

(i) Sub-Saharan Africa region (AFR)

In Sub-Saharan Africa, surge zones are concentrated predominantly in four countries: Mozambique, Madagascar, Nigeria, and Mauritania, as documented in Table 3, Column 2. These four countries alone (out of 29 countries of the region with a coastline) account for 53% (9,600 km^2) of the total increase in the region's surge zones (18,300 km^2) resulting from SLR and intensified storm surges.

Although percentage increases in surge zones when compared to current surge zones, are largest for Côte d'Ivoire followed by Benin, Congo - Republic, Mauritania and Liberia, as presented in Figure 2, the coastal population impacted is mainly concentrated in Nigeria, Mozambique, Côte d'Ivoire and Benin (Table 3, Column 4). It should be noted, however that more than one-half of coastal population in Djibouti, Togo, Mozambique, Tanzania, and Sudan would be subject to inundation risks from intensification of storm surges and SLR (Table 3, Column 5).

Figure 2: Percentage increase in storm surge zone, AFR Region



Mozambique, Ghana and Togo may lose more than 50% of their coastal GDP, while GDP loss in absolute terms will be highest in Nigeria ($407.61 million) (Table 3, Columns 6 and 7). Coastal agriculture, in terms of extent of croplands, will be affected 100% in Nigeria and 66.67% in Ghana, 50% in Togo and Equatorial Guinea (Table 3, Column 9).

Numerous countries of the Sub-Saharan Africa region: Djibouti, Togo, Mozambique, Tanzania, Equatorial Guinea, Côte d'Ivoire, Namibia and Sudan will experience significant increases in the percentage of their coastal urban extent falling within surge zones with SLR and intensified storm surges (Table 3, Column 11).

As far as coastal wetlands are concerned, absolute impacts will be largest in Nigeria (1,365 km^2), Mozambique (1,318 km^2) and Madagascar (617 km^2). Although small in terms of area measured in square km, up to 82% of the coastal wetlands of Namibia, 62% of Guinea, 59% of Sudan, and 53% of Kenya would be susceptible to significant damages from SLR and intensified storm surges.

