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# Sea-Level Rise and Storm Surges: High Stakes for a Small Number of Developing Countries

**Henrike Brecht[1], Susmita Dasgupta[1], Benoit Laplante[1], Siobhan Murray[1], and David Wheeler[2]**


## 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 article, we explore the implications for 31 developing countries and 393 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 50% of the burden falling on the residents of 10 Asian cities and over 40% falling on Manila, Karachi, and Jakarta alone. In light of these huge asymmetries, 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.



## Keywords

climate change, cyclonic storm surge, developing countries, GIS overlays, population


[1]The World Bank, Washington, DC, USA
[2]Center for Global Development, Washington, DC, USA

**Corresponding Author:**
Susmita Dasgupta, The World Bank, 1818 H Street, Washington, DC 20433, USA
Email: sdasgupta@worldbank.org

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## 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 more than 3,000 people, injuring more than 50,000, damaging or destroying more than 1.5 million homes, and affecting the livelihoods of more than 7 million people (Bangladesh Disaster Management Information Centre, 2007; United Nations [UN], 2007). Cyclone Nargis struck Myanmar's Irrawaddy delta in May 2008, creating the worst natural disaster in the country's recorded history. It killed more than 80,000 people and affected the livelihoods of more than 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 m or more during this century (Hansen, 2006, 2007; Hansen & Sato, 2011; Overpeck et al., 2006; Pfeffer, Harper, & O'Neel, 2008; Rahmstorf, 2007; Vermeer & Rahmstorf, 2009).[2] These results include estimates significantly beyond the upper limit of the range cited by the Intergovernmental Panel on Climate Change's (IPCC, 2007) Fourth Assessment Report: A 90% confidence interval of 18 to 59 cm based principally on thermal expansion, with an additional 10 to 20 cm allowed for a potential dynamic response from the Arctic and Antarctic ice sheets. The more recent research cited above has focused on the dynamic implications of ice sheet instability.

Second, the current scientific consensus, summarized by IPCC (2011), holds that a warmer ocean is likely to intensify cyclone activity and heighten storm surges.[3] 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 when surges make landfall during high tide.[4]

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.

Rising storm surges in a changing climate and growing population in coastal urban areas may collide with disastrous consequences during the 21st century. As average effects increase, variations in coastal morphology may magnify the effects in some areas, while largely insulating others. In this article, combining the most recent scientific and demographic information, we explore the implications of intensified storm

**Table 1.** Percent of National Population in Coastal Cities, 1980-2000

| World Bank region | 1980 | 1990 | 2000 |
|---|---|---|---|
| Sub-Saharan Africa (AFR) | 7.19 | 9.12 | 11.98 |
| East Asia and Pacific (EAP) | 7.09 | 8.55 | 9.36 |
| Latin American and Caribbean (LCR) | 15.58 | 16.61 | 17.53 |
| South Asia (SAR) | 4.19 | 4.80 | 5.55 |

Source: CIESIN, Global Rural Urban Mapping Project GRUMPv1.
Note: Population in coastal urban zone, defined as elevation <10 m.

surges for 393 coastal cities with populations greater than 100,000, in 31 developing countries that have experienced tropical storms in the past. 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 article is organized as follows. The section on global warming, tropical cyclone intensity, and disaster preparedness section reviews recent scientific evidence on global warming and tropical cyclone intensity, and motivates the article. Section on research strategy and data sources describes our research strategy and data sources, whereas the next section describes our methodology. In section on city results, we present our results for coastal cities. The last section summarizes and concludes the article.

## *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 (Bengtsson, Hodges, & Roeckner, 2006; Emanuel, 2005; Webster et al., 2005). 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, Harper, Hoarau, & Knaff, 2006). Although the science is not yet conclusive (International Workshop on Tropical Cyclones, 2006; Pielke, Landsea, Mayfield, Laver, & Pasch, 2005), the World Meteorological Organization (2006) has recently noted that "it 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" and "if the projected rise in sea level due to global warming occurs, then the vulnerability to tropical cyclone storm surge flooding would increase."

