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The impact of sea level rise on developing countries: a comparative analysis

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Abstract Sea-level rise (SLR) due to climate change is a serious global threat: The scientific evidence is now overwhelming. Continued growth of greenhouse gas emissions and associated global warming could well promote SLR of 1 m in this century, and unexpectedly rapid breakup of the Greenland and West Antarctic ice sheets might produce a 3–5 m SLR. In this paper, we assess the consequences of continued SLR for 84 coastal developing countries. Geographic Information System (GIS) software has been used to overlay the best available, spatially disaggregated global data on critical impact elements (land, population, agriculture, urban extent, wetlands, and GDP), with the inundation zones projected for 1–5 m SLR. Our results reveal that tens of millions of people in the developing world are likely to be displaced by SLR within this century; and accompanying economic and ecological damage will be severe for many. At the country level results are extremely skewed, with severe impacts limited to a relatively small number of countries.

1 Introduction

Sea-level rise (SLR) due to climate change is a serious threat to countries with heavy concentrations of population and economic activity in coastal regions. The rate of

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global sea level rise was faster over 1993 to 2003, about 3.1 [2.4 to 3.8] mm per year, as compared to the average rate of 1.8 [1.3 to 2.3] mm per year over 1961 to 2003 (IPCC 2007). The recent IPCC AR4 report predicted increased SLR between 0.18 m and 0.59 m across various emission scenarios over the next 100 years. However, this range has been criticized by many experts as being too conservative and not adequately reflecting the uncertainty (Krabill et al. 2004; Overpeck et al. 2006; Rahmsdorf 2007).

The three primary contributing factors to SLR often cited are: (1) ocean thermal expansion; (2) glacial melt from Greenland and Antarctica (plus a smaller contribution from other ice sheets); and (3) the change in terrestrial storage. Until recently, ocean thermal expansion was expected to be the dominating factor behind the rise in sea level. However, new data on rates of deglaciation in Greenland and Antarctica suggest greater significance for glacial melt, especially due to the uncertainty surrounding the dynamics of outlet glaciers (Hansen et al. 2005; Hanna et al. 2005; Howat et al. 2007; Krabill et al. 2004; Meier et al. 2007; Rignot and Kanagaratnam 2006; Stroeve et al. 2007; Velicogna and Wahr 2006). Although there is continued evidence of ice sheet growth in the Eastern regions of Antarctica (Davis et al. 2005), when coupled with the measured losses in the West, and including Greenland, the evidence appears to point in the direction of increased SLR. The implications of these findings for sea-level rise could be dramatic: The Greenland and Antarctic ice sheets contain enough water to raise the sea level by almost 70 m (Hansen et al. 2005), so even small changes in their volume would have a significant effect.[1]

Paleoclimatic information also indicates that the warmth of the last half-century is unusual in at-least the past 1,300 years. The last time the Polar Regions were significantly warmer than at present for an extended period (about 125,000 years ago), reductions in polar ice volume led to 4–6 m of sea level rise (IPCC 2007). As new research of the impacts of warming come in, we will be able to have more confidence in the ranges of impact, but current evidence leads to an alarming possibility that a threshold triggering many meters of sea level rise could be crossed well before the end of this century (Hansen 2006; Overpeck et al. 2006).

In this research, we have assessed the impact of multiple SLR scenarios, ranging from 1 to 5 m, for 84 coastal developing countries in 5 regions.[2] We have used 6 indicators: land, population, gross domestic product (GDP), urban area, agricultural land, and wetlands. Mendelsohn et al. (2006) provide complementary evidence, by examining the market impacts of climate change on rich and poor countries for a number of different climate scenarios. However, their work does not assess the impact of SLR on multiple physical and economic indicators. In this regard and to our knowledge, this is the first such exercise.[3]

[1] If the Greenland ice sheet were to melt completely, it would raise average sea level by approximately 7 meters (Church et al. 2001).

