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Exposure of developing countries to sea-level rise and storm surges

Susmita Dasgupta · Benoit Laplante ·
Siobhan Murray · David Wheeler

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Abstract An increase in sea surface temperature is strongly evident at all latitudes and in all oceans. The scientific evidence to date suggests that increased sea surface temperature will intensify cyclone activity and heighten storm surges. The paper assesses the exposure of (coastal) developing countries to sea-level rise and the intensification of storm surges. Geographic Information System (GIS) software is used to overlay the best available, spatially-disaggregated global data on critical exposed elements (land, population, GDP, agricultural extent and wetlands) with the inundation zones projected with heightened storm surges and a 1 m sea-level rise. Country-level results indicate a significant increase in exposure of developing countries to these climate-induced changes.

1 Introduction

An increase in sea surface temperature is strongly evident at all latitudes and in all oceans. The scientific evidence suggests that increased surface temperature will intensify cyclone activity and heighten storm surges.[1] These surges[2] may, in turn,

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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 et al. 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).

S. Dasgupta (✉) · S. Murray
Development Research Group, World Bank, Washington, DC, 20433, USA
e-mail: SDasgupta@worldbank.org

B. Laplante
Montreal, Canada

D. Wheeler
Center for Global Development, 1776 Massachusetts Avenue NW,
Washington, DC, 20036, USA

create more damaging flood conditions in coastal zones and adjoining low-lying areas. 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). Tropical cyclone Sidr[3] in Bangladesh (November 2007) and cyclone Nargis[4] in the Irrawady delta of Myanmar (May 2008) provide recent examples of devastating storm-surge impacts in developing countries.

Some recent scientific studies suggest that observed 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 et al. 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 Cyclone (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 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."

IPCC (2007) reports 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; Woodworth and Blackman 2004; Woth et al. 2006; Emanuel et al. 2008).[6]

These consensus projections from the global scientific community point to the need for greater disaster preparedness in countries that are vulnerable to storm surges. Fortunately, significant adaptation has already occurred, and many lives have been saved by improvements in disaster forecasting, evacuation and emergency shelter procedures (Shultz et al. 2005; Keim 2006). At the same time, as recent disasters in Bangladesh and Myanmar have demonstrated, storm-surge losses remain large in many areas. Such losses could be reduced by allocating more resources to increased disaster resilience especially given the expectations pertaining to the intensification of storms and storm surges.

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[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 Myanmar, 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).

[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 (Emanuel et al. 2008).

Research to date on the potential impacts of storm surges has been confined to a relatively limited set of impacts[7] and locations.[8] In this paper, we significantly broaden the assessment to 84 coastal developing countries, and 6 indicators of exposure.[9] We consider the potential exposure to a large (1-in-100-year) storm surge, and then compare it with intensification which is expected to occur in this century. In modeling exposure to storm surges, we take account of changes in sea level rise, geological uplift and delta subsidence (where relevant) along the world's coastlines. Our analysis includes indicators for exposed territory (land area), population, economic activity (GDP), urban extent, agricultural extent, and wetlands. As far as we know, this is the first such exercise for developing countries.

At the outset, we acknowledge the following limitations in this analysis. First, we do not assess the relative likelihoods of alternative storm surge scenarios. Following Nicholls et al. (2007), we assume a homogeneous future increase of 10% in extreme water levels identified as the 1-in-100 year storm surge experienced for any given coastal segment of each of the 84 countries. In all likelihood, 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 (with the support of hurricane generator models) is needed to better forecast changes in storm surges.[10] Second, among the 84 developing countries included in this analysis, we restrict our analysis to coastal segments where historical storm surges have been documented, and ignore the possibility that coastal segments which have never experienced storm surges may in the future do so as a result of global climate change.[11] Third, the absence of a global database on shoreline protection has prevented us from incorporating the effect of existing protection measures (e.g., sea dikes) on exposure estimates. Fourth, the lack of data on exposure indicators has prevented us from including small islands in our analysis. Fifth, we assess the exposure to storm surges using existing populations, socioeconomic conditions and patterns of land use, rather than attempting to predict their future states. As human activity is generally increasing more rapidly in coastal areas, our estimates are undoubtedly conservative on this score. On the other hand, we do not attempt to estimate the countervailing effects of local adaptation measures related to infrastructure (e.g., coastal embankments) and coastal-zone management (e.g., land-use planning, regulations, relocation).