IPCC (2007, 2011) cite 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, IPCC (2007) notes that hurricanes/cyclones occur in places where they have never been observed 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; Emanuel, Sundararajan, & William, 2008; see also Hansen & Sato, 2011; Woodworth & Blackman, 2004; Woth, Weisse, & von Storch, 2006).[6]

These 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, Russell, & Espinel, 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.

## Research Strategy and Data Sources

Previous research on storm-surge impacts on coastal cities has been confined to relatively limited cases. For example, Hanson et al. (2011) assessed the exposure associated with surge-induced flood events in 136 port cities with populations of more than one million in 2005. The impacts of storm surges have been assessed for Bangladesh (Dasgupta et al., 2010), Copenhagen (Hallegatte et al., 2011), Southern Australia (McInnes, Hubbert, Macadam, & O'Grady, 2008), the Irish Sea (Wang et al., 2008), and Shanghai (Wang, Gao, Xu, & Yu, 2010). In this article, we broaden the assessment to 393 coastal cities[7] with populations greater than 100,000, located in 31 coastal countries that have experienced tropical storms. These cities are located in four developing regions: East Asia and Pacific, Latin America and Caribbean, South Asia, and Sub-Saharan Africa.[8] We consider the potential exposure of these cities to a storm surge that is large (1 in 100 years) by contemporary standards, and then compare it with a more intense storm surge later in the century. In modeling future conditions, we take account of sea-level rise, geological uplift, and subsidence along the world's coastlines.

At the outset, we acknowledge several limitations in the analysis. Although we use the best available data for estimating the relative exposure of various coastal segments to increased storm surge, several gaps in the data limit our analysis. First and foremost, the absence of a global database on shoreline protection (e.g., coastal embankments), and coastal-zone management (e.g., land-use planning, regulations, relocation) has prevented us from incorporating the effect of existing man-made protection measures (e.g., sea dikes), natural underwater coastal protective features

**Table 2.** Summary of Data Sources

| Dimension | Data set name | Unit | Resolution | Source(s) |
|---|---|---|---|---|
| Coastline | SRTM v2 Surface Water Body Data | | | NASA |
| Elevation | Hydrosheds Conditioned SRTM 90 m DEM | $km^2$ | 90 m | Lehner, Verdin, and Jarvis, 2008 |
| Watersheds | Hydrosheds Drainage Basins | $km^2$ | | Lehner et al., 2008 |
| Coastline attributes | DIVA GIS database | | | Vafeidis et al., 2008 |
| Cities | City Polygons With Population Time Series | | | Urban Risk Index[a], Brecht, 2007 |

[a]Urban extents from GRUMPv1 (http://sedac.ciesin.columbia.edu/gpw) joined with World Cities Data from http://www.econ.brown.edu/faculty/henderson/worldcities.html

(e.g., mangroves) and coastal zone management policies on exposure estimates. Incorporation of existing or planned protective measures might significantly alter our exposure estimates, but the requisite information is not available. Second, 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] Third, among the developing countries included in this analysis, we restrict our analysis to coastal segments where historical storm surges have been documented.

## Method

To quantify the implications of intensified storm surges for coastal cities in a changing climate, we have used geographic information system (GIS) software to overlay the city locations with the inundation zones projected for three cases: a current 1-in-100-year tropical storm surge, a 10% intensification over the next 100 years, and a 15% intensification.[10] Table 2 summarizes our data sources for assessments of inundation zones and impacts.

Our analysis involves a multistep procedure. First, we use a base hydrologically conditioned elevation data set to identify inundation zones and subject them to alternative storm-surge scenarios. Second, we construct a surface for the location of major cities. Third, we overlay the city surface with the inundation zone layers to determine the spatial exposure of each city under alternative storm-surge conditions.

