Climate Change and the Future Impacts of Storm-Surge Disasters in Developing Countries

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Abstract

As the climate changes during the 21st century, larger cyclonic storm surges and growing populations may collide in disasters of unprecedented size. As conditions worsen, variations in coastal morphology will magnify the effects in some areas, while largely insulating others. In this paper, we explore the implications for 84 developing countries and 577 of their cyclone-vulnerable coastal cities with populations greater than 100,000. Combining the most recent scientific and demographic information, we estimate the future impact of climate change on storm surges that will strike coastal populations, economies and ecosystems. We focus on the distribution of heightened impacts, because we believe that greater knowledge of their probable variation will be useful for local and national planners, as well as international donors. Our results suggest gross inequality in the heightened impact of future disasters, with the most severe effects limited to a small number of countries and a small cluster of large cities.

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1. Introduction

Large tropical cyclones create storm surges that can strike crowded coastal regions with devastating force.[1] During the past 200 years, 2.6 million people may have drowned during surge events (Nicholls 2003). These disasters have continued to inflict heavy losses on the people of developing countries. Cyclone Sidr struck Bangladesh in November 2007, killing over 3,000 people, injuring over 50,000, damaging or destroying over 1.5 million homes, and affecting the livelihoods of over 7 million people (UN 2007; BDMIC 2007). Cyclone Nargis struck Myanmar's Irrawaddy delta in May 2008, creating the worst natural disaster in the country's recorded history. It killed over 80,000 people and affected the livelihoods of over 7 million (UN 2009).

The scientific evidence indicates that climate change will intensify storm surges for two reasons. First, they will be elevated by a rising sea level as thermal expansion and ice cap melting continue. The most recent evidence suggests that sea-level rise could reach 1 meter or more during this century (Dasgupta, et al. 2009; Rahmstorf 2007). Second, a warmer ocean is likely to intensify cyclone activity and heighten storm surges.[2] As storm surges increase, they will create more damaging flood conditions in coastal zones and adjoining low-lying areas. The destructive impact will generally be greater when the surges are accompanied by strong winds and large onshore waves.

Larger storm surges threaten greater future destruction because they will move further inland, threatening larger areas than in the past. In addition, both natural increase and internal migration are increasing the populations of coastal areas in many developing countries. Table 1 shows that coastal population shares increased in all developing regions from 1980 to 2000. Population growth is particularly strong in coastal urban areas, whose growth also reflects continued rural-urban migration in many developing countries.

During the 21st century, rising storm surges and growing populations threaten to collide in disasters of unprecedented size. And, as average effects increase, variations in

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[1] *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).

[2] 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).

coastal morphology may magnify the effects in some areas, while largely insulating others. In this paper, we explore the implications for 84 developing countries, along with 577 of their cyclone-vulnerable coastal cities with populations greater than 100,000. Combining the most recent scientific and demographic information, we estimate the future impact of climate change on storm surges that will strike coastal populations, economies and ecosystems. We focus on the distribution of heightened impacts, because we believe that greater knowledge of their probable variation will be useful for local and national planners, as well as international donors. In addition, we believe that realistic projections of the scale of these disasters will inform the current debate about the appropriate timing and strength of carbon emissions mitigation.

The remainder of the paper is organized as follows. Section 2 reviews recent scientific evidence on global warming and tropical cyclone intensity, and motivates the paper. Section 3 describes our research strategy and data sources, while Section 4 describes our methodology. In Sections 5 and 6, we present our results for countries and coastal cities. Section 7 summarizes and concludes the paper.

2. Global Warming, Tropical Cyclone Intensity and Disaster Preparedness

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 World Meteorological Organization (2006) 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) 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 temperatures. In addition, it notes that hurricanes/cyclones are occurring in places where they have never been observed before.[3] 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

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[3] The first recorded tropical cyclone (Catarina) in the South Atlantic occurred in March 2004, off the coast of Brazil. For further information on cyclone Catarina and storm surge risk, see UNISDR (2009).

speeds and heavier precipitation (IPCC 2007; see also Woodworth and Blackman 2004; Woth et al. 2006; and Emanuel et al. 2008).[4]

These consensus projections from the global scientific community point to the need for greater disaster preparedness in countries that are vulnerable to storm surges. Some 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 the recent disasters in Bangladesh and Myanmar have demonstrated, storm-surge losses remain huge in many areas. Such losses could be reduced by allocating more resources to increased disaster preparedness, especially given the likelihood that storms and storm surges will intensify. However, setting a new course requires a better understanding of expected changes in storm surge patterns.