The remainder of the paper is organized as follows. Section 2 summarizes our data sources, while Section 3 describes our methodology. Section 4 presents our results, and Section 5 provides a brief conclusion.

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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] Further in the paper, these countries are grouped in regions used by the World Bank: East Asia & Pacific, Middle East & North Africa, Latin America & Caribbean, South Asia, and Sub- Saharan Africa.

[10] As pointed out by Emanuel et al. (2008).

[11] It is of importance to note that the coast segments of all of these 84 countries have experienced a 1-in-100 year storm surge. However, while these storm surges all resulted from strong winds, some of these did not formally qualify as 'tropical storms'. 54 of the 84 countries have experienced storm surges *not* induced by tropical storms, while 30 did so.

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 90 m DEM	Km^2	90 m	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	1 km	CIESIN
GDP	2005 GDP surface	Million USD	1 km	World Bank 2008
Agricultural land	Globcover 2.1	Km^2	300 m	http://www.esa.int/due/ionia/globcover
Urban areas	Grump, revised	Km^2	1 km	CIESIN
Wetlands	GLWD-3	Km^2	1 km	http://www.worldwildlife.org/science/data/item1877.html
Cities	City polygons with population time series			Urban Risk Index[a], Brecht (2007)

[a] 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

2 Data sources

We have employed geographic information system (GIS) software to overlay the critical exposed elements (land, population, GDP, urban extent, agriculture extent and wetlands) with the inundation zones projected for a current 1-in-100-year storm surge and a 10% intensification of these surges. We have used the best available spatially-disaggregated data sets from various public sources, including the National Aeronautics and Space Administration (NASA), the US Geological survey (USGS), the European Space agency (ESA), Dynamic Interactive Vulnerability Assessment (DIVA), the World Wildlife Fund (WWF), the Center for International Earth Science Information Network (CIESIN), and the World Bank. Table 1 summarizes the data sources for assessing inundation zones and exposure.

3 Methodology

Our analysis involves a multi-step procedure. First, we use the SRTM database to identify inundation zones and subject them to alternative storm-surge (wave height) scenarios. In doing so, it should be noted that the SRTM database suffers from known limitation in urban as well as forested areas where the SRTM elevation data may capture the height of building or trees instead of ground level elevation.[12]

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[12] A similar limitation is noted by Nicholls et al. (2007).

Second, we construct a country surface for each exposure indicator (population, GDP, urban extent, agricultural extent,[13] and wetlands). Third, we overlay these indicator surfaces with the inundation zone layer. Then we determine the spatial exposure of each indicator under storm-surge conditions. More detailed descriptions of these steps are as follows.

1. For elevation, we downloaded all 5° × 5° coastal tiles of 90 m SRTM data from http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php.
2. In the calculation of storm surges (wave heights or extreme sea levels), we follow the method outlined by Nicholls et al. (2007) where storm surges are calculated as follows:

$$\begin{aligned} \text{Current storm surge} &= \text{S100} \\ \text{Future storm surge} &= \text{S100} + \text{SLR} + \left(\text{UPLIFT } \times \text{ 100 years}\right)/1000 \\ &\quad + \text{SUB} + \text{ S100} \times \text{x} \end{aligned}$$

where:

S100	1-in-100-year surge height (m)
SLR	sea-level rise (1 m)[14]
UPLIFT	continental uplift/subsidence in mm/year
SUB	0.5 m (applies to deltas only)
x	0.1, or increase of 10%, applied only in coastal areas currently prone to tropical cyclone or hurricane.[15]

We calculate surges using data associated with the coastlines.
We extract vector coastline masks from SRTM version 2, and download coastline information from the DIVA GIS database. We use the following attributes in this analysis:

1. S100: 1-in-100-year surge height, based on tidal levels, barometric pressures, wind speeds, seabed 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/year from Peltier (2000), including a measure of natural subsidence (2 mm/year) for deltas.