[2] East Asia & Pacific, Middle East & North Africa, Latin America & Caribbean, South Asia, Sub Saharan Africa

[3] A number of studies have provided estimates of the potential impacts for specific developed countries (e.g. France, the Netherlands, Poland, Singapore and the United States); developing countries (e.g. Bangladesh, Benin, China, Nigeria, and Senegal); or specific areas of individual countries (e.g. deltas of the Nile and Bengal; Rhine Delta, Thames Estuary and the Rhone Delta).

Table 1 Summary of data sources

Dimension	Dataset name	Unit	Resolution	Source(s)
Coastline and country boundary	WVS		1:250,000	NOAA/NASA
Elevation	SRTM 90 m DEM V2	km^2	90 m	CIAT
Population	GPW-3	Population counts	1 km	CIESIN
Economic activity	GDP2000	Million US dollars	5 km	World Bank, based on Sachs et al. (2001)
Urban areas	GRUMP V1	km^2	1 km	CIESIN
Agricultural land	GAE-2	km^2	1 km	IFPRI
Wetlands	GLWD-3	km^2	1 km	CESR, Lehner and Döll (2004)

At the outset, we acknowledge several important limitations in this analysis. First, we do not assess the likelihood of alternative SLR scenarios. We take each scenario as given, and assess the *exposure* impact using our 6 indicators for each of the 84 developing countries and 5 regions. Second, the digital elevation (90 m DEM V2) data we use in our analysis gives altitude in 1-m increments, preventing us from sub-meter SLR modeling.[4] Third, the lack of spatially disaggregated secondary information on indicators prevented us from including small islands in our analysis. Fourth, we assess the impacts of SLR 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 SLR will be more pronounced in these areas. This effect is countered by adaptation measures, which we also do not attempt to estimate in this exercise. Adaptation measures from the purely technological (e.g., sea defenses), to managerial (e.g., altering land-use planning, relocation), to policy (e.g., planning regulations) 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. Fifth, our study should be considered conservative since we do not consider any storm surge augmentation. Even a small increase in sea level can significantly magnify the impact of storm surges, which occur regularly and with devastating consequences in some coastal areas.

2 Data sources

We have employed geographic information system (GIS) software to overlay the critical impact elements (land, population, agriculture, urban extent, wetlands, and GDP) with the inundation zones projected for 1–5 m. SLR. We have used the best available, spatially disaggregated data sets from various public sources, including the Center for Environmental Systems Research (CESR), the Center for International

[4]One can interpolate the elevation data we have used for sub-meter SLR modeling, but in that case, precision of the estimates would be difficult to justify. The potential use of LIDAR survey (laser-based elevation measurement from low-flying aircraft) was beyond scope of our analysis.

Earth Science Information Network (CIESIN), the International Centre for Tropical Agriculture (CIAT), the International Food Policy Research Institute (IFPRI), the National Aeronautics and Space Administration (NASA), the National Oceanographic and Atmospheric Administration (NOAA), and the World Bank. Table 1 summarizes the data sources for assessments of inundation zones and impacts.

3 Methodology

The procedure used in this analysis followed several steps. The first was to construct a base elevation data set for the identification of inundation zones and to subject this layer to the alternative SLR scenarios. The second major step was to construct a country indicator surface for each of the elements at risk (population, GDP, urban extent, agricultural extent and wetlands) and to then overlay these with the inundation zone layer. The analysis then determined the area (or population, etc) that would be exposed to increased SLR. The details of the procedure are outlined below.

(i) *Preparing country boundaries and coastlines*: Country coastlines were extracted from the World Vector Shoreline, a standard National Geospatial Intelligence Agency (formerly Defense Mapping Agency) product at a nominal scale of 1:250,000. Countries were identified for WVS coastlines and used as a mask for calculating country totals for the selected exposure indicators.