3. Research Strategy and Data Sources

Previous research on storm-surge impacts has been confined to relatively limited sets of impacts[5] and locations.[6] In this paper, we broaden the assessment to 84 coastal countries and 577 coastal cities in five developing regions.[7] We consider the potential impact of a storm surge that is large (1 in 100 years) by contemporary standards, and then compare it with a more intense impact later in the century. In modeling future conditions, we take account of sea-level rise, geological uplift and subsidence along the world's coastlines. Our analysis includes exposure indicators for affected territory, population, economic activity (GDP), agricultural lands, wetlands, major cities and other urban areas. As far as we know, this is the first such exercise for developing countries.

We have employed geographic information system (GIS) software to overlay the critical impact elements (land, population, agriculture, urban extent, wetlands, GDP and city locations) with the inundation zones projected for two cases: a current 1-in-100-year storm surge and a 10% intensification over the next 100 years. We have used the best available spatially-disaggregated data sets from various public sources, including the National Aeronautics and Space Administration (NASA), US Geological Survey (USGS), European Space Agency (ESA), Dynamic Interactive Vulnerability Assessment (DIVA),

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[4] 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 surface and in the upper atmosphere. If global warming increases temperatures at the earth's surface but not the upper atmosphere, it is likely to produce tropical cyclones with more power (Emmanuel et al. 2008).

[5] Nicholls et al. (2008) assess the impacts of climate extremes on port cities of the world.

[6] 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).

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

World Wildlife Fund (WWF), Center for International Earth Science Information Network (CIESIN), and World Bank. Table 2 summarizes our data sources for assessments of inundation zones and impacts.

At the outset, we acknowledge several limitations in the analysis. First, we do not assess the relative likelihoods of alternative storm surge scenarios. We follow Nicholls, et al. (2007) in assuming an homogeneous future increase of 10% in extreme water levels during tropical storms. In all likelihood increases will vary across regions, and better area-specific modeling will be needed to improve regional forecasts.[8] Second, among the 84 developing countries included in this analysis, we restrict our study to coastal segments where historical storm surges have been documented. Third, the absence of a global database on shoreline protection prevents us from incorporating the effects of existing protection measures (e.g., sea dikes) on exposure estimates. Fourth, we have not been able to include small island states because the best available satellite system cannot accurately measure ground elevation over small areas.[9]

In our country-level study, we assess the impacts of storm surges using existing populations, socioeconomic conditions and patterns of land use, rather than attempting to predict their future states. This approach is conservative, since human activity is generally increasing more rapidly in coastal areas (Table 1). 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). Our city-level study goes further by incorporating the UN's medium-term population projections for the 21st century. This enables us to provide better comparative estimates of potential impacts across cities within countries, as well as across countries.

4. Methodology

Our analysis involves a multi-step procedure. First, we employ a base hydrologically-conditioned elevation data set to identify inundation zones and subject them to alternative storm-surge (wave height) scenarios. Second, we construct a country surface for each vulnerability indicator (population, GDP, urban extent, agricultural extent,[10] wetlands, major cities). Third, we overlay these indicator surfaces with the

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[8] As noted by Emanuel et al. (2008).

[9] Our SRTM data source is described on page 8.

[10] We use the Globcover database for agriculture, which includes 3 land use indicators. The first indicator includes areas in which most of the coverage is rainfed/irrigated/post-flooding cropland. The second includes areas for which 50-70% is mosaic cropland and the rest is grassland, shrubland and forest. The third includes areas for which 20-50% is mosaic cropland and the rest is grassland, shrubland, and forest. For the purpose of identifying impacted agricultural extent, we have retained only the agricultural land

inundation zone layer. Then we determine the spatial exposure of each vulnerability indicator under storm-surge conditions. More detailed descriptions of these steps are as follows.