The height of a tropical storm-induced surge in a changing climate will depend on sea-level rise and the power of the future storm, as determined by the change in ocean surface temperature and nonclimate effects: uplift and subsidence of land[11] caused by natural processes (tectonics and glacial-isostatic adjustments) and anthropogenic processes (e.g., ground water withdrawal). Taking all these factors into account, in estimating future storm surges we follow the method outlined by Hanson et al. (2011):

$$\text{Future storm surge} = \text{S100} + \text{SLR} + (\text{UPLIFT} \times 100 \text{ year}) / 1000 + \text{SUB} + \text{S100} \times \text{x}$$

where, S100 = 1-in-100-year current storm surge height (m), SLR = sea-level rise (m), UPLIFT = continental uplift/ natural subsidence (mm/year), SUB = anthropogenic subsidence (m) applies to deltas only, x = increase in storm-surge height (%), applied only in coastal areas that have been affected by cyclones/hurricanes.

More detailed descriptions of the steps followed are provided below:

1. For elevation, we use a recently released hydrologically conditioned version of 90 m Shuttle Radan Topography Mission (SRTM) data, part of the hydrosheds data set (Lehner, Verdin, & Jarvis, 2008). We have downloaded all 5° × 5° coastal tiles of the 90 m SRTM data, and conditioning of the SRTM data in this case involves steps that alter elevation values to produce a surface that drains to the coast,[12] including filtering, lowering of stream courses and adjacent pixels, and carving out barriers to stream flow.[13]
2. We extract vector coastline masks from SRTM Version 2, and download coastline information from the Dynamic Interactive Vulnerability Assessment (DIVA) coastal GIS database. In the calculation of storm surges in a changing 2100 climate, we use the following attributes drawn from the DIVA database:
   a. S100: 1-in-100-year surge height, based on tidal levels, barometric pressures, wind speeds, seabed slopes and storm-surge levels from monitoring stations;
   b. DELTAID: coastline segments associated with river deltas;
   c. UPLIFT: estimates of continental uplift/subsidence in mm/year from the geophysical model of Peltier (2000), including a measure of natural subsidence (2 mm/year) for deltas.

In addition, to approximate conditions in 2100, we assume a SLR of 1 m[14], 0.5 m anthropogenic subsidence (SUB) applicable to deltas only[15], and x = (0.1, 0.15): alternative increases of 10% and 15% in storm-surge height[16] in coastal areas where tropical cyclones have occurred.

3. We compare surges 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, to better capture the movement of water inland, we use hydrological drainage basins. We apply the surge height calculated for the coastline segment closest to the basin outlet to inland areas within that basin.

As a surge 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 to 0.4 m per kilometer 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 surge 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.[17]

4. Following McGranahan, Balk, & Anderson (2007), we delineate low-elevation coastal zones using inland pixels with less than 10 m elevation near coastlines.[18]
5. For identifying major coastal cities, we have considered all urban agglomerations containing suburbs and adjacent towns with more than 100,000 inhabitants in the year 2000 from the World Cities database[19]. The city points were then matched with the Center for International Earth Science Information Network (CIESIN)[20] information on global urban extent based largely on NOAA's night-time satellite data from 1994 to 1995. For each city a corresponding raster urban area was identified and converted into a polygon. Where multiple city points fell within a large contiguous area, Thiessen polygons were used to allocate a portion of the area to each point, creating a unique urban footprint for each city.
6. Calculating exposure indicators: We overlay our delineated inundation zones with locations of cities with more than 100,000 inhabitants in 2000 to determine exposure of 393 coastal cities to storm-surge conditions under current and future climate scenarios.[21]

It should be noted that our estimates may be conservative because (a) the analysis is based on a sea-level rise estimate of 1 m by 2100, although the previously cited scientific literature suggests that multi-meter sea-level rise is possible in this century and (b) the estimates 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 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, Laplante, Murray, & Wheeler, 2011). 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.

