COASTAL RISKS, NATURE-BASED DEFENSES AND THE ECONOMICS OF ADAPTATION: AN APPLICATION IN THE GULF OF MEXICO, USA

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ABSTRACT

The need to reduce risks from coastal storms and climate change in coastal areas has given rise to efforts to make greater use of integrated ecosystem-based approaches. Assessment of the role and cost efficiency of adaptation measures is increasingly demanded. Applying the Economics of Climate Adaptation framework in the US Gulf Coast, we compare nature-based defenses, artificial defenses, and policy measures for adaptation and risk reduction and quantify their costs and benefits under a variety of economic growth and climate change scenarios. Our analyses are spatially explicit and all models, tools and information are open source. The framework includes (i) a probabilistic assessment of hazards, (ii) estimation of damages and (iii) assessment of adaptation and risk reduction measures. We perform sensitivity analyses to understand the parameters that created the most variation in risk assessment and most influenced estimates of cost effectiveness. We find that high rates of economic growth and coastal development are likely to create greater risks in the near term than climate change, due to the increase in exposed assets. Nature-based solutions such as oyster reef and marsh restoration are particularly cost effective, but their cost-effectiveness is highly dependent on where these measures are used. As decision-makers look for the most cost effective group of measures for adaptation and risk reduction, these approaches and results should be particularly useful for informing management priorities.

Keywords: Economics; Climate Adaptation; Risk; Nature based Defenses; Ecosystem Based Adaptation

1. Introduction

Coastal areas are physically and socioeconomically dynamic zones that hold important economic activities and a large part of the global population (McGranahan et al., 2007; Hinkel et al., 2013). They are also home to species and habitats that provide many benefits to society. Many of the worst impacts to coastal zones often come from difficult management choices implemented in a dynamic coastal zone of high complexity. Coastal disasters are an ever-present threat brought home most recently by cyclonessuch Katrina (2005), Sandy (2012) and Haiyan (2013). Coastal systems are increasingly vulnerable to flooding as a result of the combined influence of coastal storms, urban development and population growth, geomorphic change, and sea level rise (Woodruff et al. 2013). Worldwide, it is estimated that erosion, flooding and extreme weather events affect hundreds of millions of vulnerable people, important infrastructure and tourism, with significant losses to national economies and major impacts on livelihoods.

Coastal development and climate change are dramatically increasing risks to coastal areas (IPCC, 2014). Coastal flood risks are likely to increase over the coming decades owing to global and regional changes in the mean sea level, storm intensity, and land subsidence (Woodruff et al., 2013; Hallegatte et al., 2013; Knutson et al., 2010; Lin et al., 2012). Meanwhile, growing coastal populations means more people will be exposed to these increasing flood risks. It is estimated that at least 40 million people and US$3 trillion are located in flood-prone coastal cities today, and these numbers are expected to increase to 150 million people and $35 trillion by 2070 (Nicholls et al., 2007). In particular in the US, it has been estimated that climate change, increased socioeconomic exposure and land subsidence could cost communities along the US Gulf Coast more than USD 350 billion in cumulative economic losses over the next 20 years (Entergy, 2010).

In a world of increasing coastal risks, ecosystem degradation worsens the situation by further exposing communities and assets. Coastal and marine ecosystems are being increasingly lost worldwide. Estimates point to 50% of marshes, 35% of mangroves, 30% of coral reefs and 29% of sea grasses damaged or lost (FAO, 2007; MEA, 2005; Orth et al. 2006; UNEP, 2006; Valiela et al. 2001; Waycott et al. 2009). With their disappearance, the benefits they provide, including coastal protection,

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are also degraded and lost (Barbier et al., 2007, 2008, 2011; Halpern et al. 2008; Lotze et al. 2006; Worm et al. 2006).

There is a growing body of evidence that suggests that nature-based solutions can be effective for risk reduction (Ferrario et al. 2014; Temmerman et al., 2013; Spalding et al., 2013 and references therein). A greater appreciation of the risk reduction benefits from these habitats should help motivate local and global actions needed to maintain and restore these ecosystems and the services they provide. For instance, reefs and wetlands face growing threats yet there is opportunity to guide adaptation and hazard mitigation investments towards restoration to strengthen this first line of coastal defense.