(i) For elevation, we use a recently-released hydrologically-conditioned version of SRTM data, part of the HydroSHEDS dataset. We have downloaded all 5º×5º coastal tiles of 90m SRTM data from http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php. In this case, conditioning the SRTM data involves steps that alter elevation values 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.

(ii) In the calculation of storm surges (wave heights or extreme sea levels), we follow the method outlined by Nicholls (2008), where storm surges are 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 = sea-level rise (1 m)[11]
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/hurricanes.

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;

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identified as rainfed/irrigated/post-flooding cropland (the first indicator above). As a result, our calculations underestimate the impacts on agricultural extent.

[11] Nicholls (2008) assumed a SLR of 0.5 meters.

2. DELTAID: coastline segments associated with river deltas;

3. UPLIFT: estimates of continental uplift/subsidence in mm/yr from Peltier (2000), including a measure of natural subsidence (2 mm/yr) for deltas.

(iii) We compare surges (wave heights) associated with current and future storms with the elevation values of inland pixels with respect to a coastline, to delineate potential inundation areas.

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.

(iv) Following McGranahan et al. (2007), we delineate low-elevation coastal zones using inland pixels with less than 10m elevation near coastlines.

Our processing uses 5º x 5º tiles, employing aml (ArcInfo Macro Language) for automation.

We should note that our estimates are conservative because they do not take future shoreline erosion into account. As we noted previously, the absence of a global database on shoreline protection has prevented us from modeling likely changes in shorelines associated with a 1m sea-level rise. Even a 1m 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 Figure 2. Coastal morphology will change with receding shorelines, and potential inundation areas for storm surges will be determined by the characteristics of the changed coastlines. To improve coastal security, future research and adaptation planning should consider such likely shoreline changes.

(v) *Calculating exposure indicators*: We overlay our delineated inundation zones with our indicators for land area, GDP, population, urban extent, agriculture extent, wetlands and locations of cities with more than 100,000 inhabitants in 2000.[12] We have collected exposure surface data from various public sources. 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.

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.

(vi) *Adjusting absolute exposure indicators:* For exposure indicators such as land area, population and GDP, which have measured country coastal zone totals available, we adjust the exposed value using the following formula:

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

where

V_{adj} = Adjusted exposed value;
V_{cal} = Exposed value calculated from exposure grid surfaces;
CT_{mea} = Country coastal zone total obtained from statistics;
CT_{cal} = Country coastal zone total calculated from exposure grid surface.

5. Country Results

We summarize our results for 84 developing countries in Table 3. It indicates that approximately 19.5% (391,812 km^2) of their combined coastal territory is vulnerable to inundation from a 1-in-100-year storm surge (by current reference standards). A 10% future intensification increases the potential inundation zone to 25.7% (517,255 km^2) of coastal territory, taking into account sea-level rise. This translates to potential inundation for an additional 52 million people; 29,164 km^2 of agricultural area; 14,991 km^2 of urban area; 9% of coastal GDP and 7% of wetlands.

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[12] The delineated surge zones and coastal zones 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. 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.

These exposures are far from uniformly distributed across the regions and countries of the developing world. As Figure 1 shows, Latin America and the Caribbean have the largest percentage increase in storm-surge zone area (35.2%), but the coastal population exposures are largest for the Middle East and North Africa (56.2%), while coastal GDP exposures are most severe in East Asia (51.2%). Similar disparities characterize the exposures of urban areas, agricultural lands and wetlands. 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 East Asia and the Pacific, $12.7 billion in the Middle East and North Africa, $8.4 billion in South Asia, $14.4 billion in Latin America and the Caribbean, and $1.8 billion in Sub-Saharan Africa.

We also estimate exposures for individual countries and territories. Table 4 summarizes our results for each indicator by presenting the top-10 impacted countries (as a percentage of their own coastal values). Our results suggest that numerous low-income countries are susceptible to very significant 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 exposed populations, the top-5 low-income countries/territories are Djibouti, Yemen, Togo, El Salvador, and Mozambique. More than 50% of coastal urban areas lie within the potential impact zones in Guyana, Djibouti, Togo, Yemen, Mozambique, Tanzania, Cote 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 the GDP generated in their coastal regions. Finally, nearly 100% of the coastal wetlands in El Salvador and more than 60% of the wetlands in Namibia, Ecuador, Tunisia, Guinea, Yemen and Pakistan will be subject to inundation risk. For the majority of indicators used in this research, we observe the most consistently-severe exposure risks for El Salvador, Yemen, Djibouti, Mozambique and Togo.