**Table 3.** Exposure to Future Storm Surge: Regional Top 10 Cities: Wave Height Increases of 10% and 15%

| Region | Subregion | Country | City | Rank | | Ratio | | | Pct2 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 10% | 15% | 10% | 15% | Pct1 | 10% | 15% |
| AFR | Southern Africa | Mozambique | Quelimane | 1 | 2 | 34 | 38 | 56 | 19 | 21 |
| AFR | Southern Africa | Mozambique | Nacala | 2 | 2 | 50 | 50 | 50 | 25 | 25 |
| AFR | Madagascar | Madagascar | Mahajanga | 3.5 | 4 | 13 | 13 | 67 | 8 | 8 |
| AFR | Southern Africa | Mozambique | Beira | 3.5 | 2 | 33 | 42 | 51 | 17 | 21 |
| AFR | Southern Africa | Mozambique | Maputo | 5 | 5 | 21 | 21 | 41 | 9 | 9 |
| EAP | Southeast Asia | Vietnam | Rach Gia | 1 | 2 | 46 | 46 | 60 | 27 | 27 |
| EAP | Southeast Asia | Indonesia | Tegal | 2 | 3 | 60 | 60 | 48 | 29 | 29 |
| EAP | Northeast Asia | Korea, Rep | Ansan | 3 | 1 | 27 | 33 | 70 | 19 | 23 |
| EAP | Southeast Asia | Vietnam | Nha Trang | 4 | 6 | 27 | 27 | 67 | 18 | 18 |
| EAP | China | China | Dandong | 5 | 4.5 | 39 | 43 | 51 | 20 | 22 |
| EAP | Southeast Asia | Vietnam | Hue | 7 | 7 | 26 | 26 | 68 | 18 | 18 |
| EAP | Southeast Asia | Philippines | Cotabato | 7 | 9 | 22 | 22 | 73 | 16 | 16 |
| EAP | Southeast Asia | Indonesia | Cirebon | 7 | 9 | 69 | 69 | 35 | 24 | 24 |
| EAP | Southeast Asia | Philippines | Butuan | 9 | 4.5 | 63 | 67 | 38 | 24 | 25 |
| EAP | China | China | Zhuhai | 10 | 9 | 32 | 34 | 53 | 17 | 18 |
| LCR | Central America | Mexico | Acapulco (de Juarez) | 1 | 1 | 45 | 47 | 44 | 20 | 21 |
| LCR | Caribbean Islands | Dominican Rep | La Romana | 2 | 2 | 50 | 50 | 35 | 17 | 17 |
| LCR | Central America | Mexico | Ciudad del Carmen | 3 | 3 | 24 | 24 | 73 | 18 | 18 |
| LCR | Northern South America | Venezuela | Barcelona | 5.5 | 5.5 | 55 | 55 | 29 | 16 | 16 |
| LCR | Northern South America | Venezuela | Cumana | 5.5 | 5.5 | 69 | 69 | 26 | 18 | 18 |
| LCR | Central America | Mexico | Mazatlan | 5.5 | 5.5 | 52 | 55 | 30 | 15 | 16 |
| LCR | Andean South America | Colombia | Barranquilla | 5.5 | 5.5 | 109 | 109 | 14 | 15 | 15 |
| LCR | Andean South America | Colombia | Cartagena | 8 | 8.5 | 59 | 59 | 25 | 15 | 15 |
| LCR | Northern South America | Venezuela | Puerto Cabello | 9.5 | 10 | 37 | 38 | 32 | 12 | 12 |
| LCR | Central America | Mexico | Tampico | 9.5 | 8.5 | 87 | 95 | 18 | 16 | 17 |
| SAR | Southern Asia | Bangladesh | Cox's Bazar | 1 | 1 | 42 | 47 | 47 | 20 | 22 |
| SAR | Southern Asia | Bangladesh | Khulna | 2 | 2.5 | 88 | 95 | 35 | 31 | 33 |
| SAR | Southern Asia | Bangladesh | Bakerganj | 3 | 2.5 | 28 | 30 | 70 | 20 | 21 |
| SAR | Western Asia | Pakistan | Karachi | 4 | 4 | 30 | 32 | 44 | 13 | 14 |
| SAR | Southern Asia | India | Jamnagar | 5 | 5 | 32 | 37 | 43 | 13 | 16 |
| SAR | Southern Asia | India | Vadodara | 6 | 6 | 40 | 40 | 36 | 14 | 14 |
| SAR | Southern Asia | Sri Lanka | Moratuwa | 7 | 7.5 | 74 | 76 | 21 | 16 | 16 |
| SAR | Southern Asia | India | Thane | 8.5 | 9 | 19 | 19 | 43 | 8 | 8 |
| SAR | Southern Asia | Bangladesh | Chandpur | 8.5 | 7.5 | 50 | 58 | 24 | 12 | 14 |
| SAR | Southern Asia | India | Bhavnagar | 10 | 10 | 14 | 14 | 58 | 8 | 8 |