Countries are making big investments to address risks of flooding and climate impacts (e.g. Colombia, Brazil and China). Total Fast Start Finance commitments under the UNFCCC include roughly $3 billion for climate adaptation assistance (Smith et al., 2011). In the US, FEMA spends $500 million/year to reduce flooding hazards. Cities are also mobilizing quickly. For example, cost benefit analyses in New York City include nature based approaches in the possible solutions (Aerts et al., 2014, NYC, 2013). This context creates both threats and opportunities for natural systems.

Yet in most places hazard mitigation and adaptation funds are destined for the creation of "grey infrastructure" such as seawalls, which can further degrade coastal ecosystems. However coastal ecosystems can be part of the solution for reducing the increasing risks as part of integrated strategies and hybrid portfolios (Hartig et al., 2011; Borsje et al., 2011). Governments and businesses are increasingly interested in identifying where nature-based solutions can be used cost-effectively as part of the strategy for coastal defense and as an alternative to investing solely in artificial defenses.

The need for better strategic visions for risk reduction are clear; these visions must be guided by national coastal risk assessments that identify areas most at risk and help to prioritize future investments (e.g., NAS, 2014). Cost-benefit analysis is a tool usually employed for comparing risk reduction options from an economic perspective. Similarly, risk analysis is employed for probabilistically defining damage levels and locations.

Both approaches are increasingly being used in the context of climate adaptation at local sites (e.g., Aerts et al., 2014; Broekx et al., 2010). Large scale assessments such as DIVA (Hinkel et al., 2013) also exist, but they are primarily useful for global and large regional analyses (i.e. order of 100s kms). These approaches do not include a probabilistic assessment of hazards and the range of adaptation measures is limited. On the other hand, they include dynamic interaction of climate change scenarios with socio-economic characteristics. On the other side of the spectrum, high resolution studies from the public sector (e.g. Coastal Master Plan in Lousiana: Fischbach et al., 2012, Cobell et al. 2013) or public risk models (e.g. HAZUS-Flood: Scawthorn et al 2006a,b), work at much higher resolutions (study units of the order of 100 m). Such high resolution studies are only applicable to small areas. There is a lack of available tools at a regional scale bridging the gap between large scale assessments and high resolution studies.

It is in this arena where the Economics of Climate Adaptation (ECA) approach, as an overarching framework, has been applied successfully across island states, within cities and region-wide (CCRIF, 2010; ECA, 2009 – see case studies). We used the ECA framework and modified a key ECA tool, climada, for use in the Gulf of Mexico to assess risk and cost effectiveness across hundreds of kms with basic study units covering zip codes.

This work also bridges efforts to identify where there may be aligned interests among environmental and risk reduction NGOs; reinsurance and engineering firms; and hazard mitigation agencies among others. Incorporating nature into these models is relevant for insurers, lenders and agencies who are interested in finding cost-effective solutions for risk reduction and in better pricing of risk reduction options.

2. The Economics of Climate adaptation: the methodology

The ECA framework, (ECA, 2009), developed by the Economics of Climate Adaptation Working Group, is a partnership between the Global Environment Facility, McKinsey & Company, Swiss Re, the Rockefeller Foundation, ClimateWorks Foundation, the European Commission, and Standard Chartered Bank. The approach evaluates the cost effectiveness of adaptation options, including nature-based solutions and can integrate adaptation and ecosystem management with economic development and sustainable growth. ECA is an open-source methodology that has been applied in various regions around the world (e.g. CCRIF, 2010) and provides a quantitative decision-making framework around two main points:

1. The assessment of "climate risk" from (a) the expected annual loss to the location's economy from existing climate patterns; (b) a projection of the extent to which future economic growth will put greater assets at risk; and finally, (c) an assessment of the incremental loss that could occur in the future under a range of climate change scenarios.
2. The assessment of cost effectiveness of measures for risk reduction spanning infrastructural, technological, behavioral and financial measures. The output of this cost-benefit exercise provides one key input – along with policy, capacity, and other considerations – for a country, region or city assembling a comprehensive adaptation and risk reduction strategy. Because any such strategy will need to be closely integrated with the location's broader economic development choices, many of the measures evaluated will be economic development steps.