6. City Results

6.1 Coastal Area Vulnerability

In this section we consider two measures of coastal urban exposure. The first, summarized in Table 5, lists cities in each developing region whose coastal areas will be most affected by future increases in storm surges. We calculate vulnerability in three steps. First, we rank cities in each region by percent increase in the future inundation area relative to the current inundation area. To weight for current vulnerability, we rank cities in each region by percent of coastal area in the current inundation zone. Then we compute the average for the two ranks and re-order the cities by their average

ranks. Table 5 includes the 10 highest-ranking cities in each region, using future inundation increase weighted by current vulnerability. To illustrate, Nacala, Mozambique has the highest future vulnerability in Sub-Saharan Africa. In the 21st century, 25% of its coastal area will be added to its inundation zone (Pct 2). This is a 50% increase in its current inundation zone, which is already 50% of its coastal area (Pct 1). Using the same calculations, we identify the top-ranked cities in the other four regions as Rach Gia, Viet Nam; Georgetown, Guyana; Kenitra, Morocco; and Cox's Bazar, Bangladesh. These cities join the other top-10 cities as potentially-deadly locales, since storm water drainage infrastructure is often outdated and inadequate in 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. Within regions, exposures are clearly far from balanced across countries. In each region, at least half of the top-10 cities are in only two countries: Mozambique (3) and Cote d'Ivoire (2) in Sub-Saharan Africa; Indonesia (3) and Viet Nam (3) in East Asia ; Brazil (3) and Mexico (2) in Latin America; Morocco (4) and Tunisia (3) in the Middle East and North Africa; and Bangladesh (4) and India (4) in South Asia.

6.2 Population Vulnerability

In an alternative approach, we compare cities by estimating the vulnerability of their populations to intensified storm surges in the 21st century. We consider the combined effects of projected population change, sea-level rise and storm intensification on the distribution of exposures by the end of the century. We use the UN's medium population projections for 2100, as reported by IIASA (2009), and conservatively assume that all coastal cities in each country retain their current share of the national population.[14] In addition, we assume that coastal cities' populations are uniformly-distributed across their coastal and non-coastal areas. From the work reported in Section 6.1 above, we draw the percent of coastal areas in inundation zones now, and in 2100 after a 1m sea-level rise and 10% increase in the intensity of a 1-in-100-year storm. Combining the area and demographic information, we estimate populations in the current and future inundation zones, and the implied increase in affected population. Table 6 displays the 25 cities with the largest population exposures, expressed as changes in affected populations and cumulative percents of the total change for all cities.

The most striking feature of our results is the extreme concentration of effects in a handful of cities. Over 25% of the increase in developing-country urban population

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

[14] As Table 1 shows, coastal cities increased their percent share of national populations during the period 1980-2000. However, we have no credible way to extrapolate this trend for the next 100 years.

affected by future storm surges is in only three cities:[15] Manila (3.4 million), Alexandria (2.7 million) and Lagos (2.1) million. The top 10 cities account for 53 % of total exposures, and the top 25 for 72%. The 552 other coastal cities in our dataset account for only 28% of the total. Of the top 25, 10 are in Sub-Saharan Africa (8 in coastal West Africa alone), 3 in the Middle East and North Africa, 7 in Southeast Asia, 4 in South Asia, and 1 in South America. We should emphasize that our results are not closely tied to the current distribution of coastal city populations. As Table 6 shows, many of the cities with top-25 changes in vulnerable populations are not among the world's most populous urban areas at present. Their future top-25 status stems from two factors: future urban growth, and coastal characteristics that make them particularly vulnerable to greater storm surges.