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[13] Note that the Globcover database for agriculture covers three different types of 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 exposed agricultural extent, in this paper we have retained solely the agricultural land identified as rainfed/irrigated/post-flooding cropland (the first of the three indicators discussed above). As a result, our calculations under-estimate the extent of the exposed agricultural extent.

[14] Nicholls et al. (2007) assumed a SLR of 0.5 m.

[15] As pointed out earlier in footnote 14, 30 countries out of 84 have experienced tropical cyclones induced storm surges. The 10% increase in storm surges is applied solely to these 30 countries.

3. We compare surge (wave height) associated with current and future storms with the elevation values of inland pixels with respect to a coastline, to delineate potential inundation areas.[16]

   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, we use hydrological drainage basins. We apply the wave height calculated for the coastline segment closest to the basin outlet to inland areas within that basin.

   As a wave moves inland its 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) uses 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 use an intermediate value (0.3 m per 1 km distance from the coastline) to estimate the wave height for each inland cell.

   We delineate surge zones by comparing projected wave heights with SRTM values in each cell. A cell is part of the surge zone if its elevation value is less than the projected wave.
4. Following McGranahan et al. (2007), we delineate low-elevation coastal zones using inland pixels with less than 10 m elevation near coastlines.

   Our processing uses $5^\circ \times 5^\circ$ tiles, employing aml (ArcInfo Macro Language) for automation.
5. *Calculating exposure indicators*: We overlay our delineated inundation zones with our indicators for land area, GDP, population, urban extent, agriculture extent, and wetlands.[17] We have collected exposure surface data from various public sources. Unless otherwise indicated, latitude and longitude are specified in decimal degrees. Our horizontal datum is the World Geodetic System 1984 (WGS 1984). For area calculation, we create grids representing cell areas in square kilometers at different resolutions, using length of a degree of latitude and longitude at cell center.

   We have built two GIS models for calculating the exposure surface values. Employing the appropriate units (e.g. GDP in millions of dollars, individuals for population), we calculate total exposure by summing over exposed units in inundation zones. We measure exposure for land surface, urban extent, agriculture extent and wetlands in square kilometers.

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[16] There are four components of the storm surge height: 1-in-100 year storm surge, a 10% increase of this storm surge height, delta subsidence, and continental uplift. The contribution of each of these four components is added (summed) together to calculate the revised wave height. The sum of these individual contributions is then compared to the SRTM value. If, for example, the SRTM value at a location is 4 m while the sum of the components of wave height equals 4.2 m, then the location is considered part of the inundation area.

[17] The delineated surge zones and coastal zones are at a resolution of 3 arc sec (approximately 90 m). The resolution of indicator datasets ranges from 9 to 30 arc sec. Because of 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 to the appropriate proportion of the indicator cell value.

Table 2 Exposure to sea-level rise and intensification of storm surges: global exposure

	Current storm surge	With intensification
Coastal land area (Total = 1,512,967 km^2)		
Exposed area	118,255	202,172
% of total coastal area	7.82	13.36
Coastal population (Total = 555,651,963)		
Exposed population	35,617,817	66,965,259
% of total coastal population	6.41	12.05
Coastal GDP (Total = 1,094,402 million USD)		
Exposed GDP (USD)	76,094,729,952	136,741,729,430
% of total coastal GDP	6.95	12.49
Coastal urban extent (Total = 158,500)		
Exposed area	11,131	19,890
% of total coastal urban extent	7.02	12.55
Coastal agricultural area (Total = 401,699 km^2)		
Exposed area	17,111	35,566
% of total coastal agricultural area	4.26	8.85
Coastal wetlands area (Total = 529,555 km^2)		
Exposed area	53,337	90,680
% of total coastal wetlands area	10.07	17.12