The approach involves data collection and generation in three key areas (Figure 1):

1. Hazards – the variables defining the hazards (e.g. wind, flooding potential, etc.) should be defined probabilistically for present and future conditions, as well as their geophysical extent
2. Damages – geospatial distribution of assets in the coastal zone (residential, commercial and infrastructure assets) need to be assembled in order to estimate the expected damages from coastal impacts for present situation and under different future socioeconomic scenarios;
3. Adaptation & Risk Reduction Measures – This step involves the estimation of the costs and benefits of adaptation through a variety of coastal defenses such as seawalls, wetland restoration or home elevation. The adaptation can be materialized in either reducing (1) the hazard or (2) the damages, by different means such as: physical protection, structural modification, thoughtful planning, socioeconomic development, etc.

Each step of the process are described below. The specifics of the coastal system play a role at the estimation of the damages and the cost-benefit analysis of measures in the adaptation step. The approach is robust and flexible enough to include considerations for many risk reduction measures including natural, artificial and socio-economic (e.g., policy) measures. The reduction of risk can be done by:

1. Reducing the hazards
2. Reducing the exposure through change of courses in policy, socio-economic paths or development planning
3. Protective measures that can reduce the damage expected from the hazards
4. Informing decision making on risk management options and strategies

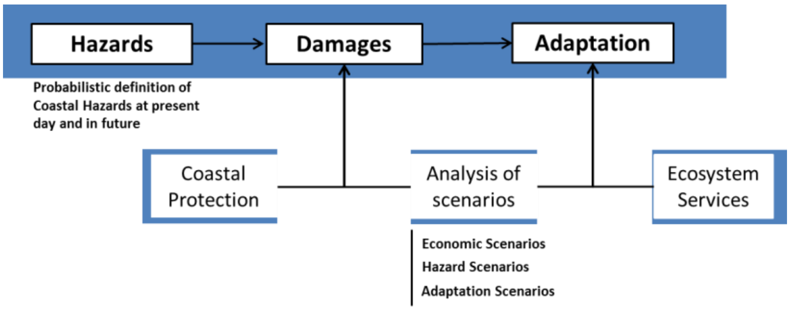

Figure 1 – Methodology of Economics of Climate Adaptation in Coastal Areas

3. Application of ECA to coastal areas: a case in the Gulf Coast of US

3.1. Defining the Hazards

Several models are used to define the different hazards:

3.1.1. Hazards from Tropical Storms

As a first step towards assessing the role and cost effectiveness of coastal habitats in reducing coastal risks, we started with Climada, an open source version of Swiss Re's private natural catastrophe loss model (available at: **https://github.com/davidnbresch/climada**) that follows the principles in ECA and provides a probabilistic assessment of risk. Prior versions of Climada only included models for assessing risks from wind and rain but not storm flooding. We incorporated a few coastal specifics into the tool such as: a wave model, 1D storm surge flooding model, other coastal auxiliary tools for tide estimation, bathymetry, topography and sea-level rise. Overall, these additions create a publicly available suite of models to examine risks from wave, rain and coastal flooding for assessing the cost effectiveness of alternative solutions.

Storm track characteristics are obtained from http://weather.unisys.com/hurricane providing data on storm characteristics from 1851 onwards. From the historical dataset, a probabilistic future set is simulated using random walks on each historical track (Figure 2). Subsequently, for each of these storm tracks, semi-empirical parametrical models define the hazard fields along the track and time as follows:

- Pressure- a Hydromet-Rankin Vortex model (1980)
- Wind- two models were implemented, for symmetric fields, Holland (1980); and for non-symmetric fields, Bretscneider (1990)
- Rainfall- symmetric rainfall field and persistence model in Tuleya et al. (2006)
- Wind waves- three different models were tested and implemented - Bretschneider (1990); Young (1988); and Shore Protection Manual (SPM, 1984)
- Storm Surge- computed from the sea level pressure effect and the wind thrust using the approximation in Dean and Dalrymple (1984)

Although there are significant simplifications behind these parametrical models, they are easy to implement and computationally efficient (e.g. Silva, et al. 2002); both requirements for the scope of a probabilistic analysis with multiple components and scenarios in a large scale analysis.