7. Conclusions

In this paper, we have assessed the vulnerability of coastal areas in developing countries to larger storm surges associated with global warming and a 1m sea-level rise. After identifying future inundation zones, we have overlaid them with indicators for coastal populations, settlements, economic activity and wetlands. Our results indicate large effects that are much more concentrated in some regions, countries and cities than others. We have also incorporated population projections for the 21st century, and computed the exposures of coastal urban populations as conditions worsen. Our results suggest a huge asymmetry in the burden of sea-level rise and storm intensification, with only 3 of 577 cities accounting for 25% of the future coastal population exposure and 10 cities for 53% of the future exposure. Our results suggest that the residents of a small number of developing-country cities will bear the additional brunt of heightened storm surges, while many other coastal cities will experience little change in population exposure. In light of the huge asymmetries in our country- and city-level results, we believe that careful targeting of international assistance will be essential for the effective and equitable allocation of resources for coastal protection and disaster prevention. In addition, the large magnitudes of potential impacts on people,

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[15] Many large coastal cities have only small increases (or even decreases), because projected populations and coastal inundation zones have countervailing trends during the 21st century. All future coastal inundation zones increase at least somewhat with a 1m sea-level rise and a 10% increase in storm intensity. However, the UN projects rapidly-declining fertility and significant population loss for many countries by 2100. In our methodology, their cities follow suit because we assume fixed city/country population ratios. Shanghai provides a useful illustration of these countervailing forces. Our spatial analysis indicates that Shanghai's inundation zone will increase from 15.7% of its coastal area in 2000 to 25.8% in 2100. However, the demographic projection indicates that Shanghai's coastal-zone population will decline from 13.2 million in 2000 to 7.5 million in 2100. These two factors combine to produce a small *decrease* between 2000 and 2100 in the population affected by severe storm-surge conditions.

economies and ecosystems provide strong evidence in support of rapid action to reduce global warming by mitigating greenhouse gas emissions.

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Table 1
Percent of National Population in Coastal Cities,
1980 – 2000

World Bank Region	1980	1990	2000
Sub-Saharan Africa	7.19	9.12	11.98
East Asia and Pacific	7.09	8.55	9.36
Latin American and Caribbean	15.58	16.61	17.53
Middle East and North Africa	7.64	8.00	8.57
South Asia	4.19	4.80	5.55

Data Source: CIESIN, Global Rural Urban Mapping Project (GRUMP), 2005: Population in coastal urban zone, defined as elevation < 10 m

Table 2
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*, Henrike Brecht, 2007

*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

Table 3
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

Table 4
Top 10 Countries at Risk From Intensification of Storm Surges[*]
(Percentage impacts in coastal zones in parentheses)

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 (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)	PuertoRico (52.7)	Ghana (66.7)	Yemen (55.4)	Qatar (75.0)
8	PuertoRico (51.8)	PuertoRico (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)

Table 5: Future Storm-Surge Impacts on Coastal Areas: Regional Top-10 Cities

Pct 1 = Current Inundation Zone as Percent of Coastal Area
Pct 2 = Future Increase in Inundation Zone as Percent of Coastal Area
Ratio = 100 x [Pct 2 / Pct 1]