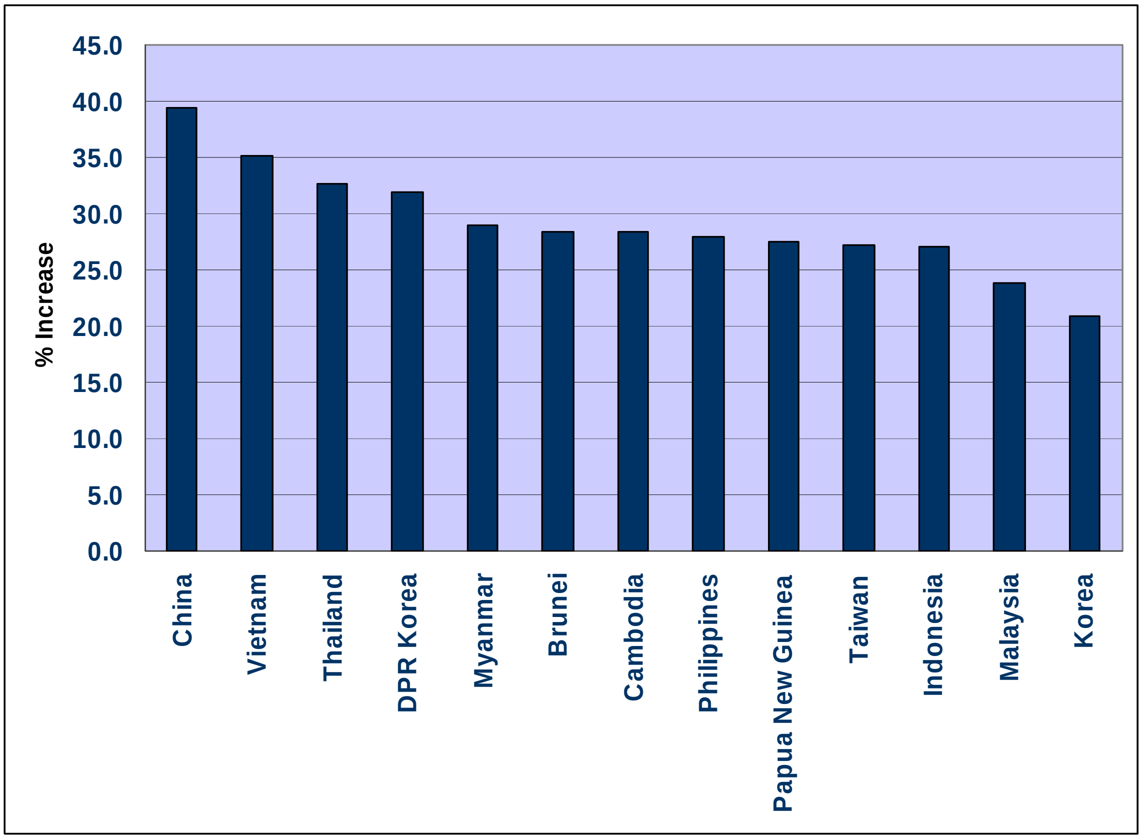
Table 3: Sub-Saharan Africa

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agr. Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
Mozambique	**3,268**	41.21	380,296	**51.73**	140.73	**55.02**	291	23.58	78	**55.06**	1,318	47.07
Madagascar	**2,312**	44.69	102,439	42.69	27.89	44.17	0		36	44.12	617	**51.32**
Nigeria	**2,264**	30.89	**870,276**	25.40	407.61	21.96	0	100.00	94	28.51	1,365	38.84
Mauritania	**1,754**	21.39	149,576	32.93	74.21	34.89	0	1.60	59	42.70	710	33.39
Senegal	677	16.50	190,690	20.68	111.66	21.15	29	2.01	27	16.09	395	22.04
Guinea-Bissau	670	35.71	61,314	32.94	10.01	32.51	0		12	34.06	278	40.01
Cote d'Ivoire	668	29.21	315,609	48.36	176.27	43.17	0		99	**53.16**	162	38.07
Gabon	630	25.64	34,500	28.43	120.95	24.08	0		30	30.38	253	27.33
South Africa	607	43.09	48,143	32.91	174.30	30.98	70	34.48	93	**48.10**	132	46.23
Somalia	555	28.21	33,756	31.04	8.90	25.86	15	16.46	1	25.00	94	24.81
Sierra Leone	549	28.88	39,080	34.62	5.69	38.34	0		1	37.25	451	33.50
Namibia	470	**60.20**	957	42.24	2.31	37.01	0		13	50.00	18	**81.55**
Angola	457	29.10	72,448	45.76	88.54	45.39	23	13.89	19	46.20	129	14.81
Eritrea	452	32.15	8,238	31.19	0.97	28.55	0	0.00	4	42.86	31	31.79
Tanzania	426	46.71	75,493	**49.90**	34.45	49.22	64	22.47	15	**53.37**	177	42.20
Guinea	420	**58.58**	58,967	43.68	37.99	40.21	0		8	33.33	193	**62.22**
Ghana	400	39.16	137,206	49.16	45.04	**51.07**	0	**66.67**	35	48.53	268	47.83
Sudan	370	**49.67**	18,762	49.49	10.77	48.04	0	0.00	7	**50.00**	107	**58.69**
Kenya	274	41.93	27,453	40.23	10.12	32.05	40	22.13	9	38.89	177	**52.51**
Liberia	269	26.62	88,535	44.63	16.77	41.11	0		15	42.96	44	46.32
Benin	260	19.50	221,029	38.99	107.35	46.75	0	0.00	44	44.24	164	21.26
Cameroon	172	39.57	57,214	34.76	44.53	32.32	0		14	40.36	111	42.97
Togo	95	34.18	147,274	**54.18**	48.20	**54.47**	1	**50.00**	28	**59.79**	52	26.62
Djibouti	82	37.98	28,559	**60.12**	22.87	49.34	0		5	**60.42**	7	19.31
Congo	65	15.29	10,361	22.14	13.14	21.92	0		3	21.15	20	10.68
Dem. Rep. of Congo	51	17.33	1,812	7.63	0.17	11.93	0		9	31.85	21	23.29
The Gambia	39	4.40	47,233	39.95	18.54	46.89	0	0.00	8	23.86	21	4.21
Equatorial Guinea	22	17.28	892	38.45	6.32	41.46	0	**50.00**	1	**52.63**	4	8.49
Sπo Tome and Principe	2	44.44	1,053	24.01	0.30	20.37	0	33.33	1	30.00	0	

(ii) East Asia & Pacific region (EAP)

In the EAP region, the percentage increase in surge zones when compared to current surge zones, are largest for China (39.4%), followed by Vietnam (35.1%), Thailand (32.7%) and Democratic Republic of Korea (31.9%) as documented in Figure 3.

Figure 3: Percentage increase in storm surge zone, EAP Region



As expected, absolute impacts of SLR and intensified storm surges on land area and coastal population are largest in Indonesia (14,407 km^2 and 5.84 million), China (11,827 km^2 and 10.83 million) and Vietnam (5,432 km^2 and 4.4 million). Surge prone areas as a percentage of country coastal totals, however, will be highest in Republic of Korea (61.73%) followed by Taiwan, China (49.95%); and exposed population as a percentage of coastal totals will exceed 50% in the Republic of Korea (Table 3, Columns 2, 3, 4 and 5).

A similar disparity between absolute and relative impacts emerges with respect to impacted coastal GDP, agricultural croplands, urban extent, and wetlands. While a potential loss of GDP for China is \$31.2 billion, Taiwan, China \$13.8 billion, Republic of Korea \$10.7 billion, Thailand \$10.2 billion; Philippines and Myanmar are likely to lose 52.29% and 48.89% of their coastal GDP respectively (Table 3, Columns 6 and 7). Areas of croplands along the coast exposed to intensified storm surges are heavily concentrated in China (6,642 km^2), Indonesia (4,114 km^2), Vietnam (3,612 km^2) and Myanmar (2,512 km^2 ; storm-prone cropland as a percentage of coastal cropland, on the other hand is large in Republic of Korea (67%) and the Democratic Republic of Korea (58%) (Table 3, Columns 8 and 9). Urban extent of 2,901 km^2 in China and 1,285 km^2 in Indonesia will be vulnerable to storm surges but these areas account for relatively small percentages of their respective coastal urban extent. Approximately, 95% of coastal wetlands in Taiwan, China, 79% of Republic of Korea, 59% of Democratic Republic of Korea and 50% of Myanmar will be susceptible although areas measured in square km are small in number (Table 3, Columns 12 and 13).

