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Assessing the risk of cyclone-induced storm surge and sea level rise in Mozambique

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Abstract

This article considers the impact of sea level rise and storm surge on the port cities of Maputo and Beira in Mozambique. By combining a range of sea level rise scenarios for 2050 with the potential maximum storm surge level for the current 100-year storm, we analyze permanently inundated lands and temporary flood zones. In Beira, our analysis finds that a medium Intergovernmental Panel on Climate Change scenario consistent with Intergovernmental Panel on Climate Change projections through 2050 could increase the frequency of the current 100-year storm, which is associated with a storm surge of roughly 1.9 meters, to once every 40 years. The results in Maputo show similar and even more dramatic changes.../

Keywords: sea level rise, storm surge, tropical cyclone risk, flood risk, southern Africa
JEL classification: Q54, Q56, Q51

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in the return period of the 100-year storm (associated with more 1.1 meter surges), with a reduction to a 1-in-20-year event under the same scenario. In 2050, approximately 0.4 percent of the Beira study area's GDP is vulnerable to permanent inundation due to sea level rise, and 0.8 percent is vulnerable to periodic storm surge damage. The figures for Maputo are a bit higher -0.7 percent of the Maputo study area's GDP is vulnerable to permanent inundation due to sea level rise, and 1.1 percent is vulnerable to periodic storm surge damage.

Tables and figures appear at the end of the paper.

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1 Introduction

Being in the preferred path of potentially deadly tropical cyclones, the geographical location and low-lying nature of its coastal zone have made Mozambique one of the most vulnerable countries in Africa to natural disasters (INGC 2009b). This paper presents an analysis of the economic and spatial effect of sea level rise (SLR), storm surge, and cyclone damage based on data from two urban coastal sites in Mozambique.

Mozambique's coastal area is home for nearly two-thirds of its total population, with many more migrating towards the towns and villages in the coastal zone and a strong urbanizing trend (INGC 2009b). Figure 1 illustrates the confluence of population density and low-lying coastal land in Beira, one of the more vulnerable coastal cities.

Historically, Mozambique has been hit by 13 documented intense tropical cyclones killing approximately 700 people and affecting nearly 3 million people during the period 1956-2008 (INGC 2009b). These have caused significant negative social and economic consequences mainly in the central and southern provinces of the country, such as Zambezia, Manica, Sofala, Maputo, Gaza, and Inhambane (INGC 2009b). Table 1 presents a list of historic (1984-2008) cyclone events that have made landfall along the coast of Mozambique. Although cyclones due to tropical depressions originating from the Indian Ocean regularly affect the coastal regions of the country, the impacts occasionally extend to interior regions of the country as well. Figure 2 shows the extent of the cyclones and zones that are often affected.

During the rainy season of 2000 devastating floods resulted from massive amounts of precipitation coupled with tropical cyclones, affecting approximately 4.5 million people and destroying vast tracts of agricultural land and other infrastructure throughout the central part of the country and along its southern coastline (INGC 2009a). At the time, this was reported as the worst event in the country in nearly 50 years (Africa Recovery 2000). Earlier, in 1994, tropical cyclones had also affected about 2 million people along the coast in the central region of the country (INGC 2009a). Records and historic trends in the period 1950-2008 show floods to have occurred on average, every 1.6 years in the Limpopo and Pungue rivers, 2.6 years in the Licungo and Umbeluzi rivers, 2.8 years in the Maputo river and 4.8 years in the Incomati river (INGC 2009b). Although it is difficult to associate these with climate change, extreme events like these show the high vulnerability of the country to climate variability.

Flooding and tropical cyclones pose a major threat to Mozambique. Previous studies have identified potentially vulnerable sites and attempted to quantify the impacts of climate change and SLR in Mozambique.[1]

Dasgupta et al. (2009) considered a 10 percent future intensification of storm surges compared to a 1-in-100-year historical storm surge. They examined the impacts of SLR with these intensified storm surges in developing countries, assessing impacts in terms of land area, population, agriculture, urban extent, major cities, wetlands, and local economies. They concluded that Sub-Saharan African countries will suffer considerably from these changes. The study estimated that the impacted land in Mozambique, along with that in Madagascar,

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[1] See, Nicholls and Tol (2006), Boko et al. (2007), Brown et al. (2009), and Dasgupta et al. (2009).

Nigeria, and Mauritania, account for more than half—9,600km^2—of the total increase in the region's storm surge zones. For Mozambique alone, the study estimates an incremental impact loss of 3,268 km^2 land area (over 40 percent of coastal land area) of which approximately 291 km^2 is agricultural land (about 24 percent of coastal agricultural land), 78km^2 is urban (over 55 percent of coastal urban land) and 1,318 km^2 is wetland (over 45 percent of coastal wetlands). In addition, the study estimates that over 380,000 people (51 percent of the coastal population) and US$140 million GDP (55 percent of coastal GDP) could be lost.

Moreover, extending the global vulnerability analysis of Hoozemans et al. (1993) and Nicholls and Tol, (2006) show that East Africa, including small island states and countries with extensive coastal deltas, is one of the more problematic regions and could experience severe loss of land. These initial studies demonstrate Mozambique's troubling exposure to impacts of tropical cyclones, from the high vulnerability of long stretches of coastline and the low adaptive capacity due to poverty in the country.