4 Results

Results for the 84 developing countries are presented in Table 2. It indicates that approximately 7.82% (391,812 km^2) of their combined coastal territory is currently exposed to inundation from a 1-in-100 year storm surge. A 1 m sea-level rise accompanied by a 10% intensification of storm surges increases the potential inundation zone to 13.36% (202,172 km^2) of coastal territory. This would translate to potential inundation for an additional 31 million people (an approximate doubling of the

Table 3 Exposure to sea-level rise and intensification of storm surges: global exposure

	SSA	EAP	SA	MENA	LAC
% of coastal land exposed					
Without CC	7.1	7.8	9.6	11.0	6.5
With CC	13.8	12.7	17.7	17.8	11.1
% of coastal population exposed					
Without CC	5.1	6.0	7.3	7.6	5.6
With CC	10.9	11.0	14.0	15.7	9.6
% of coastal GDP exposed					
Without CC	3.9	5.9	7.9	15.1	5.5
With CC	8.6	11.1	14.4	23.8	9.9
% of coastal urban extent exposed					
Without CC	6.68	5.95	8.16	12.32	6.21
With CC	13.01	11.07	14.6	20.20	10.77
% of coastal agriculture exposed					
Without CC	1.3	4.6	4.2	1.0	1.7
With CC	3.5	9.0	10.7	4.1	4.1
% of coastal wetlands exposed					
Without CC	7.6	11.3	12.2	18.9	5.5
With CC	14.6	18.1	22.0	29.3	9.9

SSA Sub-Saharan Africa; *EAP* East Asia and Pacific; *SA* South Asia; *MENA* Middle East and North Africa; *LAC* Latin America and Caribbean

Table 4 Percentage increase in exposed indicators

	Land	Population	GDP	Urban	Agriculture	Wetlands
SSA	93.6	115.3	120.0	94.8	165.9	93.1
EAP	62.8	83.3	87.9	86.2	93.1	60.7
SA	85.2	90.4	81.7	79.0	155.7	81.1
MENA	62.5	106.1	57.4	64.0	313.5[a]	54.5
LAC	71.1	72.6	79.7	73.3	142.2	80.4

[a] The large incremental impact of storm surges on 'agricultural area' in the Middle East and North Africa region arises mostly from the estimated incremental impact in Egypt and Algeria

exposed population); 18,000 km^2 of agricultural area; and 37,000 km^2 of wetlands. GDP exposed to storm surges would increase from the existing 6.95% to 12.49%.

Similar results hold at the regional level (Table 3): With sea-level rise and storm intensification, South Asia (SA) and the Middle East and North Africa (MENA) find almost 18% of their coastal land exposed to flooding. The percentage of coastal population and GDP exposed to possible flooding is also the highest in these two regions: Approximately 24% of MENA's GDP and 20% of its coastal urban extent is exposed to sea-level rise and storm surges. A larger share of coastal agriculture is exposed to these events in SA and East Asia and the Pacific (EAP). Finally, almost 30% of the MENA's wetlands are exposed to the intensification of storm surges and sea-level rise. As shown in Table 4, across all regions the percentage increase in exposed indicators is particularly severe for coastal agriculture.[18]

We have also estimated exposed indicators for individual countries and territories. We present these results in two different ways which are each revealing. First, we examine the most exposed countries as a percentage of their own coastal values (e.g. 68.5% of Kuwait's total coastal area is exposed to sea-level rise and intensified storm surges). Second, we examine which countries would experience the largest increase in the value of the exposed indicators as a result of sea-level rise and intensified storm surges (e.g. when compared to the *existing* exposed coastal area, sea-level rise and intensified storm surges would *increase* Cote d'Ivoire's exposed coastal area by 285.2%).