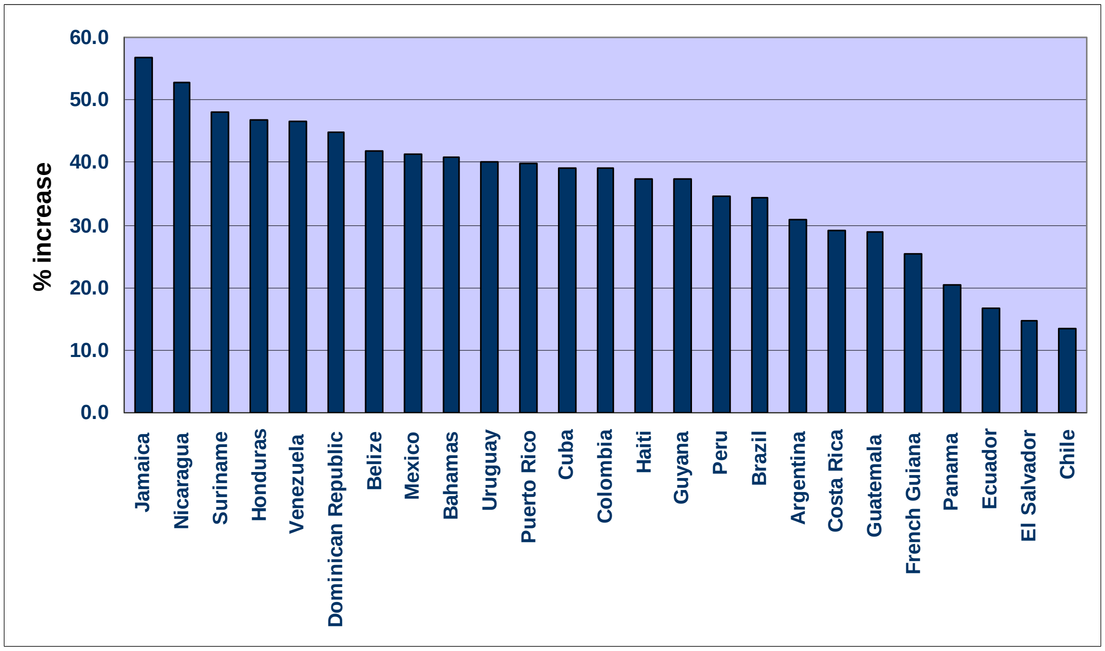
Table 4: East Asia & Pacific

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agr. Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
Indonesia	**14,407**	26.64	**5,835,462**	32.75	7993.67	38.71	4,114	26.12	1,285	33.25	2,686	26.97
China	**11,827**	17.52	**10,830,658**	16.67	31243.13	17.15	6,642	11.66	2,901	15.70	4,360	39.77
Vietnam	5,432	28.41	**4,371,059**	27.27	3653.64	31.66	3,612	23.79	466	35.84	3,528	29.43
Myanmar	4,641	33.45	1,106,570	40.85	361.86	48.89	2,512	22.88	158	39.93	3,001	**50.23**
Philippines	2,913	40.93	2,393,411	46.59	4264.22	**52.29**	851	30.71	363	42.93	255	44.98
Malaysia	2,238	29.09	522,430	33.54	2430.28	32.67	677	29.74	386	34.35	850	34.91
Thailand	1,956	19.21	1,564,403	24.82	10204.60	31.55	827	11.64	766	24.59	720	14.65
Papua New Guinea	1,623	19.46	18,340	21.72	14.47	22.32	245	20.82	14	26.67	907	15.87
Rep. of Korea	902	**61.73**	863,427	**50.48**	10669.87	47.86	237	**66.75**	335	48.15	77	**78.81**
Dem. People's Rep. of Korea	694	42.90	370,209	28.87	177.78	27.59	27	**58.28**	42	20.96	258	**58.98**
Taiwan, China	446	**49.95**	780,109	45.43	13755.95	44.17	274	39.78	374	44.06	2	**95.24**
Cambodia	248	3.26	41,691	2.44	18.85	2.69	79	1.04	19	13.17	44	1.50
Brunei	64	39.48	10,304	42.18	127.32	39.87	13	38.06	33	45.36	15	38.35

(iii) Latin America & Caribbean region (LAC)

In the LAC region, the percentage increase in surge zones when compared to current surge zones, are largest for Jamaica (56.8%), followed by Nicaragua (52.7%) as documented in Figure 4.

Figure 4: Percentage increase in storm surge zone, LAC Region



Absolute impacts of SLR and intensified storm surges on land area and coastal population, however, appear particularly severe in Mexico and Brazil (Table 5, Column 2 and column 4). The large figures for Mexico and Brazil result mostly from their relatively large coastal zones as compared to other countries in the region.[11] Relative exposure of coastal population, on the other hand, will be high for the Bahamas (73.02%), Dominican Republic (56.15%), Puerto Rico (53.81%) and El Salvador (53 %) (Table 5, Column 5), with potential loss of coastal GDP also projected to be most severe for the same countries; in all cases estimated losses exceed 50% (Table 5: Column 7).

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[11] Brazil and Mexico's coastal zones reach 163,199 and 107,441 km^2, respectively. The third largest coastal zone in the region belongs to Argentina with 56,488 km^2.

Coastal agriculture, in terms of extent of croplands, will be affected 100% in Guyana and 66.67% in El Salvador (Table 5: Column 9). Urban extent along the coast will be highly vulnerable to inundation from storm surges in Bahamas (94.12%), Suriname (66.41%), Puerto Rico (51.23%) and El Salvador (49.64%) (Table 5, Column 11).

Finally, inundation risk from storm surges will cover 100% of coastal wetlands in Dominican Republic and El Salvador followed by 71.4% in Bahamas, 67.34% in Belize, 54.26% in Ecuador and 52.25% in Mexico (Table 5, Column 13).