2 Materials and methods: modeling the impact

Global climate change may alter the intensity, frequency, and track of individual storms and cyclones. Changes in temperature may be one of the most important factors in altering storm patterns, but because cyclones are relatively rare events, differences in storm generation activity that might be realized by 2050 are difficult to quantify with current methods (Emanuel et al. 2008). Due to the scarcity of historical storm surge data in Mozambique, extrapolation of trends in past storm activity is generally not a useful approach.

SLR as a result of climate change may also have an important effect on the damage that could result from cyclones. Higher sea levels provide a higher 'launch point' for storm surges in the region. This increases both the areal extent of surge and the depth of surge in areas already vulnerable to coastal storms. In addition, future SLR, while uncertain, is more reliably forecast to 2050 than future storm activity. In general, the increase in sea level would make existing storms significantly more damaging, even for minimal changes in storm activity. This analysis focuses on the more reliably forecast marginal effect of SLR on the extent and effective return period of these already damaging storms. Using a simulated dataset of storms and surges along with three alternative forecasts for future SLR in Mozambique, we estimates effect of climate change induced SLR on surge risk from cyclones. The overall method involves four steps:

1. *Simulate storm generation activity over the 21st century*: three thousand 'seeded' events were generated. These events were used to estimate the level and track of future cyclone activity.
2. *Use wind fields as inputs to a storm surge model*: the US National Weather Service's Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model was used to estimate how wind-driven water during a cyclone event generates a storm surge over coastal land.
3. *Generate a cumulative distribution function of storm surge heights for selected locations in the SLOSH domain*: SLOSH results generated without SLR for each of the simulated events provide a 'base case' of surge heights against which future storms can be evaluated.
4. *Estimate the effect of SLR on the return-time of storms*: using the distribution of storm surges in the base case, the study estimates how SLR effectively increases the

frequency of damaging storm surges; comparing three scenarios of future SLR magnitude in 2050.

Each of these steps is described briefly in the remainder of this section.

2.1 Storm generation

Existing event set generation techniques begin with historical compilations of hurricane tracks and intensities, such as the so-called ‘best track’ data compilations maintained by forecasting operations such as the National Oceanic and Atmospheric Administration’s Tropical Prediction Center (TPC) and the US Navy’s Joint Typhoon Warning Center (JTWC). These records typically contain storm center positions every six hours together with a single intensity estimate (maximum wind speed and/or central pressure) every time period. Early risk assessments (e.g., Georgiou et al. 1983; Neumann 1987) fit standard distribution functions, such as log-normal or Weibull distributions, to the distribution of maximum intensities of all historical storms coming within a specified radius of the point of interest. Then, drawing randomly from such distributions, use standard models of the radial structure of storms together with translation speed and landfall information, to estimate the maximum wind achieved at the point of interest. A clear drawback of this extrapolation procedure is that estimates of the frequency of high intensity events are sensitive to the shape of the tail of the assumed distribution, for which there is very little supporting data.

Many wind risk assessment techniques rely directly on historical hurricane track data to estimate the frequency of storms passing close to points of interest, and must assume that the intensity evolution is independent of the particular track taken by the storm. Moreover, the relative intensity method must fail when storms move into regions of small or vanishing potential intensity, as they often do in higher latitudes, which have experienced infrequent but enormously destructive storms, though the historical record is extremely sparse.

As a step toward circumventing some of these difficulties, Emanuel et al. (2008) developed a technique for generating large numbers of synthetic hurricane tracks, along each of which we run a deterministic, coupled numerical model to simulate storm intensity. The method is based on randomly seeding a given ocean basin with weak tropical cyclone-like disturbances, and using an intensity model to determine which one of these develop to tropical storm strength or greater. A filter is applied to the track generator to select tracks coming within a specified distance of a point or region of interest (e.g., a city or county). In filtering the tracks, a record is kept of the number of discarded tracks and this is used to calculate the overall frequency of storms that pass the filter. In this work, two locations in Mozambique were selected as focal points, the city centers of port cities Maputo and Beira.

Once the tracks have been generated, a coupled hurricane intensity model is then run along each of the selected tracks to produce a history of storm maximum wind speed. This model uses monthly climatological atmospheric and upper ocean thermodynamic information, but is also affected by ambient environmental wind shear that varies randomly in time according to the procedure described above. The coupled deterministic model produces a maximum wind speed and a radius of maximum winds, but the detailed aspects of the radial storm structure are not used, owing to the coarse spatial resolution of the model. Instead, we use an idealized radial wind profile, fitted to the numerical output, to estimate maximum winds at fixed points in space away from the storm center. This overall method has been described in several published sources (see, for example, Emanuel et al. 2008).

For each point of interest, the intensity model is run several thousand times to produce desired statistics such as the wind speed exceedance probabilities for that point. Both of the synthetic track generation methods and the deterministic model are fast enough that it is practical to estimate exceedance probabilities to a comfortable level of statistical significance.