Note: Pct 1 = Current Inundation Zone as Percent of Coastal Area; Pct 2 = Future Increase in Inundation Zone as Percent of Coastal Area; Ratio = 100 × [Pct 2 / Pct 1].

## City Results

### Exposure of Coastal Area

In this section, we consider measures of coastal urban exposure. The measure summarized in Table 3 lists cities in each developing region whose coastal areas will be most affected by future increases in storm surges. This computation is done in three steps. First, we rank cities in each region by percent increase in the future inundation area relative to the current inundation area.[22] To weight for current exposure, 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 reorder the cities by their average ranks. Table 3 includes the highest ranking cities in each region, using future inundation increase weighted by current exposure. We tabulate results for 10 cities in East Asia, Latin America and the Caribbean, and South Asia. In Sub-Saharan Africa, there are fewer than 10 cities whose coastal characteristics match our criteria for inclusion in the analysis. We provide results for future wave height increases of 10% and 15%. To illustrate, Nacala, Mozambique has the highest future exposure in Sub-Saharan Africa in both the 10% and 15% cases. 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 three regions as Rach Gia, Vietnam; Acapulco de Juarez, Mexico; and Cox's Bazar, Bangladesh. These cities join the other top-ranked cities as potentially deadly locales, as storm water drainage infrastructure is often outdated and inadequate in low-income urban centers.[23] 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 2 countries: Mozambique (4) and Madagascar (1) in Sub-Saharan Africa; Indonesia (or the Philippines) (2) and Vietnam (3) in East Asia; Mexico (4) and Venezuela (3) in Latin America; and Bangladesh (4) and India (4) in South Asia.

### Exposure of Population

In an alternative approach, we compare cities by estimating the exposure 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.[24] In addition, we assume that coastal cities' populations are uniformly distributed across their coastal and noncoastal areas. From the work reported in Exposure of Coastal Area section above, we draw the percent of coastal areas in inundation zones now, and in 2100 after a 1 m sea-level rise. For 2100, we generate results for 10% and 15% increases in the intensity of a 1-in-100-year storm. Combining the area and demo-