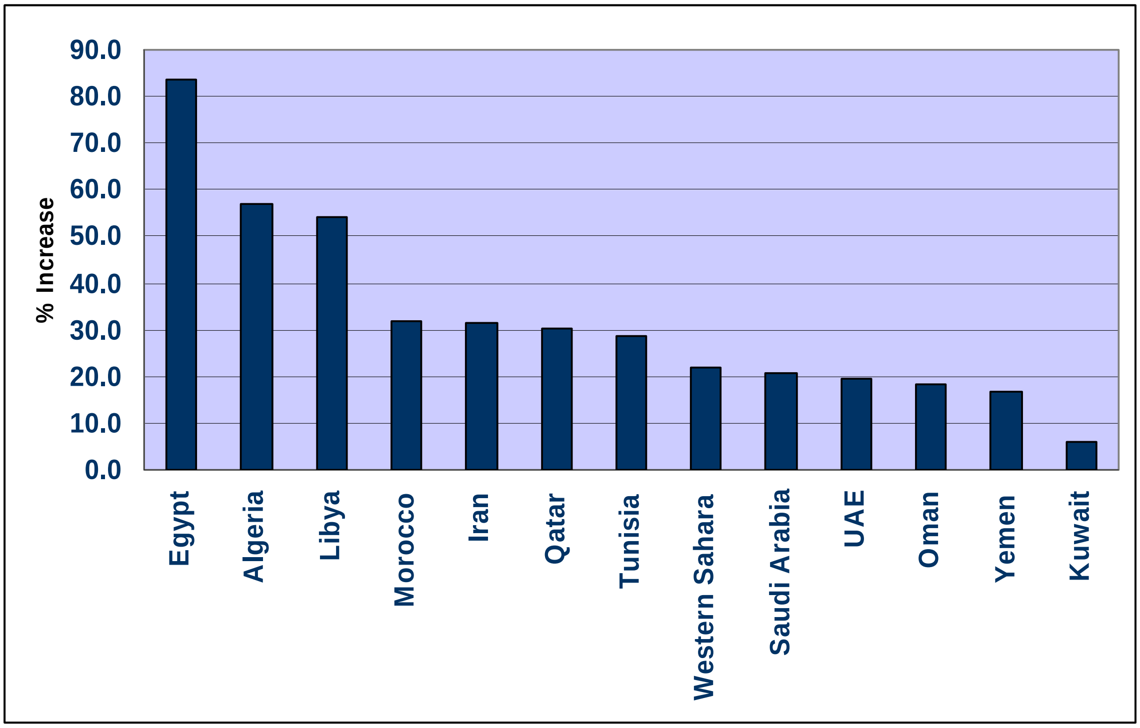
Table 5: Latin America & Caribbean

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agr. Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
Mexico	**9,136**	29.04	**463,833**	20.56	2571.55	21.22	310	10.89	701	18.35	1,765	**52.25**
Brazil	**6,281**	15.08	**1,151,493**	30.37	4889.48	28.48	275	16.47	960	33.67	2,597	11.48
Cuba	2,876	37.22	131,272	34.89	463.78	34.47	8	25.97	81	29.55	1,301	49.46
Argentina	2,407	18.03	278,155	19.52	2242.71	16.42	157	9.93	313	27.47	459	11.30
R.B. de Venezuela	2,142	14.19	119,215	33.83	619.73	33.92	28	9.30	202	29.90	763	19.99
Bahamas, The	1,517	**54.67**	3,711	**73.02**	48.92	**65.69**	24	47.39	1	**94.12**	553	**71.40**
Colombia	1,473	17.88	124,875	19.07	263.18	18.14	16	5.62	199	17.68	483	23.21
Chile	1,180	**54.67**	31,309	38.49	152.64	37.50	16	27.60	46	38.44	20	18.71
Honduras	1,055	36.07	25,592	31.03	20.84	28.56	8	22.33	8	25.97	701	39.19
Nicaragua	1,048	15.11	12,912	32.12	10.26	31.84	4	9.88	7	46.46	353	36.86
Peru	727	36.69	61,009	46.90	177.12	46.18	5	26.92	54	42.72	20	37.91
Guyana	640	20.35	29,491	37.49	43.22	46.38	0	**100.00**	93	**66.41**	234	13.75
Suriname	637	15.43	51,427	36.63	136.49	37.44	0		53	23.70	343	12.52
Panama	501	40.71	39,998	45.17	184.87	43.26	12	20.79	54	44.33	78	**54.26**
Ecuador	476	28.73	36,905	16.69	54.68	15.42	12	13.53	31	15.03	93	**67.34**
Belize	419	26.93	22,274	**56.15**	113.29	**61.14**	1	5.56	50	52.61	1	100.00
Dominican Republic	349	28.19	71,861	17.98	189.59	16.94	23	19.71	42	25.87	9	41.24
Costa Rica	343	35.85	12,939	28.95	48.29	28.16	15	33.06	15	34.39	164	41.16
Uruguay	273	10.03	17,572	27.56	118.88	27.83	12	10.03	29	22.45	0	0.00
Guatemala	213	20.97	16,365	29.51	22.26	28.08	1	26.67	9	39.68	24	29.17
Haiti	190	38.49	89,906	40.40	35.38	38.78	10	26.27	14	48.63	73	40.55
Puerto Rico (US)	173	**51.84**	104,692	**53.81**	1783.45	**52.71**	3	36.00	151	**51.23**	0	
Jamaica	137	37.54	31,029	28.49	100.95	26.62	2	26.32	56	32.60	37	36.55
French Guiana (Fr.)	130	20.98	2,491	27.93	28.55	28.02	0	0.00	6	27.22	85	20.67
El Salvador	102	**55.32**	17,654	**53.00**	28.32	**49.77**	0	**66.67**	10	**49.64**	0	**100.00**

(iv) Middle East & North Africa region (MENA)

In the MENA region, the percentage increase in surge zones when compared to current surge zones is largest for Egypt (83.6%), followed by Algeria (56.9%) and Libya (54.3%) as documented in Figure 5. The surge zones of Egypt would almost double as a result of SLR and intensified storm surges, increasing from 7.4% of the coastal area at present to 13.6%.

Figure 5: Percentage increase in storm surge zone, MENA Region



While Egypt, Iran, Saudi Arabia, and Libya would experience large increases in the extent of their respective surge zones, ranging from 1,183 km^2 – 2,290 km^2, the surge prone area as a percentage of country coastal zone total will be highest in Kuwait (81.07%), followed by Yemen (50.20%) and Oman (50.06%) (Table 6, Columns 2 and 3).

Absolute impact of SLR and intensified storm surges on coastal population will be particularly severe in Egypt with potential inundation risk for additional 2.67 million people (Table 6, Column 4). Relative exposure of coastal population, on the other hand, will be high in Kuwait (69.86%), United Arab Emirates (59.89%), and Yemen (55.65%).

Estimates further indicate that increase in inundation exposure from storm surges translates to a potential loss of 65.27% coastal GDP in Kuwait, 58.08% in United Arab Emirates, 52.58% in Morocco and 51.98% in Yemen. Nearly all coastal cropland of United Arab Emirates and 85.71% in Qatar will be prone to inundation (Table 6, Column 9); and urban extent along the coast will be highly vulnerable in United Arab Emirates (60.21%), Kuwait (56.42%), and Yemen (55.35%) (Table 6, Column 11).

Coastal wetlands of the MENA region will also be affected by storm surges. In terms of percentage of coastal total, impacts will be particularly severe in Kuwait (95.75%), Qatar (74.97%), Tunisia (63.50%), Yemen (62.22%), and Saudi Arabia (51.04%).