2.2 Sea, lake, and overland surge from hurricanes model

The SLOSH model is a computerized model developed by the Federal Emergency Management Agency (FEMA), United States Army Corps of Engineers (USACE), and the National Weather Service (NWS) to estimate storm surge depths resulting from historical, hypothetical, or predicted hurricanes by taking into account a storm's pressure, size, forward speed, forecast track, wind speeds, and topographical data (Jelesnianski et al. 1992).

Graphical output from the model displays color-coded storm surge heights for a particular area in feet above the model's reference level, the National Geodetic Vertical Datum (NGVD). Figure 3 illustrates one of the graphical outputs from SLOSH, showing storm surge above sea level at a simulated point in time when a storm generated by the above-described method is offshore of Beira. Wind field output from the storm generation step described above is one of the key inputs to the SLOSH model. Storm surge generation calculations are applied to a specific locale's shoreline, incorporating the unique bay and river configurations, water depths, bridges, roads, and other physical features.

The SLOSH model is generally accurate within plus or minus 20 percent. For example, if the model calculates a peak 10-foot storm surge for the event, users can expect the observed peak to range from 8 to 12 feet. The model accounts for astronomical tides, which can add significantly to the water height, by specifying an initial tide level, but does not include rainfall amounts, streamflow or wind-driven waves, relying only on wind-driven 'stillwater' flood heights.

The location of a hurricane's landfall is crucial for determining which areas will be inundated by the storm surge. This information is also available from the storm generation step of the analysis, but the synthetic nature of those results and the fact that it is a forecast, adds uncertainty to the landfall location. Where the precise landfall location is uncertain, the SLOSH model developers state that the SLOSH model is best used for defining the potential maximum surge for a location.

2.3 Sea level rise overlay and effect on storm return times

The base case, without SLR, results provide a probabilistic representation of the likelihood of storm surge height at a particular point on the coast over a future period: over the 21st century, for this work. This storm surge exceedance curve can then be modified to reflect the effects of SLR on surge height and the effect of SLR on the effective return time can be identified. The modification of the exceedance curve is done for three future SLR scenarios through 2050.

The three SLR scenarios used are low (0.156 meters), medium (0.285 meters), and high (0.378 meter). These same scenarios were used in analyses supporting the World Bank's Economics of Adaptation of Climate Change (EACC) (World Bank 2010) project and are based on the work of the IPCC (Meehl et al. 2007) and Rahmstorf (2007). The low scenario is based on the midpoint of the range of general circulation model results reported in the IPCC AR4 (Meehl et al. 2007); the medium scenario is based on Rahmstorf's (2007) modeling of the SLR implications of the A2 temperature trajectory; and the high scenario is based on Rahmstorf's 'maximum' scenario (Rahmstorf 2007).

A function for the effect of SLR on effective return time is generated through the following procedure. First, the storm surge height for a particular 'reference storm' in the base case data is identified—in the example results presented below, the no-SLR 100-year storm surge heights were chosen as the reference. Then the modified exceedance curves for the SLR scenarios are examined to determine the modified return period for that storm surge height under each of three SLR scenarios. Finally, a curve is estimated, using regression techniques, for the relationship of return period with SLR magnitude. Typically this relationship is not linear but exponential in form.

3 Results and discussion

3.1 Effects of sea level rise on storm return times

The results of this four-step process are presented below. Figures 4 and 5 illustrate the results of the storm generation step for Beira and Maputo in two forms: the tracks for the ten highest wind-speed storms at either Beira or Maputo, and the exceedance curve for wind speeds. The tracks traced in Figure 4 also indicate storm intensity, with blue being the least intense and red being the most intense. Although the storm tracks illustrated in Figure 4 might suggest comparable risks in the two locations, the data in Figure 5 provide an interesting result: wind risks in Beira are much higher than in Maputo. This difference is attributable to two factors. First, Maputo has higher latitude, so storms dissipate energy to a greater extent before they make landfall. Second, Maputo is more effectively 'shielded' by the Madagascar land-mass, which also tends to dissipate cyclone energy. As a result, the probability of intense wind events is much higher in Beira than in Maputo.

Wind risks correlate well with storm surge risks, as estimated by the SLOSH model. The exceedance curves for storm surge, with and without SLR, are shown in Figure 6. These results further support the conclusion that, while storms of high intensity may strike Maputo with significant frequency, the risks of intense storms in Beira are much greater. As noted in the figure, storm surges in Beira of over one meter are at the 90th percentile in the base case—meaning they are estimated to be a roughly 1-in-10-year event—but with the highest scenario of SLR they are at the 60th percentile, which suggests they could become a roughly 1-in-2.5-year event. In Maputo, by contrast, a one-meter storm surge is very rare in the base case, and becomes a 1-in-10-year event only along the highest SLR scenario.

Finally, Figure 7 provides the estimates of the changes in effective return time for the current 100-year storm surge event, as affected by the height of SLR in 2050. In Beira, the 100-year event in the base case can be expected to occur more frequently with SLR. Rather than every 100 years with no SLR, it can be expected to occur approximately every 60 years by 2050 under the Low SLR scenario; every 40 years under the Medium SLR scenario, and every 33 years under the High SLR scenario. We see similar reductions in expected return periods for storms with other base case return periods as well.