(ii) *Building coastal terrain models (DTM)*: Coastal terrain models were derived from the CIAT SRTM 90 m digital elevation model (DEM) data (Version 2), released in 2005.[5] Zipped data files covering approximately 500 by 500 km (5 geographic degrees latitude and longitude) were downloaded from the CIAT website, converted into an ArcGIS data format, and merged to conform to country boundaries in the ArcGIS environment.

(iii) *Identifying inundation zones*: Inundation zones were derived from the DTM by setting the value to 1 for each of the SLR scenarios examined in this study. Areas in the DTM that were not connected to coastlines, such as inland wetlands and lakes, were masked out manually.

(iv) *Calculating exposure indicators*: Estimates for each indicator were calculated by overlaying the inundation zone with the appropriate exposure surface dataset (land area, GDP, population, urban extent, agriculture extent, and wetland). Exposure surface data were collected from various public sources. Unless otherwise indicated, latitude and longitude are specified in decimal degrees. The horizontal datum used is the World Geodetic System 1984 (WGS 1984). For area calculation, all units are projected to World Equal Area.

For the exposure surfaces, two GIS models were built for calculating the exposed value. Since the units for GDP and population are in millions of US dollars and number of people, respectively, the exposure was calculated by multiplying the exposure surface with the inundation zone and then summing to a country total. Exposure indicators, such as land surface, urban extent, agriculture extent and wetlands were measured in square kilometers.

[5]Shuttle Radar Topography Mission 90 m global digital elevation model (http://srtm.usgs.gov/).

(v) *Adjusting absolute exposure indicators*: For exposure indicators such as land area, population and GDP, which have measured country totals available, the exposed value is adjusted to reflect its real value by using the following formula:

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

where

V_{adj}	Exposed value adjusted;
V_{cal}	Exposed value calculated from exposure grid surfaces;
CT_{mea}	Country total obtained based on statistics;
CT_{cal}	Country total calculated from exposure grid surface.

(vi) *Conducting data quality assurance and control*: Quality control was conducted to adjust for errors caused by overlaying grid surfaces of different resolutions, such as the 90-m resolution inundation zone with 1-km or 5-km exposure grid surfaces. The following procedure was employed:

1) Calculate the country total from the grid surface using the country boundary;
2) Calculate the aspect exposure that is under 5-m SLR;
3) Calculate the aspect exposure that is over 5-m SLR;
4) Compare the country total with the sum of both aspect exposures. If the difference is less that 5%, the calculated aspect exposure was considered within the error tolerance. If not, the exposure calculation was reviewed and estimates revised until the 5% difference threshold was reached.

4 Results

Results at the global level for the 84 developing countries included in this analysis, as summarized in Table 2, indicate that approximately 0.3% (194,000 km^2) of the territory of the 84 developing countries would be impacted by a 1-m SLR. This would increase to 1.2% in a 5 m SLR scenario. Though this remains relatively small in percentage terms, approximately 56 million people (or 1.28% of the population) in these countries would be impacted under a 1 m SLR scenario. This would increase to 89 million people for 2 m SLR (2.03%), and 245 million people (5.57%) for 5 m SLR. The impact of SLR on GDP is slightly larger than the impact on population, because GDP per capita is generally above average for coastal populations and cities. Wetlands would experience significant impact even with a 1 m SLR. Up to 7.3% of wetlands in the 84 countries would be impacted by a 5 m SLR.

However, these impacts are not uniformly distributed across the regions and countries of the developing world. Our results, documented in Fig. 1, clearly indicate that the impacts are particularly severe in a limited number of regions. East Asia and the Middle East and North Africa (MENA) would experience the largest percentage