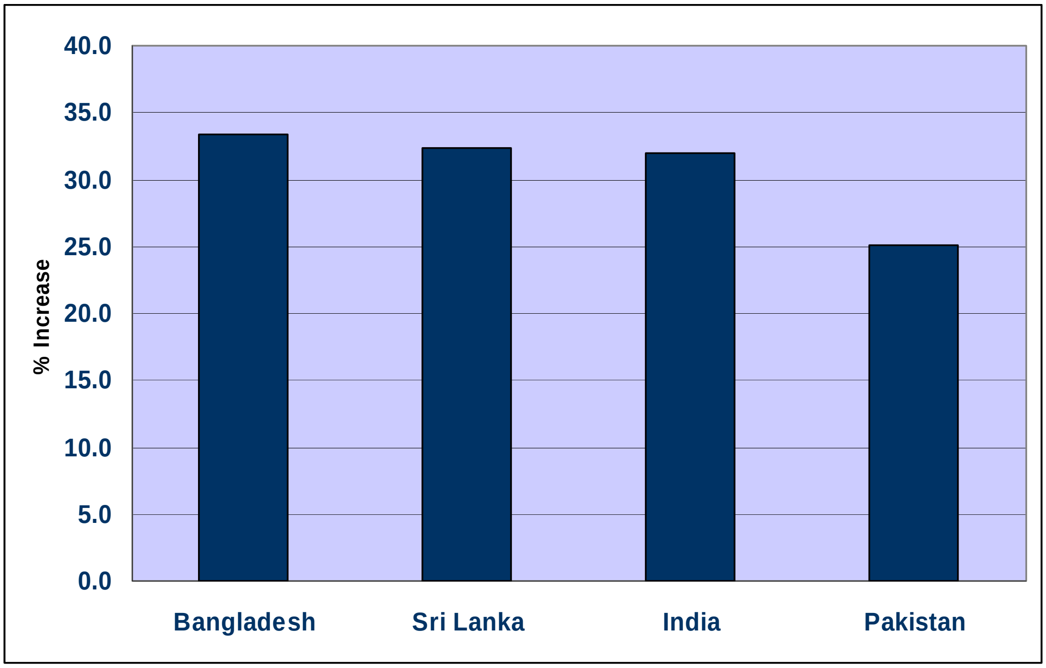
Table 6: Middle East & North Africa

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agr. Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
Arab Rep. of Egypt	**2,290**	13.61	**2,673,036**	14.68	4604.69	16.67	692	5.23	627	15.30	640	28.36
Islamic Republic of Iran	**2,189**	27.75	56,336	19.28	218.25	18.33	11	8.59	58	13.81	1,038	48.94
Saudi Arabia	1,368	41.58	**243,839**	42.92	2425.25	40.60	0	0.00	390	45.85	715	**51.04**
Libya	1,183	23.49	75,504	31.12	545.22	30.42	1	23.81	230	32.75	539	26.58
Tunisia	543	45.45	**189,241**	51.12	510.44	47.61	41	32.53	179	48.25	199	**63.50**
United Arab Emirates	532	47.37	88,327	**59.89**	2310.72	**58.08**	0	**100.00**	181	**60.21**	305	44.51
Oman	417	**50.06**	32,971	46.40	316.70	44.27	1	40.00	85	47.72	74	59.24
Rep. of Yemen	321	**50.20**	37,445	**55.65**	21.69	**51.98**	0	0.00	19	**55.35**	115	**62.22**
Qatar	294	43.06	26,842	41.29	749.40	31.43	2	**85.71**	25	29.18	138	**74.97**
Morocco	293	28.65	**130,094**	49.05	210.58	**52.58**	15	15.85	67	**51.16**	84	24.55
Algeria	181	28.79	69,553	31.49	155.06	28.91	10	14.91	53	28.31	78	19.88
Western Sahara	148	30.47	2,827	10.90	2.23	6.31	0		2	8.33	40	43.80
Kuwait	91	**81.07**	47,925	**69.86**	586.23	**65.27**	0		41	**56.42**	26	**95.75**

(v) South Asia region (SAR)

The percentage increase in storm surge zone among the countries of the South Asia region is less than the other regions. Approximately 23% to 33% of the countries' coastal zones will be subjected to inundation risk with SLR and intensified storm surges, and Bangladesh will be worst affected (33.4%).

Figure 6: Percentage increase in storm surge zone, SAR Region



As expected, in absolute numbers, exposure estimates of all indicators—coastal population, GDP[12], agricultural area, urban extent and wetlands—are larger for India and Bangladesh (Table 7). However, the relative impacts: percentage of coastal population and GDP exposed will be most severe in Pakistan (35.72% and 38.57%, respectively), and the percentage of vulnerable coastal croplands and urban extent will be most acute in Sri Lanka (43.03% and 37.42%, respectively) (Table 7, Columns 5, 7, 9 and 11).

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[12] It is estimated that storm surge intensification would cause additional GDP losses (above the current 1-in-100-year reference standard) of $5.2 billion in India and $2.2 billion in Bangladesh.

Our estimates further indicate nearly 61.38% of coastal wetlands of Pakistan and 55.46% of wetlands in Sri Lanka will be prone to storm surges (Table 7, Column 13).

Table 7: South Asia

Country	Incremental Impact: Land Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Population	Projected Impact as a % of Coastal Total	Incremental Impact: GDP (mil. USD)	Projected Impact as a % of Coastal Total	Incremental Impact: Agr. Area (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Urban Extent (sq. km)	Projected Impact as a % of Coastal Total	Incremental Impact: Wetlands (sq. km)	Projected Impact as a % of Coastal Total
India	**8,693**	29.33	**7,640,416**	28.68	5175.16	27.72	3,744	23.64	1,295	30.04	2,511	32.31
Bangladesh	**4,457**	23.45	**4,849,374**	16.01	2225.85	19.00	2,716	17.52	433	18.30	3,898	24.29
Pakistan	1,597	26.37	613,701	35.72	483.58	38.57	90	2.72	37	16.13	977	**61.38**
Sri Lanka	750	37.58	344,832	29.08	537.83	26.37	256	43.03	174	37.42	186	**55.46**

III.3 Summary of results

This section summarizes the results of world and regional results. It then summarizes results for each of the six indicators used in this analysis by presenting the most (top 10) impacted countries (as a percentage of national parameters).

Table 8 summarizes our results for each indicator by presenting the top-10 impacted countries and/or territories (as a percentage of their own coastal values). Results suggest that numerous low-income countries are susceptible to significant coastal damage. For land area, the most vulnerable low-income countries are Namibia, Guinea, El Salvador and Yemen, with more than 50% of their coastal areas at risk.

For impacted population, the top five low-income countries and/or territories worldwide are Djibouti, Yemen, Togo, El Salvador, and Mozambique. More than 50% of the coastal urban areas lie within the potential impact zones in Guyana, Djibouti, Togo, Yemen, Mozambique, Tanzania, Côte d’Ivoire, Equatorial Guinea, and Morocco.

Coastal agriculture would be significantly affected in Guyana, Nigeria, North Korea, El Salvador, Ghana, Togo and Equatorial Guinea. Our estimates indicate that areas prone to storm surge in Mozambique, Togo, Morocco, Philippines, Yemen, Djibouti, El Salvador and Ghana account for more than 50% of GDP generated in their coastal regions. Finally, nearly 100% of the coastal wetlands in El Salvador and more than 60% of the wetlands of Namibia, Ecuador, Tunisia, Guinea, Yemen and Pakistan will be subject to inundation risk. In sum, for the majority of indicators used in this research, El Salvador, Yemen, Djibouti, Mozambique, and Togo are projected to experience the most severe impacts.

Table 8. Top 10 countries at risk with intensification of storm surges*

Rank	Coastal Land Area	Coastal Population	Coastal GDP	Coastal Agricultural Land	Coastal Urban Areas	Coastal Wetlands
1	Kuwait (81.1)	Bahamas (73.0)	Bahamas (65.7)	Guyana (100.0)	Bahamas (94.1)	El Salvador (100.0)
2	Korea (61.7)	Kuwait (70.0)	Kuwait (65.3)	UAE (100.0)	Guyana (66.4)	Belize (100.0)
3	Namibia (60.2)	Djibouti (60.1)	Belize (61.1)	Nigeria (100.0)	Djibouti (60.4)	Kuwait (95.8)
4	Guinea (58.6)	UAE (60.0)	UAE (58.1)	Qatar (85.7)	UAE (60.2)	Taiwan, China (95.2)
5	El Salvador (55.3)	Belize (56.2)	Mozambique (55.0)	Korea (66.8)	Togo (59.8)	Namibia (81.6)
6	Chile (54.7)	Yemen (55.7)	Togo (54.5)	El Salvador (66.7)	Kuwait (56.4)	Korea (78.8)
7	Bahamas (54.7)	Togo (54.2)	Puerto Rico (52.7)	Ghana (66.7)	Yemen (55.4)	Qatar (75.0)
8	Puerto Rico (51.8)	Puerto Rico (53.8)	Morocco (52.6)	DPR Korea (58.3)	Mozambique (55.1)	Bahamas (71.4)
9	Yemen (50.2)	El Salvador (53.0)	Philippines (52.3)	Togo (50.0)	Tanzania (53.4)	Ecuador (67.3)
10	Oman (50.0)	Mozambique (51.7)	Yemen (52.0)	Equatorial Guinea (50.0)	Cote d'Ivoire (53.2)	Tunisia (63.5)

* Numbers in parentheses indicate percentage impact in “coastal zone”.