The results in Maputo show similar and even more dramatic changes in the return period of the 1-in-100-year storm, with a reduction to a 1-in-20-year event along the medium SLR scenario. As shown in Figure 6, however, the current 100-year storm surge in Maputo (about 1 meter) is much less than in Beira (where it is almost 2 meters). It is important to keep in mind that risk levels incorporate both frequency and severity of extreme events, with the former characterized in Figure 7 and the latter characterized in terms of the height of storm surge in Figure 6.

3.2 Potential economic impacts of storm surge and sea level rise

A further estimate of the potential severity of cyclone-induced storm surge is the economic damage caused by flooding. Ideally, an assessment of the economic damages associated with storm surge and SLR would rely on land value data to calculate the value of areas at risk. Because detailed land value data does not exist for Beira and Maputo, we use GDP. Economists often interpret land value as the present discounted value of future returns to the land—as such it represents a stock valued as the sum of future flows. GDP, which is spatially attributed to land, is a fundamentally different concept, as GDP is itself a flow. Using spatially attributed GDP rather than land value requires some care.

Following the methodology employed in the Dynamic and Interactive Vulnerability Assessment (DIVA) model (Vafeidis et al. 2008) we used gridded population data (2.5-minute resolution) from the Center for International Earth Science Information Network (CIESIN, FAO, and CIAT 2005) combined with estimated 2010 country level GDP data for Mozambique (CIA 2009) to calculate a proxy for site-specific economic value. For inundated lands, the land value would be permanently lost—for storm surge we calculate the annual expected GDP value lost. The implicit assumption of this methodology is that land with a greater population is of higher value. While there are good reasons to suggest this may understate values for some less populous lands (e.g., agricultural lands), and perhaps for some more populous areas as well, we believe that this is a reasonable assumption when considering damages over a relatively large area, and the approach has been used in the DIVA model for many years (Vafeidis et al. 2008).

We estimate the annual expected value of storm surge damage using the storm surge cumulative density function from SLOSH, both without SLR while taking SLR into account later. The methodology for calculating storm surge damages follows that outlined in Kirshen et al. (in press). First, the storm surge cumulative density function from SLOSH is used to develop an exceedance curve of surge heights; surge heights increase over time with SLR. If damages are assigned to each point along the storm surge exceedance curve, then it would become a damage frequency curve. The area under this curve is the annual expected value, or average, storm surge damage. We calculate GDP value lost at every point along the storm surge exceedance curve. These damage values and their corresponding exceedance probabilities are used to estimate the annual expected value of storm surge damage. Due to limitations of the elevation data used, we are only able to define areas affected at the integer level. Therefore, only minimal distinction can be made between areas impacted at various points along the exceedance curve and between areas impacted by SLR versus storm surge.

Table 2 presents the expected value of the GDP at risk from storm surge in the base case. The study area for Beira includes areas within 75 km of the city. The study area for Maputo includes areas within 50 km of the city. The smaller study area for Maputo reflects the smaller extent of the city. Without SLR, the expected value of GDP at risk of being lost in a given year due to episodic flooding is US$7.5 million in Beira and US$12 million in Maputo. These figures represent 0.8 and 0.4 percent of the total GDP within the Beira and Maputo study areas, respectively.

Table 3 presents the GDP at risk of being permanently lost due to SLR inundation by 2050 and the undiscounted expected value of GDP at risk from storm surge under the high-end SLR scenario (0.378 meters) in 2050. In the Beira study area, approximately US$3.9 million is at risk of being permanently lost due to SLR. This value represents the GDP attributable to areas with an elevation less than 0.378 meters assuming that the damage function is linear between zero and one meters. In Beira, the undiscounted expected value of the GDP at risk in 2050 due to storm surge under the high-end SLR scenario is US$7.0 million. In the Maputo study area, the estimated GDP at risk of being permanently lost due to 0.378 meter SLR by 2050 is US$18 million. The GDP at risk annually due to storm surge in 2050 with 0.378 meter SLR is US$30 million.

4 Conclusions

This analysis demonstrates a proof of concept for storm surge and SLR risk analysis for two port cities in Mozambique. The method developed for this analysis has the advantage of being able to be applied in areas where elevation and economic data are relatively sparse. This analysis allows us to consider the implications for climate risk management in areas where the potential for future damages is much greater than current damages.

In the current baseline scenario without SLR, our simulated storm generation activity and storm surge modeling showed that while storms of high intensity may strike Maputo with significant frequency, the risks of intense storms in Beira are much greater. Taking SLR into account, the frequency of these high intensity storms increases dramatically in both Beira and Maputo. Using GDP as a proxy for land value, we find that only a small portion of the study areas’ GDP is at risk from SLR and storm surge. This may be due in part to the implicit assumption that land with a greater population is of higher value. For Beira and Maputo damage to the ports caused by SLR and storm surge may actually by greater than that reflected by our analysis.

Our results have important implications for disaster risk management, which need to be addressed in further research. Structural options for adapting the area to address the risks of inundation and episodic flooding include constructing or reinforcing new and existing levees, and elevating vulnerable structures in low-lying areas subject to episodic flooding. Nonstructural approaches include planning a managed retreat from the areas which face the most severe risks, and utilization of financial mechanisms, such as crop and property insurance programs. Such programs, like all others, should be carefully analyzed for their financial and economic implications. In the case of financial mechanisms, care should be taken to ensure that insurance premiums are both actuarially fair and, if they are to be effective, reasonably affordable. These analyses need to consider the economic and policy context to a far greater degree than was possible for this paper—nonetheless, our approach could be usefully applied by local governments as an effective coastal risk screening tool using information that is already widely available, which would allow future more detailed efforts to be most appropriately focused on the most vulnerable areas.