Table 2 Impacts of sea-level rise across indicators at the global level

	1 m	2 m	3 m	4 m	5 m
Land area (total = 63,332,530 sq. km)					
Impacted area	194,309	305,036	449,428	608,239	768,804
% of total area	0.31	0.48	0.71	0.96	1.21
Population (total = 4,414,030,000)					
Impacted population	56,344,110	89,640,441	133,049,836	183,467,312	245,904,401
% of total population	1.28	2.03	3.01	4.16	5.57
GDP (total = 16,890,948 million USD)					
Impacted GDP (USD)	219,181	357,401	541,744	789,569	1,022,349
% of total GDP	1.30	2.12	3.21	4.67	6.05
Urban areas (total = 1,434,712 sq. km)					
Impacted area	14,646	23,497	35,794	50,742	67,140
% of total area	1.02	1.64	2.49	3.54	4.68
Agricultural land (total = 17,975,807 sq. km)					
Impacted area	70,671	124,247	196,834	285,172	377,930
% of total area	0.39	0.69	1.09	1.59	2.10
Wetlands area (total = 4,744,149 sq. km)					
Impacted area	88,224	140,355	205,697	283,009	347,400
% of total area	1.86	2.96	4.34	5.97	7.32

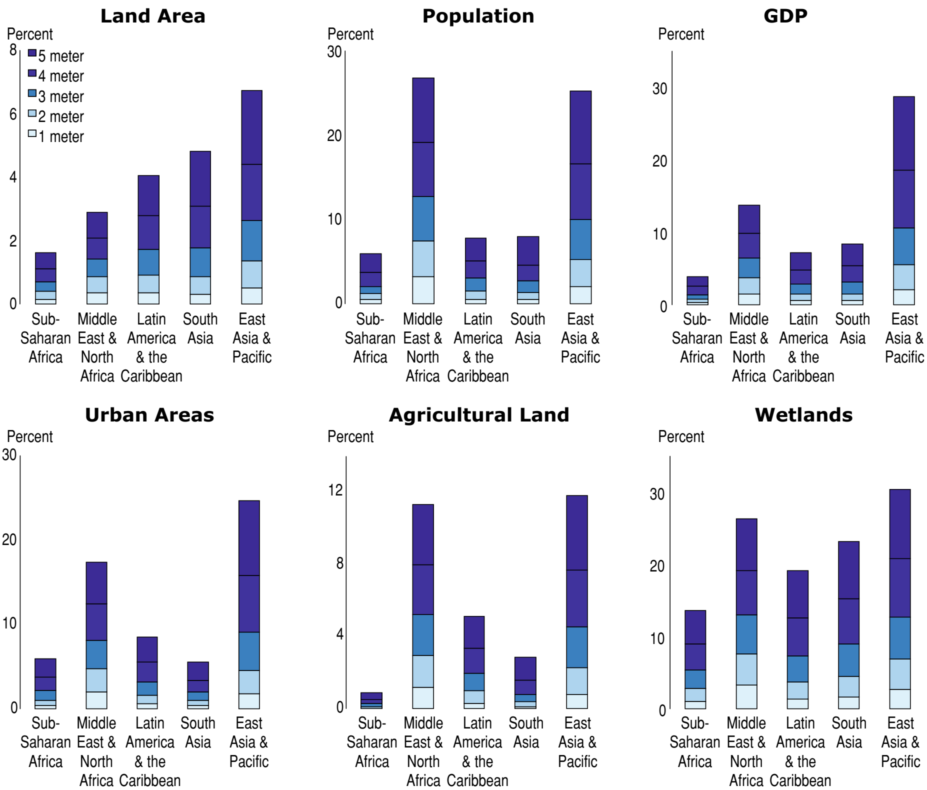

Fig. 1 Regional impacts of sea-level rise for each indicator

Table 3 Top 10 most impacted countries with a 1-m sea-level rise (percentage impact in parenthesis)

