‘Read Me’
Intensification of Storm Surges & SLR-Impacts: Data

An increase in sea surface temperature is strongly evident at all latitudes and in all oceans. The scientific evidence to date indicates that increased sea surface temperature will intensify cyclone activity and heighten storm surges. These surges will, in turn, create more damaging flood conditions in coastal zones and adjoining low-lying areas. The destructive impact will generally be greater when storm surges are accompanied by strong winds and large onshore waves. In this research, we have considered the potential impact of a large (1-in-100-year) storm surge by contemporary standards, and then compared it with its 10% intensification which is expected to occur in this century. In modeling the future climate, we took account of changes in sea level rise, geological uplift and subsidence along the world’s coastlines. Geographic Information System (GIS) software has been used to overlay the best available, spatially-disaggregated global data on critical impact elements (Area, population, economic activity (GDP), agricultural land, urban areas, and wetlands), with the inundation zones projected for 84 coastal developing countries.

Country-level impacts have been summarized in the Excel Workbook “Storm Surge-Impacts”.

- **The Excel Workbook is divided into Worksheets to match the major critical impact elements: area, population, GDP, agriculture, urban extent, and wetlands.**
- **Impacts/ exposure of current storm surge are presented in Column F**.
- **Increments in impacts are presented in Columns G-K**.

Methodology

Our analysis involved a multi-step procedure. First, we employed a base hydrologically-conditioned elevation data set to identify inundation zones and subjected them to alternative storm-surge (wave height) scenarios. Second, we constructed a country surface for each vulnerability indicator (population, GDP, urban extent, agricultural extent,[1] wetlands). Third, we overlaid these indicator surfaces with the inundation zone layer. Then we determined the spatial exposure of each vulnerability indicator under storm-surge conditions. More detailed descriptions of these steps are as follows.

(i) For elevation, we used a recently-released hydrologically conditioned version of SRTM data, part of the HydroSHEDS dataset. We have downloaded all 5ºx5º coastal tiles of 90m SRTM data from http://gisdata.usgs.net/Website/HydroSHEDS/viewer.php. In this case, conditioning of 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 followed the method outlined by Nicholls (2008) where storm surges are calculated as follows:

Current storm surge = S100

[1] Note that the Globcover database for agriculture covers 3 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 impacted agricultural extent, in this paper we have retained solely the agricultural land identified as rainfed/irrigated/post-flooding cropland (the first indicator above). As a result, our calculations under-estimate the extent of the impacts on agricultural extent.

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)[2]
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 cyclone/hurricane.

We calculated surges using data associated with the coastlines.

We extracted vector coastline masks from SRTM version 2, and downloaded coastline information from the DIVA GIS database. We used 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/yr from Peltier (2000), including a measure of natural subsidence (2 mm/yr) for deltas.

(iii) We compared 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.

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 used hydrological drainage basins. We applied 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 have used an intermediate value (0.3 m per 1 km distance from the coastline) to estimate the wave height for each inland cell.

We delineated 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 delineated 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.

(v) *Calculating exposure indicators*: We overlaid our delineated inundation zones with our indicators for land area, GDP, population, urban extent, agriculture extent, wetlands and location of cities with more than 100,000 inhabitants in 2000).[3] We have collected exposure surface data from various public sources. Unless otherwise indicated, latitude and longitude are specified in

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

[3] 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.

decimal degrees. Our horizontal datum is the World Geodetic System 1984 (WGS 1984). For area calculation, we created 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 calculated total exposure by summing over exposed units in inundation zones. We measured 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 adjusted 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.

Original data sources for assessments of impacts:

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

Limitations of the research:

1. The relative likelihoods of alternative storm surge scenarios have not been assessed in this research. Following Nicholls et al (2007), a homogeneous future increase of 10% in extreme water levels during tropical storms is assumed. 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.
2. Among the 84 developing countries included in this analysis, our estimation is restricted to coastal segments where historical storm surges have been documented.
3. 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.
4. Lack of spatially disaggregated secondary information on indicators prevented us from including small islands in this analysis.
5. The impacts of intensification of storm surges and SLR have been assessed using existing population, socio-economic conditions and patterns of land use, rather than attempting to predict their future states. Human activity is generally increasing more rapidly in coastal areas and thus the impacts of storm surges will be more pronounced in these areas. This effect is countered by adaptation measures (e.g., sea dikes), which we also do not attempt to estimate in this exercise. Adaptation measures from the purely technological (e.g., coastal embankments), to coastal-zone management (e.g., land-use planning, regulations, relocation) are often context, location and community-specific. Thus in our analysis, we refrain from generalizing any adaptive measures across our sub-set of developing countries.

This research was carried out by the World Bank in 2008. Financial support for this research was provided by the Research Department of the World Bank, and the Economics of Adaptation to Climate Change study administered by the Environment Department of the World Bank. Funding for the Economics of Adaptation to Climate Change study has been provided by the governments of the United Kingdom, the Netherlands and Switzerland.

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