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Table 1: Historic tropical cyclone

Date and Year	Category and name	Landfall Location	Strength	Recorded wind speed (km/h)
28 January 1984	TS – Domoina	South	TS	102
09 January 1986	TS	Central	TS	83
02 March 1988	Category 2 – Filao	Central	Category 1	121
25 November 1988	TS	North	TS	74
24 March 1994	Category 4 – Nadia	North	Category 1	139
22 January 1995	TS – Fodah	Central	TD	37
14 January 1996	Category 4 – Bonita	Central	Category 1	130
02 March 1997	Category 1 – Lisette	Central	TS	111
17 January 1998	TS	North	TD	56
22 February 2000	Category 4 – Eline	Central	Category 4	213
08 April 2000	Category 4 – Hudah	Central	Category 1	148
02 March 2003	Category 4 – Japhet	South	Category 2	167
13 November 2003	TS – Atang	North	TD	46
01 January 2004	TS – Delfina	Central	TS	93
22 February 2007	Category 4 – Favio	South	Category 3	185
08 March 2008	Category 4 – Jokwe	North	Category 3	180

Note: Categories 1-4, Tropical Storms and depressions incidents that have made landfall at different parts of the coast of Mozambique from 1984 through 2008.

Source: INGC (2009a).

Table 2: Annual GDP at risk from storm surge without sea level rise

Study area	Annual GDP at risk due to storm surge (2010 US$ million)	% of total GDP within study area
Beira	US$7.54	0.81%
Maputo	US$ 2.4	0.44%

Table 3: Annual GDP at risk from sea level rise by 2050 and storm surge in 2050

Study area	Annual GDP at risk due to SLR (2010 US$ million)	% of total GDP within study area	Annual GDP at risk due to storm surge (2010 US$ million)	Percent of total GDP within study area
Beira	US$3.9	0.4%	US$7.0	0.8%
Maputo	US$18	0.7%	US$30	1.1%

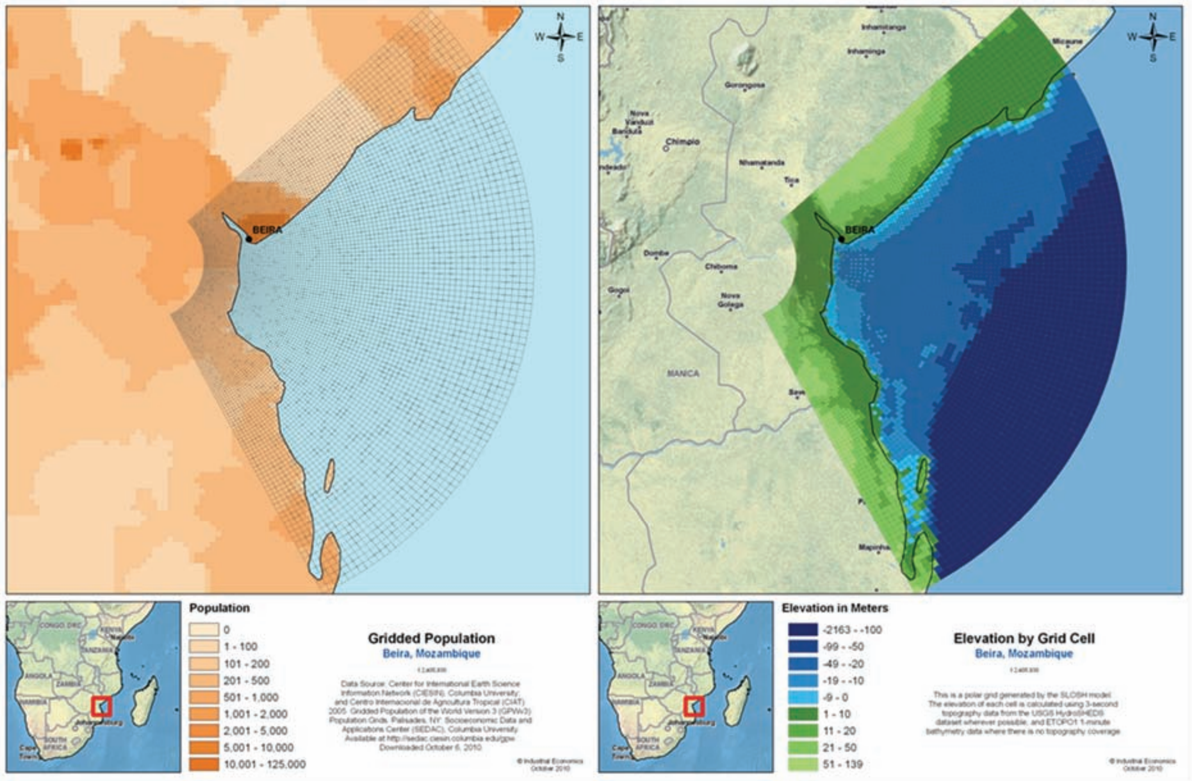


Figure 1**:** Population and elevation of Beira and Mozambique

Source: Industrial Economics.