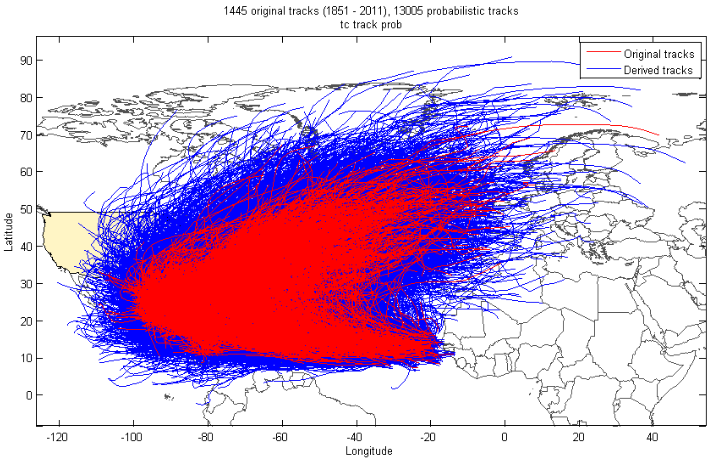

Figure 2. Tracks of historical storms (red) and simulated storm tracks using random walks (blue)

Results of these storm models were compared for different NOAA stations across the Gulf of Mexico showing statistical agreement with observations although discrepancies with the magnitude of the peak of the events should be expected due to the simplicity of the parametrical approximations. For validation of these parametrical models, we refer to the software documentation. Figure 3 represents the wind footprint for Hurricane Katrina in the model and Figure 4 shows some of the statistics associated with different return periods across the Gulf.

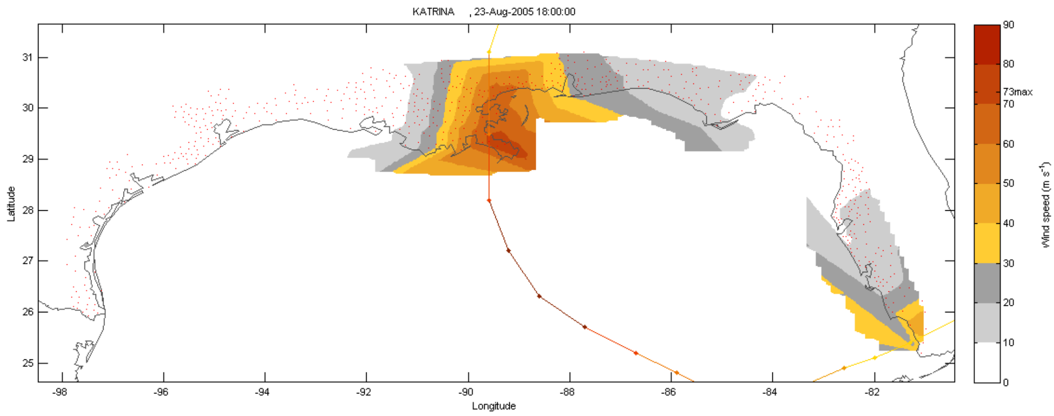

Figure 3. Wind footprints for Hurricane Katrina.

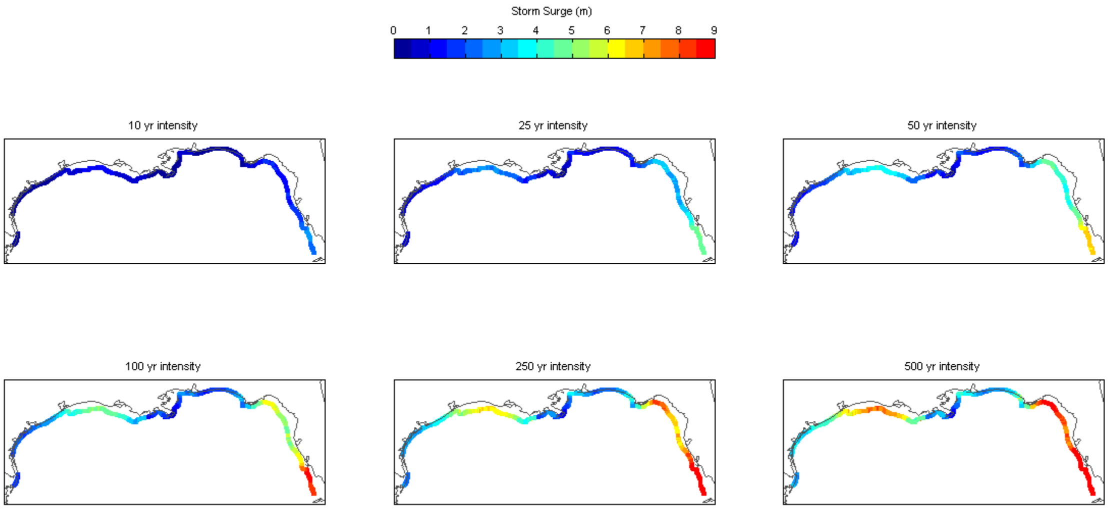

Figure 4. Statistics computed for Storm Surge along the Gulf Coast

3.1.2. Long term relative sea level rise

Historic sea-level rise (SLR) was obtained from tidal gauges (NOAA, http://tidesandcurrents.noaa.gov/) and interpolated along the Gulf Coast (see Figure 5). Subsidence was digitalized from Ivins et al (2007) showing rates comparable, or even above, historical change in the mean sea level along Lousiana’s coastline.