Finally, we examine the impact of SLR and intensified storm surges on specific urban centers of the developing world. Table 4 lists the top-10 major cities worldwide that are located in storm-surge zones. Alarmingly, most of these cities are in low-income countries. This highlights the potentially deadly exposure of their inhabitants, since storm water drainage infrastructure is often outdated and inadequate in such low-income urban centers.[13] The risks may be particularly severe in poor neighborhoods and slums, where infrastructure is often nonexistent or poorly designed and ill-maintained. Eight out of the 10 most impacted cities in the East Asia and Pacific region are located in Vietnam and the Philippines. In the South Asia region, three of five most impacted cities are located in Bangladesh. In the Sub-Saharan Africa and in the Middle East and North Africa regions, four cities out of the 10 most impacted cities of the region are in Mozambique and Morocco, respectively.

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[13] For port cities vulnerable to storm surge, see Nicholls et al. (2007).

Table 4. Major cities at risk from intensification of storm surges
Indicator: Percent of coastal area exposed*

Rank	EAP	SAR	AFR	LAC	MENA
1	Hai Phong (Vietnam)	Barisal (Bangladesh)	Bugama (Nigeria)	Ciudad del Carmen (Mexico)	Port Said (Egypt)
2	San Jose (Philippines)	Mumbai (India)	Okrika (Nigeria)	Manzanillo (Cuba)	Dubai (UAE)
3	Vung Tau (Vietnam)	Cox's Bazar (Bangladesh)	George (South Africa)	Georgetown (Guyana)	Rabat (Morocco)
4	Manila (Philippines)	Khulna (Bangladesh)	Quelimane (Mozambique)	Bahia Blanca (Argentina)	Kenitra (Morocco)
5	Roxas (Philippines)	Bhaunagar (India)	Mahajanga (Mozambique)	Cienfuegos (Cuba)	Aden (Yemen)
6	Cotabato (Philippines)	Karachi (Pakistan)	Nacala (Mozambique)	Vina del Mar incl. Concon (Chile)	Abu Dhabi (UAE)
7	Ansan (Korea)	Jamnagar (India)	Bathurst (Gambia)	Aracaju ♦ (Brazil)	Al Ain (UAE)
8	Poryong (Korea)	Surat (India)	Beira (Mozambique)	Puerto la Cruz incl. Pozuelos (Venezuela)	Ajman (UAE)
9	Rach Gia (Vietnam)	Thane (India)	Tanga (Tanzania)	La Plata (Argentina)	Mohammedia (Morocco)
10	Hue (Vietnam)	Vadodara (India)	Free Town (Sierra Leone)	Acapulco de Juarez (Mexico)	Nador (Morocco)

***** In the Urban Risk Index database allocation of urban extent to adjacent city limits may sometimes have a margin of error due to potential inaccuracies associated with the thiessen polygon technique. ♦Aracaju in Brazil has been identified as one such example of allocation error.

IV. Conclusions

Coastal areas of the world face a range of risks related to climate change (IPCC 2007). Anticipated risks include an accelerated rise in sea level, an intensification of cyclones, and larger storm surges among others. This paper assesses the vulnerability of the world's coastal zones to intensification of storm surges. A detailed GIS analysis is used to estimate the impact of future storm surge increases associated with more intense storms and a 1 m sea-level rise. After delineating future inundation zones, this information is overlaid with indicators for coastal populations, settlements, economic activity, and wetlands. Our results indicate very heavy potential losses that are much more concentrated in some regions and countries than others. A particularly striking finding is the concentration of highly vulnerable large cities at the low end of the international income distribution. We believe that these large, globally pervasive potential impacts further strengthen the case for rapid action to protect endangered coastal populations.