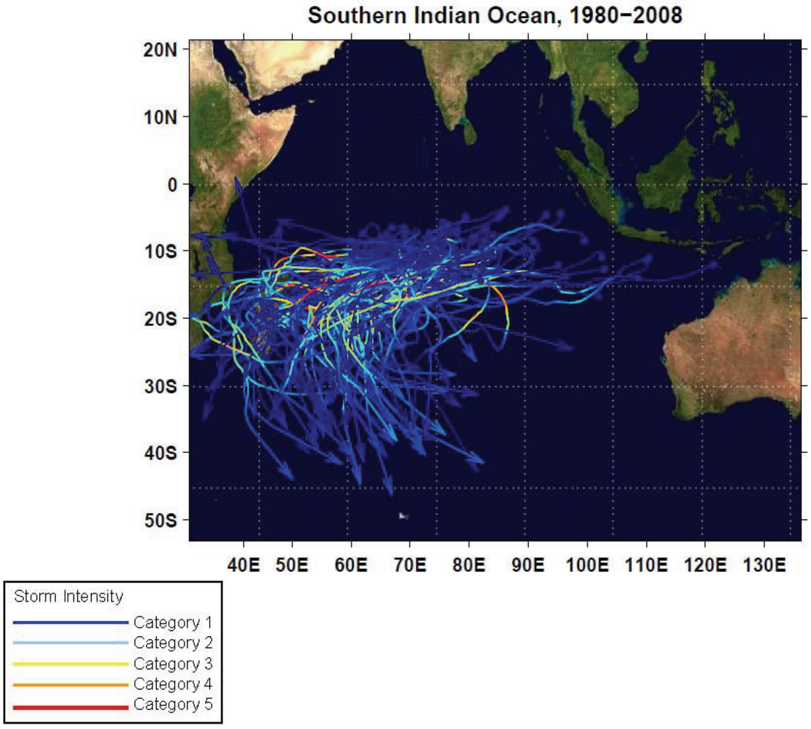


Figure 2: Historical event tracks and intensity of tropical cyclones in the South Indian Ocean from 1980 through 2008.

Note: Using the Saffir-Simpson scale.

Source: authors' analysis.