Table 5 summarizes our results for each indicator by presenting the top-10 most exposed countries (as a percentage of their own coastal values). Results suggest that numerous low-income countries are susceptible to very significant damage. For coastal land area, the most vulnerable low-income countries are Namibia, Tunisia, Ghana, Kenya, and DPR Korea with more than 25% of their coastal areas exposed. For exposed coastal population, the top-5 low income countries worldwide are Yemen, Tunisia, Tanzania, Guinea, and Mozambique. Coastal agriculture would

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[18] Note that the Globcover database covers 3 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 exposed 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 under-estimate the extent of exposed agricultural extent.

Table 5 Top 10 countries most exposed to sea-level rise and intensification of storm surges

Rank	Land area	Population	GDP	Urban	Agriculture	Wetlands
1	Kuwait (68.5)	Kuwait (57.8)	Kuwait (60.6)	Yemen (39.1)	Guyana (100.0)	Kuwait (83.3)
2	Korea (49.8)	Yemen (38.3)	Yemen (40.8)	UAE (38.7)	UAE (100.0)	Taiwan, China (65.0)
3	Namibia (36.5)	UAE (37.2)	UAE (36.0)	Kuwait (35.8)	Rep. of Korea (55.0)	Korea (54.9)
4	Tunisia (31.5)	Tunisia (31.9)	Tunisia (29.6)	Guyana (32.9)	DPR Korea (42.0)	Pakistan (53.4)
5	Oman (28.2)	Korea (29.8)	Tanzania (27.4)	Tanzania (32.8)	Ghana (33.3)	Tunisia (52.1)
6	Taiwan, China (27.5)	Tanzania (28.3)	Mozambique (27.3)	Tunisia (31.3)	Qatar (33.1)	Ecuador (44.8)
7	Ghana (26.0)	Guinea (26.3)	Rep. of Korea (26.3)	Mozambique (30.9)	El Salvador (33.0)	Western Sahara (40.8)
8	Kenya (25.7)	Mozambique (25.7)	Pakistan (25.0)	Rep. of Korea (30.4)	Oman (20.0)	DPR Korea (39.0)
9	DPR Korea (25.3)	Kenya (23.6)	Guyana (23.4)	Saudi Arabia (25.7)	Bahamas (18.5)	Qatar (38.0)
10	UAE (25.2)	Pakistan (23.5)	Guinea (23.9)	Madagascar (23.6)	Taiwan, China (16.4)	Oman (37.6)

Numbers in parentheses indicate percentage exposure in 'coastal zone'

be significantly exposed in Guyana, DPR Korea, Ghana, and El Salvador. Our estimates indicate that areas prone to storm surge in Yemen, Tunisia, Tanzania, and Mozambique account for more than 25% of GDP generated in their respective coastal regions. Finally, more than 50% of the coastal wetlands in Kuwait, Taiwan, Korea, Pakistan and Tunisia will be subject to inundation risk. In sum, for the majority of indicators used in this research, we observe the most consistently-severe exposed low-income countries to be Yemen, Tunisia, DPR Korea, Tanzania, and Mozambique.

Table 6 presents our results pertaining to the change in the value of the exposed indicators brought upon by sea-level rise and intensified storm surges when compared to values under existing conditions. Cote d'Ivoire would experience the largest increase in its exposed land, population, GDP and urban extent. Gambia also ranks high across all 3 indicators. Egypt would experience the largest increase in terms of exposed agricultural land. Finally, the coastal wetlands of Algeria, Chile, and Angola would experience the largest increase of exposure as a result of sea-level rise and intensified storm surges.

As mentioned earlier, the SRTM dataset is known to experience difficulties in urban areas where it may capture infrastructure elevation as opposed to ground elevation. For purpose of validating our results pertaining to exposed urban extent, we have estimated our population exposure indicator for all coastal *urban* areas of the world (except North America) and compared our results to those presented in Nicholls et al. (2007) for port cities (population is the only exposure indicator in common to both analyses). However, in doing so, it is important to note that the population dataset used in Nicholls et al. (2007) is Landscan 2002, while we are using GRUMP2005 in this analysis. If only for that reason, irrespective of methodology, we