Rank	Land area	Population	GDP	Urban areas	Agricultural land	Wetlands
1	The Bahamas (11.57)	Vietnam (10.79)	Vietnam (10.21)	Vietnam (10.74)	A.R. Egypt (13.09)	Vietnam (28.67)
2	Vietnam (5.17)	A.R. Egypt (9.28)	Mauritania (9.35)	Guyana (10.02)	Vietnam (7.14)	Jamaica (28.16)
3	Qatar (2.70)	Mauritania (7.95)	A.R. Egypt (6.44)	French Guiana (Fr) (7.76)	Suriname (5.60)	Belize (27.76)
4	Belize (1.90)	Suriname (7.00)	Suriname (6.35)	Mauritania (7.50)	The Bahamas (4.49)	Qatar (21.75)
5	Puerto Rico (1.64)	Guyana (6.30)	Benin (5.64)	A.R. Egypt (5.52)	Argentina (3.19)	The Bahamas (17.75)
6	Cuba (1.59)	French Guiana (Fr) (5.42)	The Bahamas (4.74)	Libya (5.39)	Jamaica (2.82)	Libya (15.83)
7	Taiwan, China (1.59)	Tunisia (4.89)	Guyana (4.64)	United Arab Emirates (4.80)	Mexico (1.60)	Uruguay (15.14)
8	The Gambia (1.33)	United Arab Emirates (4.59)	French Guiana (Fr) (3.02)	Tunisia (4.50)	Myanmar (1.48)	Mexico (14.85)
9	Jamaica (1.27)	The Bahamas (4.56)	Tunisia (2.93)	Suriname (4.20)	Guyana (1.16)	Benin (13.78)
10	Bangladesh (1.12)	Benin (3.93)	Ecuador (2.66)	The Bahamas (3.99)	Taiwan, China (1.05)	Taiwan, China (11.70)

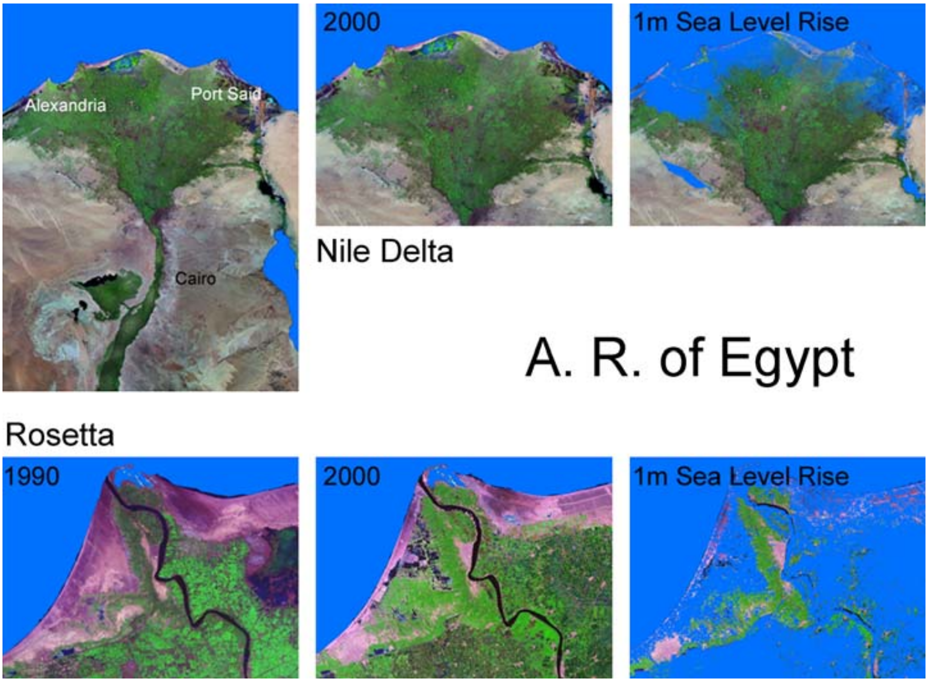

Fig. 2 Inundation zones for 1-m sea-level rise in the A.R. of Egypt and the Nile Delta

impacts from SLR.[6] Population impact is larger in MENA for a 1 m SLR, but larger in East Asia for a 5 m SLR. Similar results hold for the impacts on urban areas, agricultural land, and wetlands. Impact on GDP is much larger in East Asia than in any other region of the world, reaching 10.2% with a 5 m SLR. It is important to note that even with a 1 m SLR, affected populations will be 36.9 million in the East Asia & Pacific region, 7.9 million in the Middle East & North Africa, 6.4 million in South Asia, 2.7 million in Latin America & the Caribbean and 2.3 million in Sub Saharan Africa.