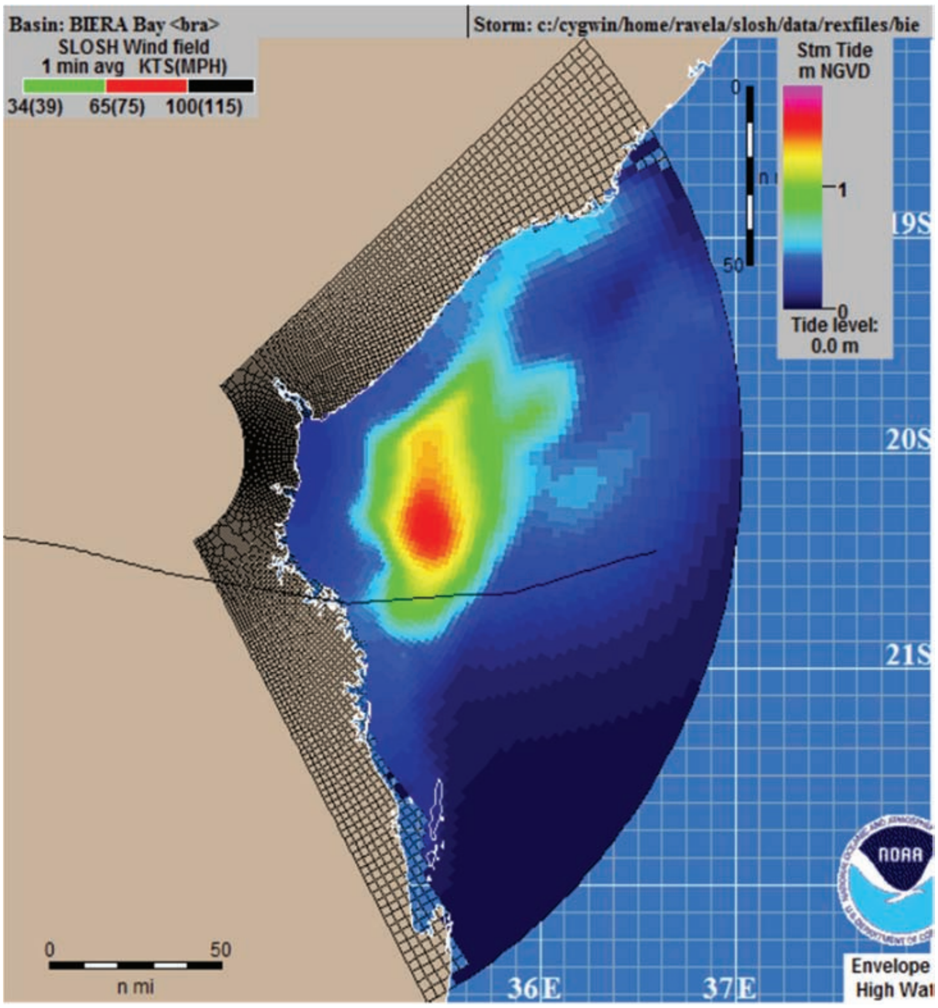
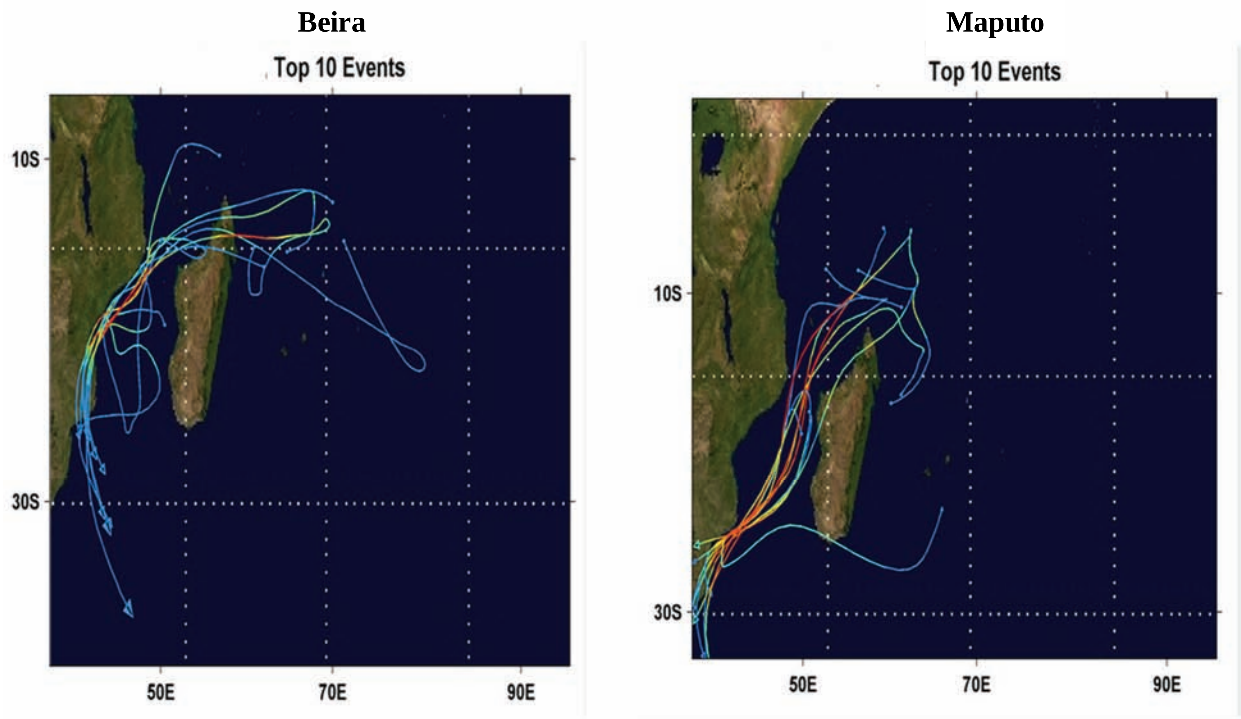


Figure 3: SLOSH model setup for Beira

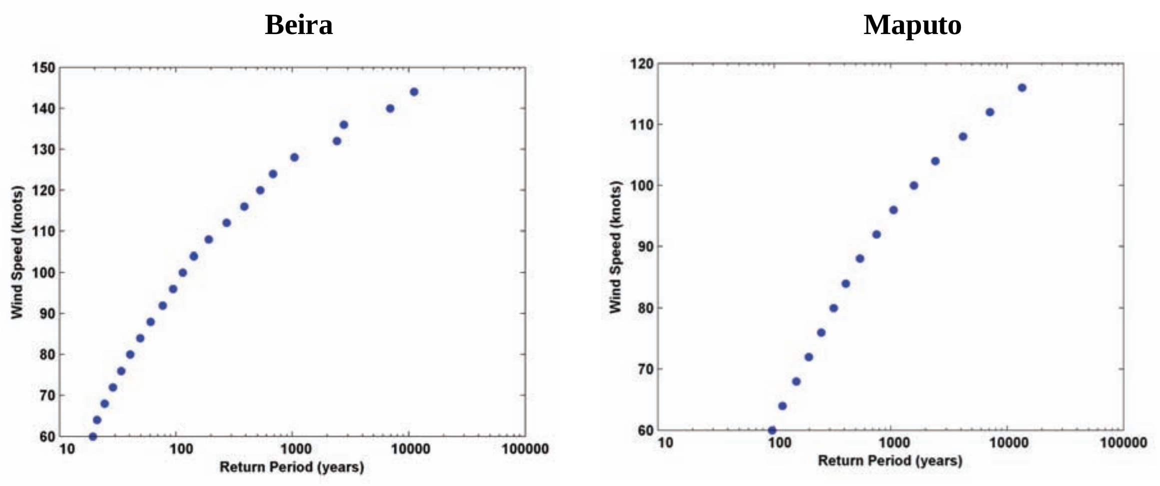
Source: NOAA.


Beira

Maputo

Figure 4: Storm tracks for Beira and Maputo.