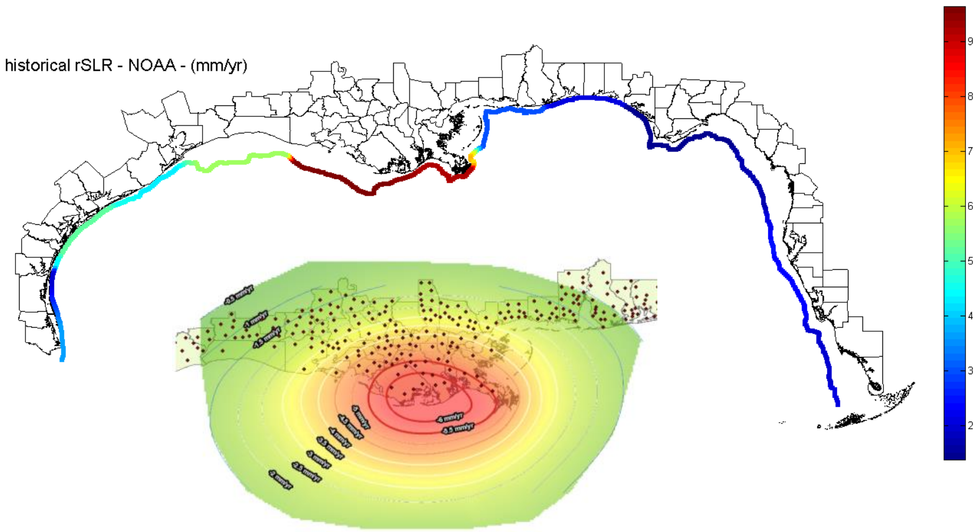

Figure 5. Historical relative Sea Level Rise trends (mm/yr) and the subsidence field digitalized from Ivins et al. (2007)

3.1.3. Future scenarios for hazards

Since we aim to compare current and future risks, we need to define timeframes and scenarios for the different factors in the analysis. For the future scenarios of hazards, two timelines were selected: 2030 and 2050. Future scenarios of climate change were developed based on a linear addition of two effects:

a) Change in storms: the probabilistic set of storms was affected by the factors identified by the Special Report on Extreme events, IPCC (2012), and each storm intensity and frequency was modified accordingly to the storm category.

b) Change in sea level: Additionally, SLR is obtained for the two timeframes and added linearly to the storms. Two different techniques were used: (i) extrapolation of long-term trends in historical records and (ii) a corresponding value for each timeline assuming a 1 m SLR scenario at the end of the century.

The final set of hazards evaluated included: (1) floods from the combined effect of SLR, subsidence, run-up from waves and storm surge; (2) wind and (3) rainfall.

3.2. Assessing Damages and Risks

To assess damages, it is necessary to obtain a good representation of the assets exposed to the hazards. Asset value was extracted from the HAZUS database at a block level, integrated by tracts and aggregated backwards into a total of 3238 centroids (Figure 6). Assets were also distributed by topographic levels across the Gulf using the national Elevation Dataset (Gesch et al., 2002; Gesch, 2007). Figure 7 shows the spatial distribution of assets in low lying areas (i.e. below 10 m of elevation). The assets were subsequently aggregated into the centroids (i.e. units of study) to calculate damages from the hazards.