| Region	Subregion	Country	City	Rank	Ratio	Pct 1	Pct 2
AFR	Southern Africa	Mozambique	Nacala	1	50	50	25
AFR	Coastal West Africa	Benin	Cotonou	2.5	62	38	24
AFR	Southern Africa	Mozambique	Quelimane	2.5	34	56	19
AFR	Southern Africa	Mozambique	Beira	4	33	51	17
AFR	Coastal West Africa	Nigeria	Warri	5	50	33	17
AFR	Coastal West Africa	Côte d'Ivoire	San-Pedro	7	44	35	16
AFR	Coastal West Africa	Côte d'Ivoire	Abidjan	7	107	27	29
AFR	Coastal West Africa	Gambia	Bathurst	7	21	60	12
AFR	Southern Africa	South Africa	George	9	17	67	11
AFR	Coastal West Africa	Liberia	Monrovia	10	32	38	12
EAP	Southeast Asia	Viet Nam	Rach Gia	1	46	60	27
EAP	Southeast Asia	Indonesia	Tegal	2	60	48	29
EAP	Northeast Asia	Korea, Rep	Ansan	3	27	70	19
EAP	Southeast Asia	Indonesia	Cirebon	4	69	35	24
EAP	Southeast Asia	Philippines	Butuan	5	63	38	24
EAP	China	China	Dandong	6	39	51	20
EAP	Southeast Asia	Viet Nam	Nha Trang	7	27	67	18
EAP	Southeast Asia	Viet Nam	Hue	8	26	68	18
EAP	Southeast Asia	Indonesia	Pemalang	9.5	86	31	27
EAP	Southeast Asia	Philippines	Cotabato	9.5	22	73	16
LCR	Northern South America	Guyana	Georgetown	1	37	56	21
LCR	Southern South America	Argentina	La Plata	2	93	33	31
LCR	Central America	Mexico	Ciudad del Carmen	3.5	24	73	18
LCR	Central America	Mexico	Acapulco (de Juarez)	3.5	45	44	20
LCR	Northern South America	Brazil	Aracaju	5	27	51	14
LCR	Caribbean Islands	Dominican Rep	La Romana	6	50	35	17
LCR	Northern South America	Brazil	Rio Grande	7	26	48	13
LCR	Northern South America	Brazil	Maceio	8	35	40	14
LCR	Northern South America	Venezuela	Barcelona	9.5	55	29	16
LCR	Andean South America	Ecuador	Esmeraldas	9.5	24	49	12
MNA	North Africa	Morocco	Kenitra	1	36	48	18
MNA	East Africa	Djibouti	Djibouti	2	20	50	10
MNA	North Africa	Morocco	Tetouan	3.5	35	37	13
MNA	North Africa	Tunisia	Binzart	3.5	40	33	13
MNA	North Africa	Tunisia	Susah	6	62	32	20
MNA	North Africa	Morocco	Mohammedia	6	19	51	10
MNA	North Africa	Morocco	Rabat	6	16	61	10
MNA	North Africa	Egypt	Bur Sa'id (Port Said)	8.5	13	75	9
MNA	North Africa	Tunisia	Tunis	8.5	25	46	11
SAR	Southern Asia	Bangladesh	Cox's Bazar	1	42	47	20

| SAR | Southern Asia | Bangladesh | Khulna | | 2 | 88 | 35 | 31 |

Region	Subregion	Country	City	Rank	Ratio	Pct 1	Pct 2
SAR	Southern Asia	Bangladesh	Bakerganj	3	28	70	20
SAR	Western Asia	Pakistan	Karachi	4	30	44	13
SAR	Southern Asia	India	Jamnagar	5	32	43	13
SAR	Southern Asia	India	Vadodara (Baroda)	6	40	36	14
SAR	Southern Asia	Sri Lanka	Moratuwa	7	74	21	16
SAR	Southern Asia	India	Thane	8.5	19	43	8
SAR	Southern Asia	Bangladesh	Chandpur	8.5	50	24	12
SAR	Southern Asia	India	Bhavnagar	10	14	58	8

Table 6
Top-25 City Population Impacts

Rank	Country	City	Change in Affected Population	Cumulative %	Global City Population Rank 2000
1	Philippines	Manila	3,438,334	11.8	8
2	Egypt	Al-Iskandariyah (Alexandria)	2,723,464	21.2	18
3	Nigeria	Lagos	2,121,263	28.5	2
4	Liberia	Monrovia	1,751,428	34.5	61
5	Pakistan	Karachi	1,417,639	39.4	6
6	Yemen	Aden	1,235,473	43.6	132
7	Indonesia	Jakarta	836,130	46.5	7
8	Egypt	Bur Sa'id (Port Said)	672,210	48.8	146
9	Bangladesh	Khulna	635,950	51.0	56
10	India	Kolkata (Calcutta)	547,004	52.9	3
11	Thailand	Krung Thep (Bangkok)	546,157	54.8	13
12	Cote d'Ivoire	Abidjan	543,928	56.6	25
13	Benin	Cotonou	491,049	58.3	100
14	Bangladesh	Chittagong	489,789	60.0	22
15	Viet Nam	Thanh Pho Ho Chi Minh	433,176	61.5	16
16	Myanmar	Yangon	384,381	62.8	17
17	Guinea	Conakry	383,551	64.1	46
18	Angola	Luanda	346,973	65.3	33
19	Brazil	Rio de Janeiro	344,034	66.5	9
20	Senegal	Dakar	299,405	67.5	40
21	Nigeria	Warri	266,667	68.5	140
22	Somalia	Mogadishu	235,670	69.3	71
23	Philippines	Taguig	232,703	70.1	147
24	Nigeria	Port Harcourt	222,714	70.8	84
25	Philippines	Kalookan	212,853	71.6	74