Table 6 Top 10 countries with larges increased in values of exposed indicators

Rank	Land area	Population	GDP	Urban	Agricultural	Wetlands
1	Cote d'Ivoire (285.2)	Cote d'Ivoire (590.7)	Cote d'Ivoire (1025.5)	Cote d'Ivoire (500.0)	Egypt (398.3)	Algeria (400.5)
2	D.Rep. Congo (266.6)	D.Rep. Congo (285.8)	Gabon (282.5)	Gabon (300.0)	Mozambique (237.8)	Chile (400.0)
3	Sri Lanka (243.0)	Mauritania (270.2)	D.Rep. Congo (252.7)	Honduras (300.00)	Sri Lanka (218.2)	Angola (398.8)
4	Honduras (226.4)	Gabon (260.6)	Gambia (232.7)	Egypt (247.6)	Pakistan (216.7)	Nigeria (274.4)
5	Nigeria (226.3)	Gambia (204.3)	Mauritania (221.3)	Bangladesh (211.9)	Mexico (210.5)	D.Rep. Congo (220.0)
6	Nicaragua (218.6)	Egypt (190.3)	Egypt (213.7)	Cameroon (200.0)	Bangladesh (209.5)	Haiti (211.1)
7	Benin (193.3)	Sri Lanka (185.1)	Bangladesh (193.6)	Gambia (198.7)	Cuba (200.0)	Guinea (200.0)
8	Gambia (159.0)	Honduras (164.4)	Belize (192.1)	Congo (197.8)	Colombia (200.0)	Dom. Republic (198.4)
9	Guatemala (158.0)	Nicaragua (160.6)	Nicaragua (189.0)	Belize (195.2)	Cambodia (191.7)	Guatemala (197.3)
10	Haiti (147.8)	Bangladesh (154.8)	Cameroon (179.2)	Cuba (194.3)	Uruguay (175.0)	Gambia (192.3)

Numbers in parentheses indicate the percentage increase in the value of indicators from values under existing climate conditions to values under sea-level rise and intensified storm surges

should expect the ranking to be different. The outcome of this comparative analysis is presented below first at the level of cities themselves, and then aggregated at the level of countries.

Table 7 Most exposed urban populations by cities

Nicholls et al. (2007)	Our results
Mumbai	**Alexandria**
Guangzhou	Thane
Shanghai	Surat
Miami	**Shanghai**
Ho Chi Minh City	Shenzhen
Kolkata	**Ho Chi Minh City**
New York City	**Rangoon**
Alexandria	Karachi
Tokyo	Tokyo
Tianjin	**Mumbai**
Bangkok	**Jakarta**
Dhaka	Nagoya
Hai Phong	Dongguan
Abidjan	**Bangkok**
Jakarta	Dandong
Rangoon	Surabaya
Khulna	Valenzuela (Philippines)
Lagos	Niigata
Ningbo	Amagasaki
Chittagong	Vitoria

In bold are cities in both sets of results

Table 8 Most exposed urban populations by countries

Nicholls et al. (2007)	Our results
China	**China**
United States	**Japan**
India	**Netherlands**
Japan	**India**
Vietnam	**Egypt**
Netherlands	**Indonesia**
Bangladesh	**Vietnam**
Egypt	**Myanmar**
Thailand	Pakistan
Indonesia	**Brazil**
Brazil	Philippines
Myanmar	South Korea
Cote d’Ivoire	**Thailand**
Nigeria	**Bangladesh**
Ecuador	**Nigeria**

In bold are cities in both sets of results

Table 7 presents results at the level of cities (top 20 cities in Nicholls et al. (2007) versus ‘our’ top 20 cities). Not considering Miami and New York City (as we did not run estimates for the United States), eight out of 18 cities are common to both set of results, especially in the first half of the rankings. At the level of countries (aggregation of city results), Nicholls et al. (2007) presents a ranking of top 15 countries by exposed population. These are presented in Table 8, and compared