**Table 4.** Top 25 City Population Exposure: Wave Height Increases of 10% and 15%

| Rank by wave height increase 10% | 15% | Country | City | Change in affected population 10% | 15% | Cumulative % 10% | 15% | Global city population rank 2000 |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Philippines | Manila | 3,438,334 | 3,438,334 | 25.7 | 24.8 | 12 |
| 2 | 2 | Pakistan | Karachi | 1,417,639 | 1,460,948 | 36.2 | 35.3 | 9 |
| 3 | 3 | Indonesia | Jakarta | 836,130 | 836,130 | 42.5 | 41.3 | 11 |
| 4 | 4 | Bangladesh | Khulna | 635,950 | 678,217 | 47.2 | 46.2 | 190 |
| 5 | 5 | India | Kolkata (Calcutta) | 547,004 | 657,439 | 51.3 | 50.9 | 5 |
| 6 | 6 | Thailand | Krung Thep (Bangkok) | 546,157 | 546,157 | 55.4 | 54.8 | 21 |
| 7 | 7 | Bangladesh | Chittagong | 489,789 | 545,826 | 59.0 | 58.8 | 47 |
| 8 | 8 | Vietnam | Thanh Pho Ho Chi Minh (Saigon-Cholon) | 433,176 | 433,176 | 62.2 | 61.9 | 36 |
| 9 | 9 | Myanmar | Yangon | 384,381 | 384,381 | 65.1 | 64.7 | 37 |
| 10 | 10 | Philippines | Taguig | 232,703 | 251,844 | 66.9 | 66.5 | 623 |
| 11 | 11 | Philippines | Kalookan | 212,853 | 212,853 | 68.4 | 68.0 | 251 |
| 12 | 12 | Colombia | Barranquilla | 181,864 | 181,864 | 69.8 | 69.3 | 136 |
| 13 | 13 | India | Chennai (Madras) | 156,149 | 168,705 | 71.0 | 70.5 | 25 |
| 14 | 14 | Mozambique | Maputo | 137,977 | 137,977 | 72.0 | 71.5 | 63 |
| 15 | 16 | Philippines | Davao | 119,101 | 126,434 | 72.9 | 72.4 | 244 |
| 16 | 15 | Mozambique | Beira | 111,202 | 129,417 | 73.7 | 73.4 | 650 |
| 17 | 18 | Indonesia | Ujungpandang | 107,612 | 107,612 | 74.5 | 74.1 | 291 |
| 18 | 17 | Philippines | Butuan | 102,901 | 108,203 | 75.3 | 74.9 | 981 |
| 19 | 19 | Bangladesh | Bakerganj | 97,056 | 100,112 | 76.0 | 75.6 | 1018 |
| 20 | 20 | Philippines | Malabon | 89,497 | 91,420 | 76.7 | 76.3 | 803 |
| 21 | 21 | Philippines | Iloilo | 87,548 | 91,369 | 77.3 | 77.0 | 756 |
| 22 | 23 | Venezuela | Maracaibo | 82,628 | 82,628 | 77.9 | 77.6 | 118 |
| 23 | 25 | Indonesia | Surabaya | 81,921 | 81,921 | 78.6 | 78.1 | 87 |
| 24 | 24 | Madagascar | Mahajanga | 80,353 | 80,353 | 79.2 | 78.7 | 1659 |
| 25 | 22 | Mozambique | Quelimane | 77,646 | 83,375 | 79.7 | 79.3 | 1371 |

graphic information, we estimate populations in the current and future inundation zones, and the implied increase in affected populations. Table 4 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. Although the 10% and 15% cases have slightly different rankings, the same cities are in the top 25 in both cases.

**Table 5.** Projected National Totals ('000) for 2100: Coastal Cities With Populations Greater Than 100,000

| Country | Population | Population affected by storm surges | % affected | Change in population affected, 2000-2100 | Percentage of population in 2100 |
|---|---|---|---|---|---|
| Philippines | 38,400 | 16,000 | 41.7 | 5,357 | 14.0 |
| Madagascar | 763 | 129 | 16.9 | 84 | 11.0 |
| Mozambique | 4,928 | 943 | 19.1 | 390 | 7.9 |
| Thailand | 7,289 | 854 | 11.7 | 576 | 7.9 |
| Myanmar | 5,745 | 2,499 | 43.5 | 427 | 7.4 |
| Colombia | 4,869 | 495 | 10.2 | 293 | 6.0 |
| Indonesia | 25,700 | 4,786 | 18.6 | 1,464 | 5.7 |
| Bangladesh | 26,800 | 2,447 | 9.1 | 1,404 | 5.2 |
| Vietnam | 12,400 | 3,997 | 32.2 | 643 | 5.2 |
| Pakistan | 28,200 | 2,252 | 8.0 | 1,461 | 5.2 |
| Venezuela | 12,200 | 441 | 3.6 | 204 | 1.7 |
| India | 55,600 | 11,200 | 20.1 | 858 | 1.5 |

Note: For projected wave height increase of 15%.