Figure 6. Spatial distribution of centroids across the Gulf of Mexico

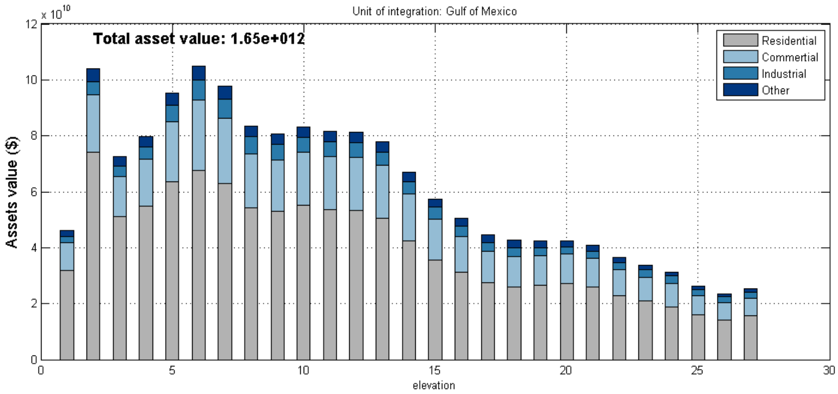

Figure 7. Distribution of asset value by elevation levels across the Gulf

Damages were calculated at each centroid using damage curves extracted from the HAZUS dataset, originally collected by the Federal Emergency Management Agency (FEMA) and the US Army Corps of Engineers. The catalog comprises over 100 damage curves for different types of buildings. They were reclassified into 10 representative types. Each curve in Figure 8 below represents the percentage of damage one would expect from flooding for different types of structures. For example, the upper curve represents mobile homes where even low water depths lead to lifting of the houses and to a high percentage of damage. For damages from winds, the default representative curve included in Climada was used as default in the absence of further information. This study does not include an assessment of damages resulting from rainfall for not having found damage curves.

The curves for damage from flooding represent structural damages (physical and content damages included) for the local water depth. Therefore, in order to use them we need to resolve the flooding process across the coastal zone, considering the topography and the physical distribution of assets. This was done by a modified bathtub approach including parameterizations to account for the large coastal landscape features and based on literature review.

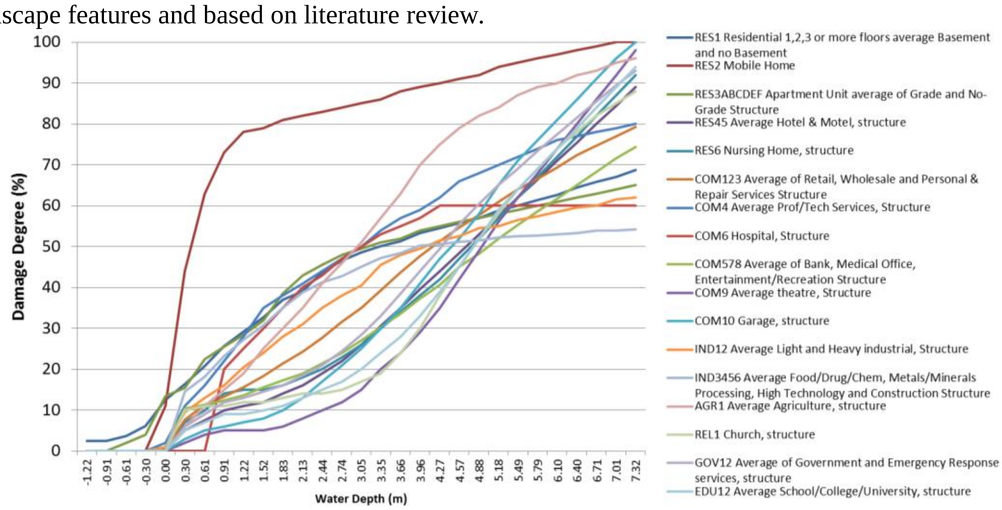

Figure 8. Damage Expected from Flooding for Various Structures

This geospatial distribution of assets only reflects the present situation in the Gulf Coast but the future can be very different across areas and depends on socioeconomic pathways. Indeed, the Gulf Coast population has increased by 109% since 1970, compared to a 52% increase in total US population (NOAA, 2011). Trying to factor this in, we needed to set up future scenarios of assets projecting socio-economic growth.

The upgrade to the two future timeframes of the asset value and number of houses considered three different scenarios: (1) past historical data on the House Price Index by state (ranging from 21.1% in Missisipi to 43.7% in Lousiana, with an average of 2.67% from 2001-2010); (2) historical evolution of economic growth, and (3) future estimates from the World Bank and PwC Economics (2013) for 2030 and 2050 (i.e. annual rates of 2.89% and 3.89%, respectively).