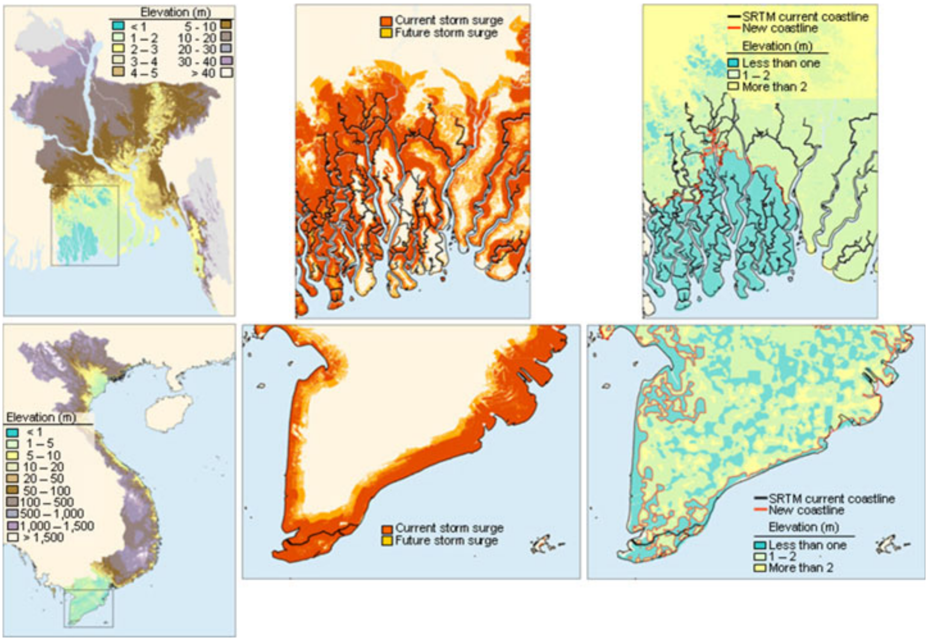

Fig. 1 Impact zones for 1 m sea-level rise and intensification of storm surge, and likely changes in unprotected shorelines. Illustrative cases: Bangladesh and Vietnam

to a similar aggregation of our city results. Of the 14 most exposed countries (excluding the United States for which we have not estimated results), 13 countries presented in Nicholls et al. are among our top 15 countries (the exception being Cote d'Ivoire); similarly, 12 out of 15 of our most exposed countries are among the top 14 (again excluding the United States) presented in Nicholls et al. (2007). Despite the known difficulties associated with the use of the SRTM data set in urban areas, this comparative assessment would appear to provide support to the methodological approach, albeit different, of both analyses.

We should finally note the uncertainty of our estimates for unprotected shorelines. As indicated earlier, the absence of a global database on shoreline protection has prevented us from modeling likely changes in shorelines associated with a 1 m sea-level rise. Even a 1 m rise in sea level will change shorelines considerably in many coastal segments, if shorelines are not protected (Dasgupta et al. 2009). We present illustrative cases for Bangladesh and Viet Nam in Fig. 1. Coastal morphology will change with receding shorelines, and potential inundation areas for storm surges will be determined by the characteristics of the changed coastline. To improve coastal security, future adaptation planning should consider such likely shoreline changes. Clearly, more multidisciplinary research is warranted in this area.

5 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. In this paper, we have assessed the vulnerability of world's coast to sea-level rise and the expected intensification of storm surges. A detailed GIS analysis was conducted to estimate the exposure to future storm surge increases associated with more intense storms and a 1 m sea-level rise. After delineating future inundation zones, we have overlaid them with indicators for coastal populations, economic activity (GDP, urban extent, and agricultural extent) and wetlands. Our results indicate very heavy potential losses that are much more concentrated in some regions and countries than others.

However, it is of importance to point out that a global analysis of this nature using global datasets and elevation information solely aims to point out areas of the developing world which *may* be more exposed to these climate changes than others, and where, in a context of limited resources, further additional studies may be prioritized. Results from this global analysis should not be used to plan country-specific adaptation investments, and certainly cannot act as a substitute to detailed and in-depth analysis at the local level.

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