The most striking feature of our results is the extreme concentration of effects in a handful of cities. In both the 10% and 15% cases, about 25% of the increase in developing-country urban population exposed to future storm surges is in only one city,[25] Manila (3.4 million). The top 10 cities account for 67% of total exposures, and the top 25 for 79%. The other 368 coastal cities in our data set account for only 21% of the total. Of the top 25, 13 are in Southeast Asia, 4 in Sub-Saharan Africa, 6 in South Asia, and 2 in South America. We should emphasize that our results are not closely tied to the current distribution of coastal city populations. As Table 4 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 exposed to greater storm surges.

Table 5 provides context by displaying our overall results for countries with coastal cities in the top 25 group. We present countries in descending order of percentage impacts from sea-level rise. Our results assign the highest rank in both absolute and percent terms to Philippines, with projected exposure of 16 million people to storm-surge risk by 2100. This is 41.7% of the projected population in coastal cities over 100,000. The projected change in population-at-risk from 2000 to 2100 is 5.4 million, or 14% of projected population in 2100. Other countries with notably high-percentage exposures in 2100 include Myanmar (43.5%), Vietnam (32.2%), India (20.1%), Mozambique (19.1%), Indonesia (18.6%) and Madagascar (16.9%). After Philippines, the countries with highest percent changes in exposed populations are Madagascar (11%), Mozambique (7.9%), Thailand (7.9%) and Myanmar (7.4%).

## Conclusions

In this article, we have assessed the exposure of coastal cities with 2000 populations greater than 100,000 in developing countries to larger storm surges associated with global warming and a 1 m sea-level rise. After identifying future inundation zones, we have overlaid them city locations. 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 1 of 393 cities accounting for 25% of the future coastal population exposure and 10 cities for 67% 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, whereas 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 exposures of people, economies, and ecosystems to storm-surge-induced inundation, even in a small number of countries, provide strong evidence in support of rapid action to reduce global warming by mitigating greenhouse gas emissions.

### Authors' Notes

Authors' names are in alphabetical order. The authors are, respectively, disaster risk-management specialist, World Bank; Lead Environmental Economist, World Bank; Consultants, World Bank; and Senior Fellow, Center for Global Development.


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### Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The views expressed here are the author's and do not necessarily reflect those of the World Bank, its Executive Directors, the countries they represent or of the funding authorities of the research.


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## Notes

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, 2007).
2. For a review of scientific literature on sea-level rise, see Dasgupta and Meisner (2009).
3. 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 in the ocean and the upper atmosphere. At present, an increase in sea surface temperature is strongly evident at all latitudes and in almost all ocean areas. 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). 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, & Davis, 2005, Knutson & Tuleya, 2004).
4. As IPCC (2011) and Knutson et al. (2010) note, variation across ocean basins may lead to smaller effects in some areas. Recent modeling exercises also suggest that tropical cyclone frequency may decline overall, with uncertain net effects in different basins.
5. 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 United Nations International Strategy for Disaster Reduction Secretariat (UNISDR, 2009).
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 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 (Emanuel et al., 2008).
7. In our analysis, using geographic information system software, all pixels with less than 10 m elevation near coastlines have been delineated as low-elevation coastal zones following McGranahan et al. (2007). Geographic overlays of the World Cities database (http://www.econ.brown.edu/faculty/henderson/worldcities.html, accessed February 2011) with the low-elevation coastal zones identified 577 coastal cities.
8. According to World Bank classification.
9. Our SRTM data source is described on Page 7.
10. Our assumed 10% intensification reflects an upper-bound estimate by Knutson et al. (2010), who cite evidence suggesting overall tropical storm intensity increases of 2% to 11% by 2100. We have extended the analysis to a 15% intensification to control for the possibility of greater risk.
11. Uplift of land counters sea-level rise to some extent and subsidence intensifies it (Nicholls, Brown, & Hanson, 2010).