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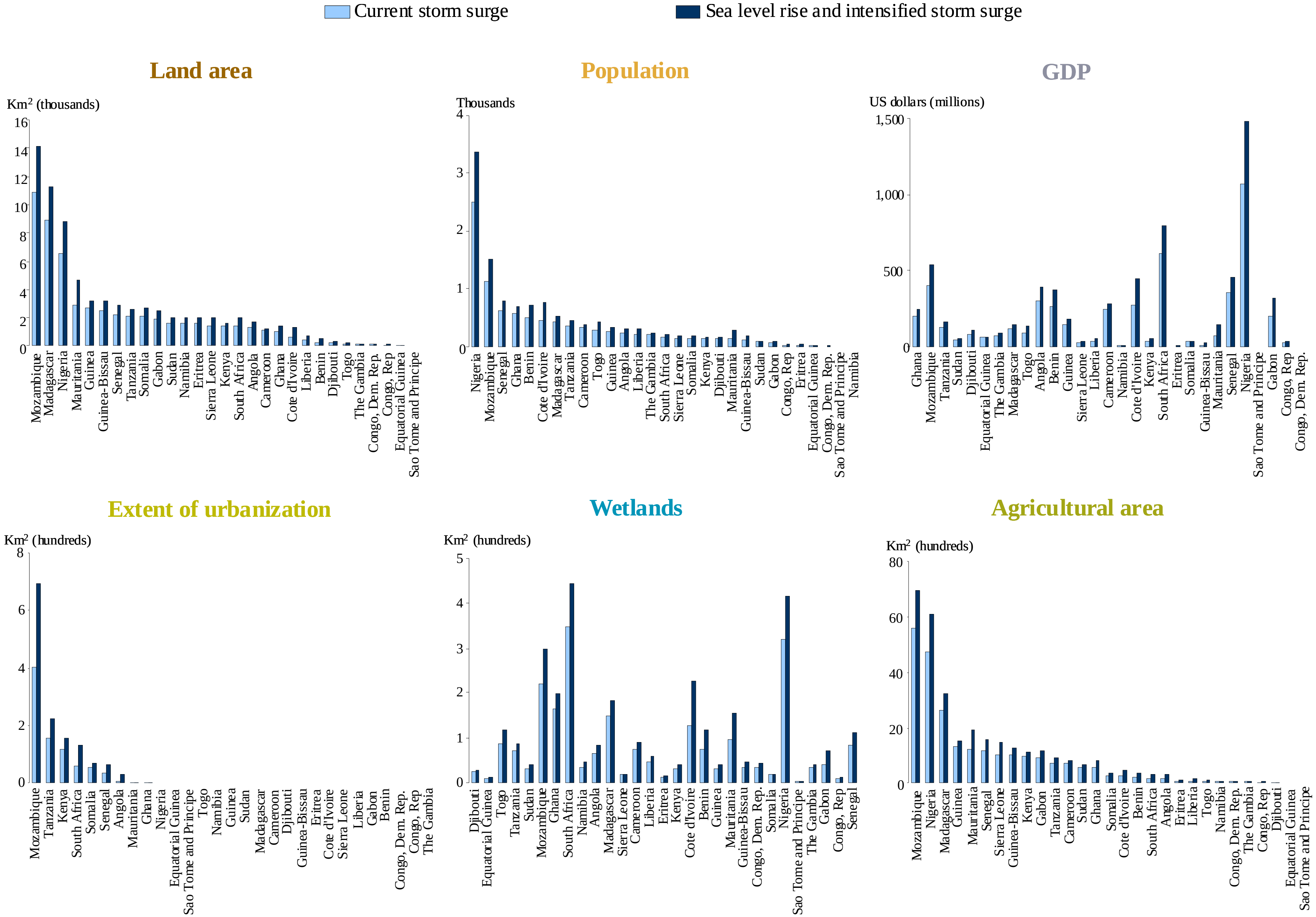
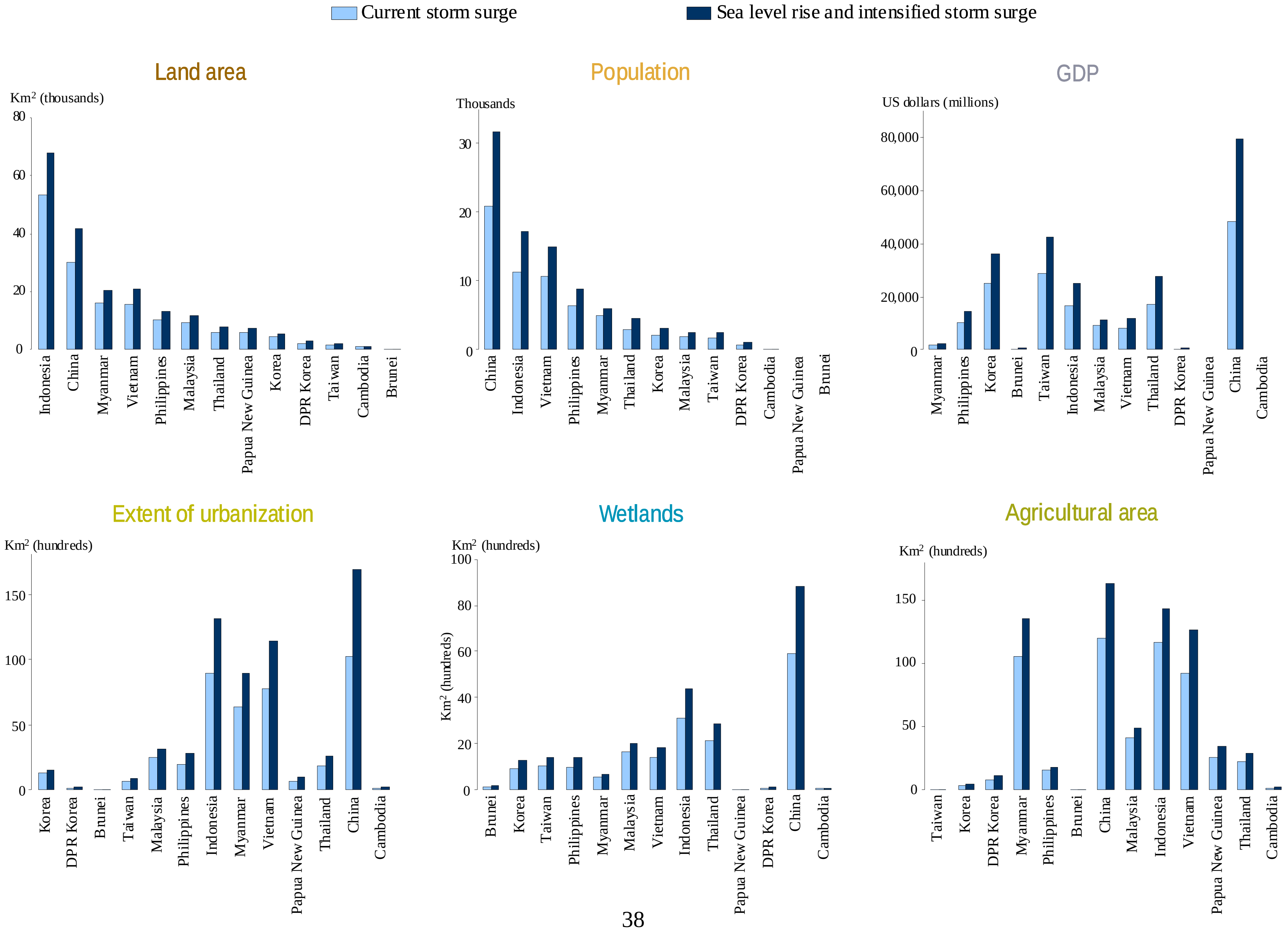
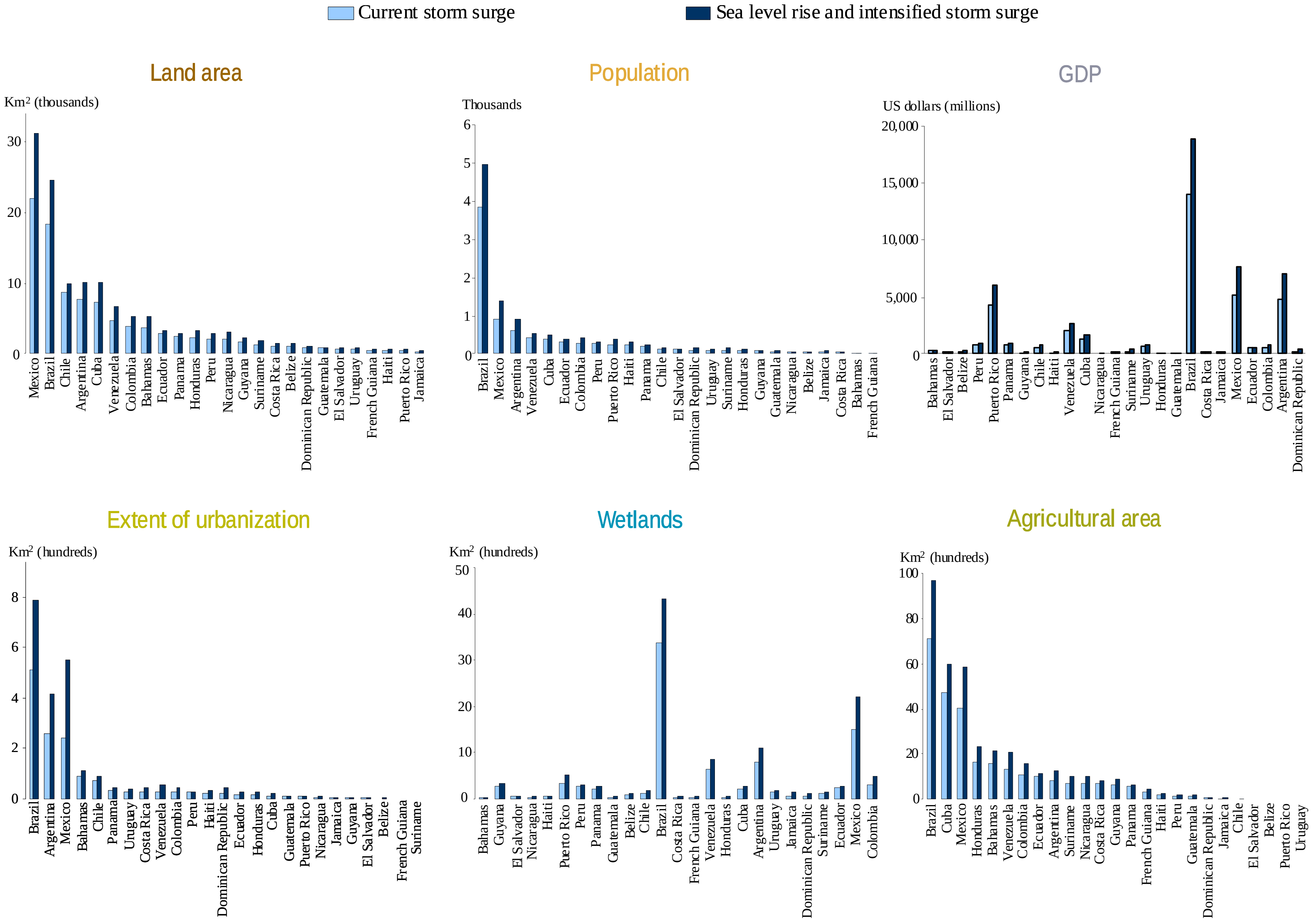
Appendix Figure A1. Current and projected impacts of sea level rise and storm surge in Africa