Figure 1
Incremental Impact of Selected Indicators of Storm Surges (Percentage)
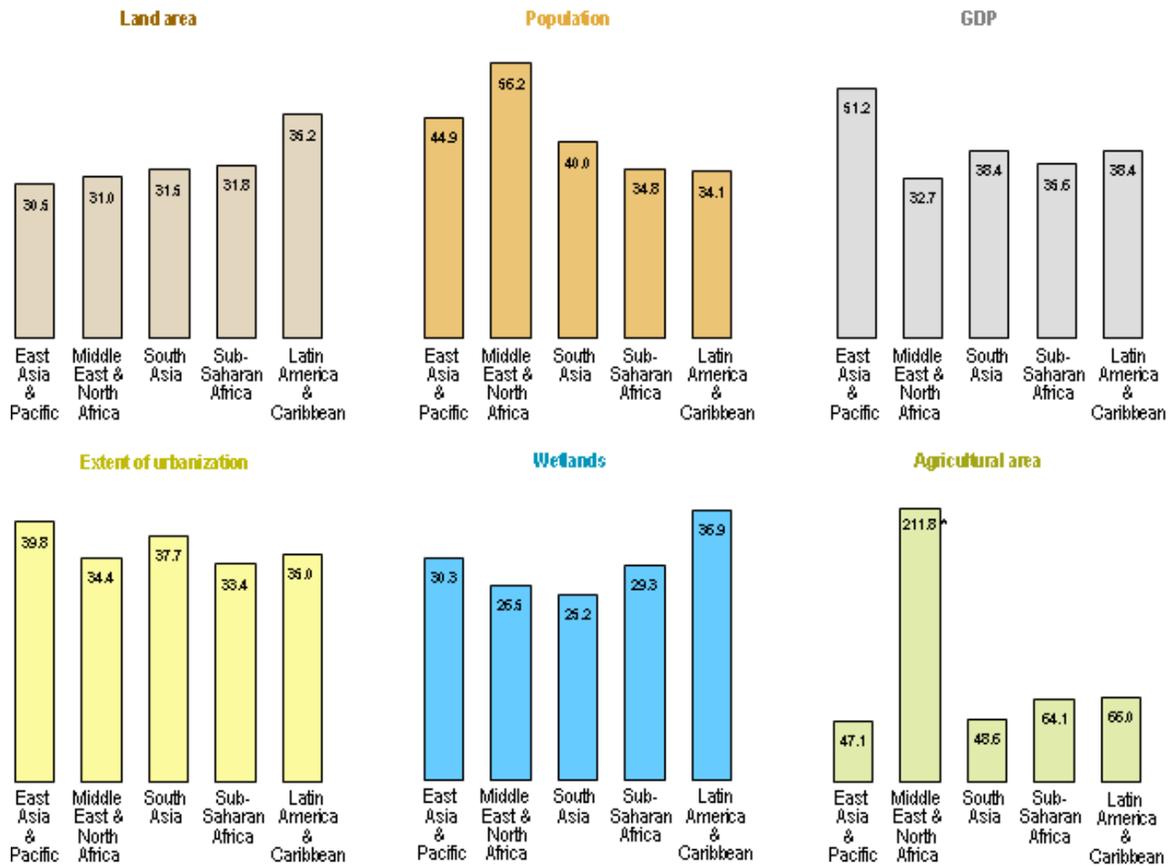
* The large incremental impact of storm surges on 'agricultural areas' in the Middle
East and North Africa arises mostly from the estimated incremental impact in Egypt
(326%) and Algeria (143%).

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Figure 2
Impact Zones for 1 Meter Sea-Level Rise and
Intensification of Storm Surges, and Likely Changes in Unprotected
Shorelines

Illustrative Cases: Bangladesh and Viet Nam