12. Except in cases of known internal drainage.
13. The SRTM data are subject to measurement uncertainty whose overall implications for the accuracy of our analysis cannot be assessed. For further discussion and suggestive findings, see Gorokhovich and Voustianiouk (2006).
14. Hansen et al. (2011) assumed a SLR of 0.5 m. The digital elevation (90 m SRTM) data we use in our analysis give altitude in 1-meter increments, preventing us from submeter SLR modeling. An estimate of 1 m SLR by 2100 adopted in this analysis may be conservative, in light of the recent evidence that multi-meter sea-level rise is possible in this century.
15. Deltas are at an elevation related to present sea level, by definition; and many of them are subsiding due to both natural and anthropogenic causes (Ericson, Vörösmarty, Dingman, Ward, & Meybeck., 2006; Syvitski et al., 2009). In the absence of location-specific data, 0.5 m anthropogenic subsidence by 2100 for deltas was adopted from Hanson et al. (2011). See also Mazzotti, Lambert, Van der Kooij, & Mainville, (2009).
16. In the absence of a scientific consensus on where tropical storms will or will not intensify, and by how much; we follow Hanson et al. (2011) and Nicholls et al. (2010), with a baseline assumption of a 10% increase in storm surges/extreme water levels for the 100-year event. This assumption of 10% increment is conservative, as a review of the regional studies of storm surges reveals predictions of storm-surge height in 100-year events that are generally above 10%. For example, Karim and Mimura (2008) showed that with a 1 m SLR and an increase of two degrees in ocean surface temperature, the storm surge in Bangladesh would increase from 7.6 m to 8.6 m (13%). For the Cairnes region, an analysis by McInnes, Macadam, Hubbert, Abbs, and Bathols (2005) of 1,000 randomly selected cyclones with current and future intensities shows that the increased intensity leads to an increase in the height of the 1-in-100 year event from 2.6 m to 2.9 m (12%). Hardy, Mason, and Astorquia (2004) found similar increases for Cairns and other coastal locations. In light of this evidence, we supplement our 10% baseline assumption with another scenario that assumes a 15% increase.
17. We recognize that our procedure involves an approximation that overstates actual exposure to some degree. Within cells identified as part of surge zones, local terrain variations will produce points of relative elevation that are likely to be favored for occupation by residents who are aware of storm-surge risk.
18. Our processing uses 5° × 5° tiles, using aml (ArcInfo Macro Language) for automation.
19. http://www.econ.brown.edu/faculty/henderson/worldcities.html (accessed February 2011).
20. Center for International Earth Science Information Network—GRUMP (v1) data set (http://sedac.ciesin.org/gpw/) (accessed February 2011).
21. The delineated surge zones and coastal zones are at a resolution of 3 arc seconds (approximately 90 m). The resolution of indicator data sets 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 data set. In this case, the surge zone is allocated to the appropriate proportion of the indicator cell value.

22. As previously noted, our results might well be affected by knowledge of existing or planned protective measures. Unfortunately, comprehensive information on such measures is not available.
23. For port cities vulnerable to storm surges, see Hanson et al. (2011).
24. 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.
25. 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 1 m 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 with a 10% increase in wave height 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.

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## Bios

**Henrike Brecht** is a disaster risk-management specialist in the East Asia and Pacific Region at the World Bank. She leads the World Bank disaster risk management agenda in a number of Southeast Asian countries and has conducted in-depth research in the areas of disaster risk assessments and climate change adaptation, often using geospatial methods.

**Susmita Dasgupta** is Lead environmental economist in the World Bank's Development Research Group. Dasgupta is a specialist in the empirical research in environmental economics

and has done extensive research on pollution control, poverty/environment nexus, and climate change. She has published numerous articles on issues related to development and environment.

**Benoit Laplante** has 20 years of experience and published numerous articles in the field of environmental policies, environmental economics, environmental financing, and in the conduct of economic valuation of environmental impacts of development projects.

**Siobhan Murray** is a GIS analyst in the World Bank's Development Research Group. She has a broad background in GIS and spatial analysis and is currently working with the Living Standards Measurement Surveys (LSMS) group on collection and use of GPS data in households surveys on agriculture.

**David Wheeler** is a senior fellow at the Center for Global Development, where he works on issues related to climate change, natural resource conservation, African infrastructure development, sustainable development indicators, and the allocation of development aid. He has published extensively on issues related to environment and development, with a particular focus on climate change.