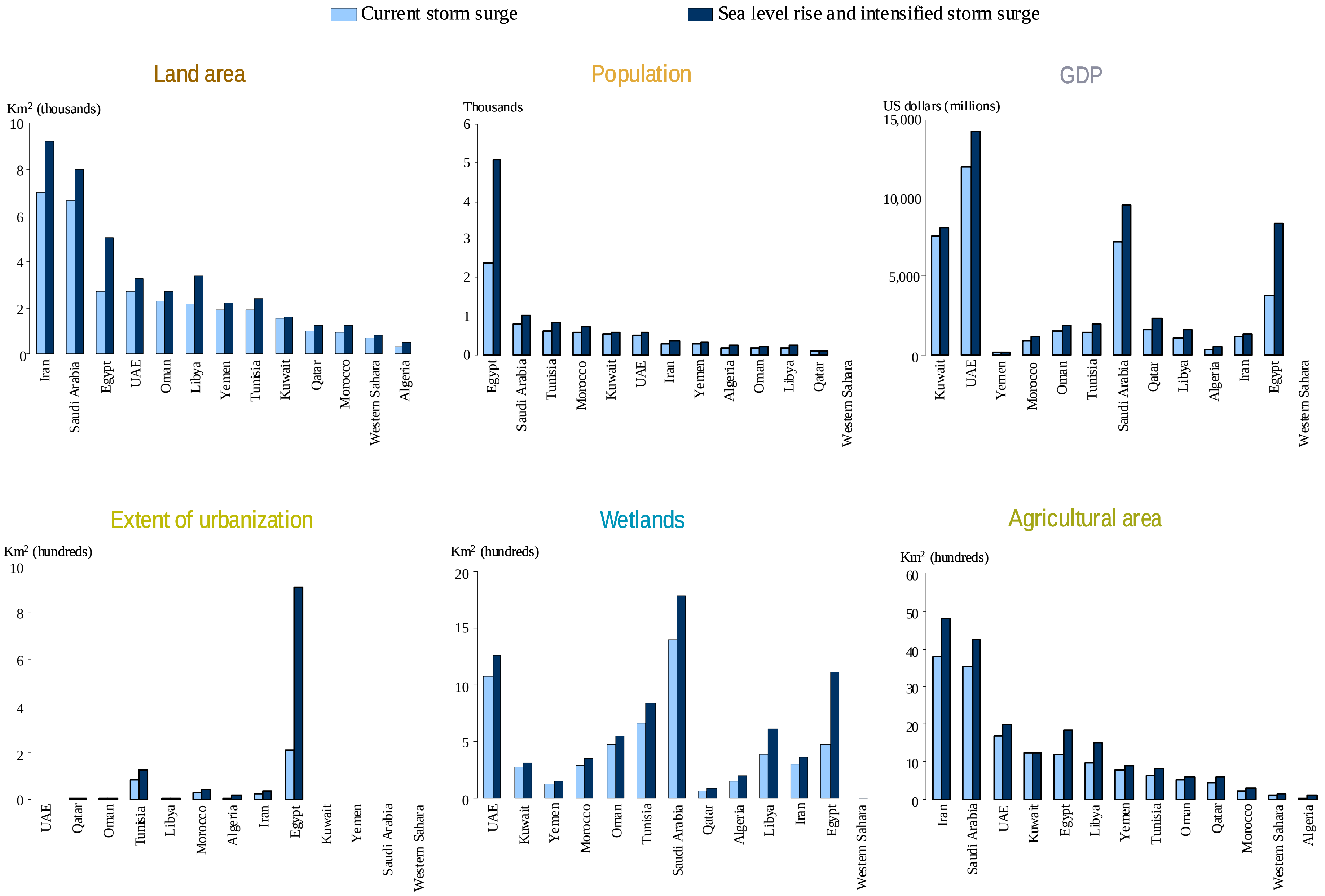
Appendix Figure A2. Current and projected impacts of sea level rise and storm surge in East Asia & Pacific



Appendix Figure A3. Current and projected impacts of sea level rise and storm surge in Latin America & the Caribbean



Appendix Figure A4. Current and projected impacts of sea level rise and storm surge in Middle East & North Africa



Appendix Figure A5. Current and projected impacts of sea level rise and storm surge in South Asia