Source: authors’ analysis.



Beira

Maputo

Figure 5: Return times for Beira and Maputo

Source: authors’ analysis.

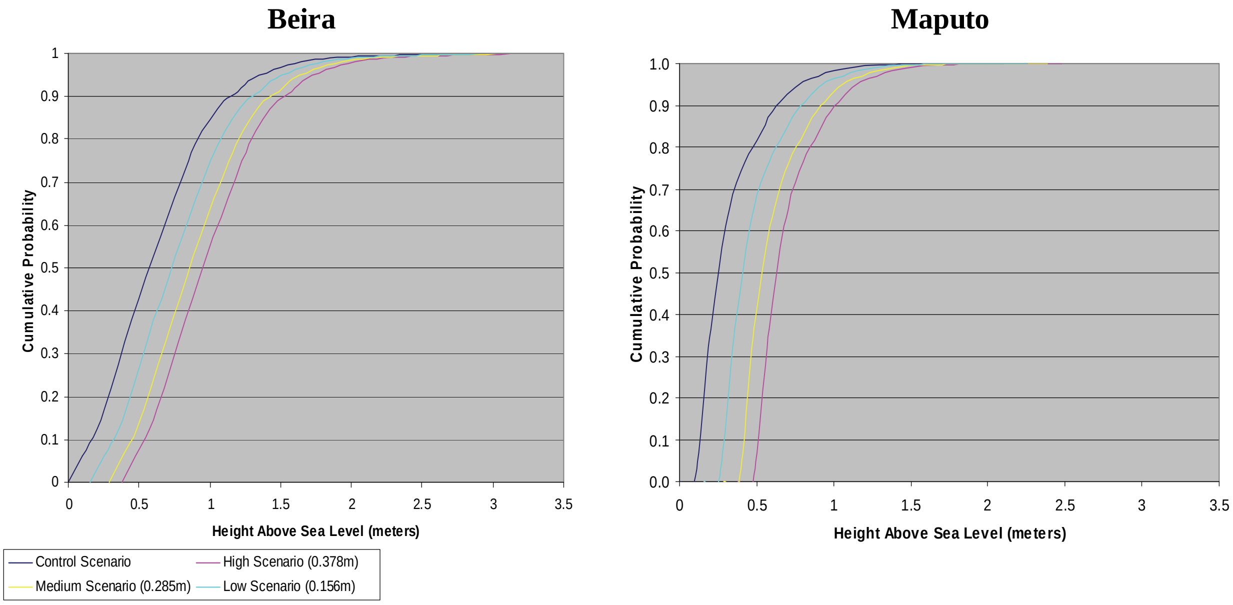


Figure 6: SLOSH-estimated storm surge exceedance curves with and without sea level rise

Source: Industrial Economics.

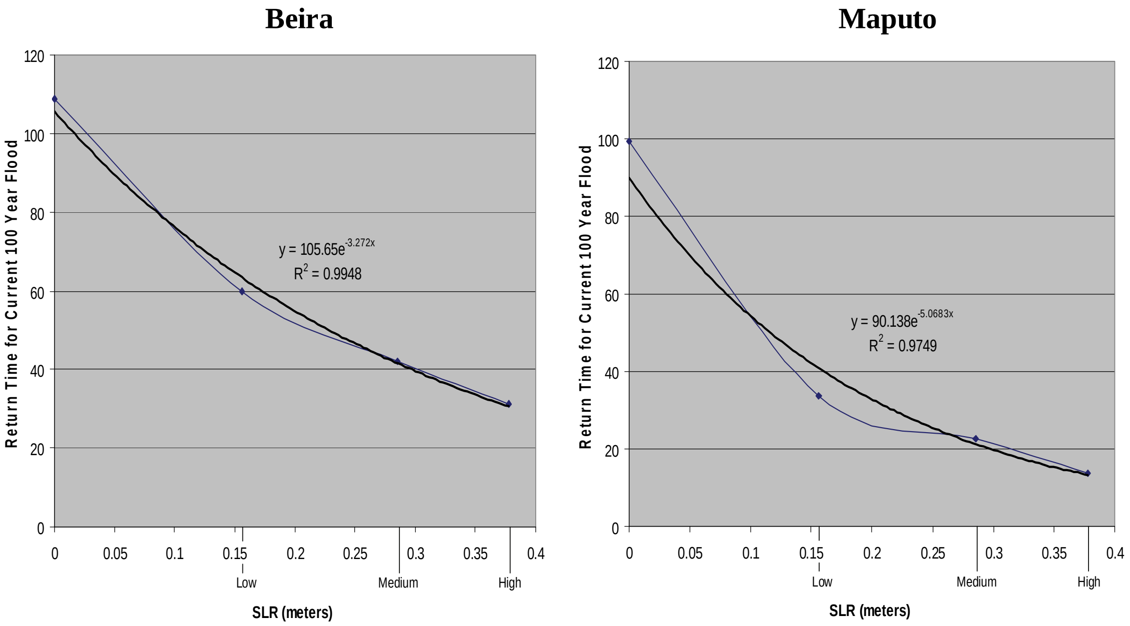


Figure 7: Estimated change in effective return time for the 100-year storm as a result of sea level rise

Source: Industrial Economics.