Impacts were also estimated for individual countries/territories. Table 3 summarizes our results for each indicator by presenting the top-10 impact cases (as a percentage of their national values). For this purpose, we use the 1 m SLR scenario. In terms of population impacted, the top 10 countries/territories worldwide are: Vietnam, A.R. Egypt, Mauritania, Suriname, Guyana, French Guiana (Fr), Tunisia, United Arab Emirates, The Bahamas and Benin. Around 10% of the populations of Vietnam and the A.R. of Egypt would be displaced with a 1 m SLR. For land area, The Bahamas is by far the most impacted country, with close to 12% of its

[6]The detailed list of countries included in each World Bank region is available at: http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20421402~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html.

area inundated. Ten percent of the urban areas of Vietnam and Guyana would be inundated by a 1 m SLR, and the A.R. of Egypt's agricultural land would experience the largest percentage impact: 13% would be submerged. Our estimates indicate that areas inundated by a 1 m SLR would account for 10% of GDP in Vietnam and more than 5% in Mauritania, A.R. Egypt, Suriname and Benin. Finally, nearly 28% of the wetlands in Vietnam, Jamaica and Belize would be inundated by a 1 m SLR. For all of the indicators used in this research, Vietnam ranks among the top 5 most impacted countries, with the A.R. of Egypt, Suriname and The Bahamas consistently ranking among the highest.

Finally, an illustrative case for A.R. of Egypt's Nile Delta is presented in Fig. 2. In A.R. of Egypt, an estimated 10.5% of the nation's population (approximately 67.9 million people) would be displaced by a 1 m SLR- and a disproportionately high impact would be in the Nile delta. A comparison of satellite images of the Nile delta for 2000 and the projected image for 1 m SLR reveals that 25% percent of the delta would be inundated. A closer view highlights the potentially catastrophic impact. In A.R. Egypt, 28,498 km^2 of agricultural land (13.09% of the nation's total); 24,953 km^2 of urban areas (5.52% of the nation's total); and 24,015 km^2 of wetlands (6.55% of the nation's total) would be submerged in case of 1 m SLR. As a result, an estimated 6.44% of GDP would be lost.

5 Conclusions

Even if greenhouse gas (GHG) emissions were stabilized in the near future, thermal expansion and deglaciation would continue to raise the sea level for many decades. In this research, we have assessed the consequences of continued SLR for 84 developing countries. Our results are extremely skewed, with severe impacts limited to a relatively small number of countries. For these countries (e.g., Vietnam, A.R. of Egypt, The Bahamas), however, the consequences of SLR are potentially catastrophic. For many others, including some of the largest (e.g., China), the absolute magnitudes of potential impacts are very large. At the other extreme, many developing countries experience limited impacts. Among regions, East Asia & Pacific and the Middle East & North Africa exhibit the greatest relative impacts.

In this conclusion, we would like to highlight two important implications of our findings. First, the overall magnitudes for the developing world are sobering: Within this century, tens of millions of people are likely to be displaced by SLR; and the accompanying economic and ecological damage will be severe for many. The trends appear to be clear and planning for adaptation should begin immediately. Second, international resource allocation strategies should recognize the skewed impact distribution that we have documented in this paper. Some countries will be little-affected by SLR, while others will be so heavily impacted that their national integrity may be threatened. Given the scarcity of available resources, it would seem sensible to allocate aid according to degree of threat.

To date, there is little evidence that the international community has seriously considered the implications of SLR for population location and infrastructure planning in many developing countries. The information provided in this paper could help spur vulnerable countries to develop national adaptation plans now in order to avoid future losses.

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