For the population estimates, data were extracted from the US Census at the tract level (reference at year 2000, to make the tracts coincide with the HAZUS delimitation). Population growth from 2000 to

2010 was updated using actual population growth for each county (extracted from the Intercensal Estimates of the Resident Population for Counties: April 1, 2000 to July 1, 2010). Growth rates were applied to each tract within each county. US Census bureau data on historical data and projections for the next decades were also employed to define possible increases in number of assets.

Table 2 shows the drastic effect of updating the values for the future timeframes.

	Low Economy (billions USD)	1.50%	High Economy (billions USD)	3%
Total value in 2010	$ 1,654	-	$ 1,654	-
2030 new value	$ 1,978	*120%*	$ 2,362	*142%*
New assets	$ 208	*12%*	$ 520	*22%*
Total value in 2030	**$ 2,186**	*132%*	**$ 2,882**	*174%*
2050 new value	$ 2,462	*149%*	$ 3,652	*221%*
New assets	$ 544	*33%*	$ 1,785	*108%*
Total value in 2050	**$ 3,006**	*182%*	**$ 5,437**	*329%*

We considered one present and two future socio-economic scenarios for analysis:

(1) Present assets

(2) ‘Low socio-economic’ growth scenario: assets in 2030 and 2050 with economic growth of 1% and demographic increase of 0.5%

(3) ‘high socio-economic’ growth scenario: assets in 2030 and 2050 with economic growth of 2% and demographic increase of 1%

Combining the probabilistic flooding height hazard dataset for present and future scenarios we were able to estimate the statistical description of damages spatially and temporally. The damages were evaluated at several scenarios for hazards:

(1) Present sea level and hurricane activity (Present Risk)

(2) Future climate risk (i.e. change in storms) atop rSLR in 2030

(3) Future climate risk (i.e. change in storms) atop rSLR in 2050

After putting together the hazards and assets data, we were able to model expected damages under different future climate change and economic growth scenarios (e.g., Figures 9 and 10). Figure 9 shows that under low economic growth, the expected future damages from flooding across the Gulf of Mexico are similar for coastal development and climate change (the two lite green bars Figure 9a). However, under higher economic growth, the increase in the value of exposed assets becomes a greater driver of risk than climate change (76% vs 44%).

Figures 9 and 10 represent the expected damages across the whole region, for flooding and wind damage, respectively. Note that these risk waterfalls are the sum of all values across the Gulf of Mexico.

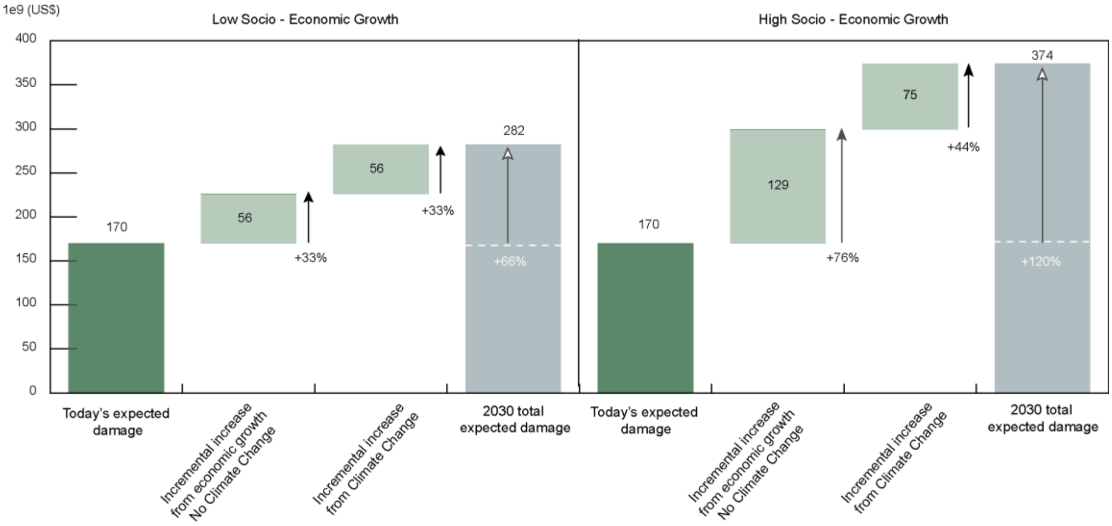

Figure 9. Flooding from coastal storms risk waterfall across the Gulf for 2030 under the two socio-economic scenarios

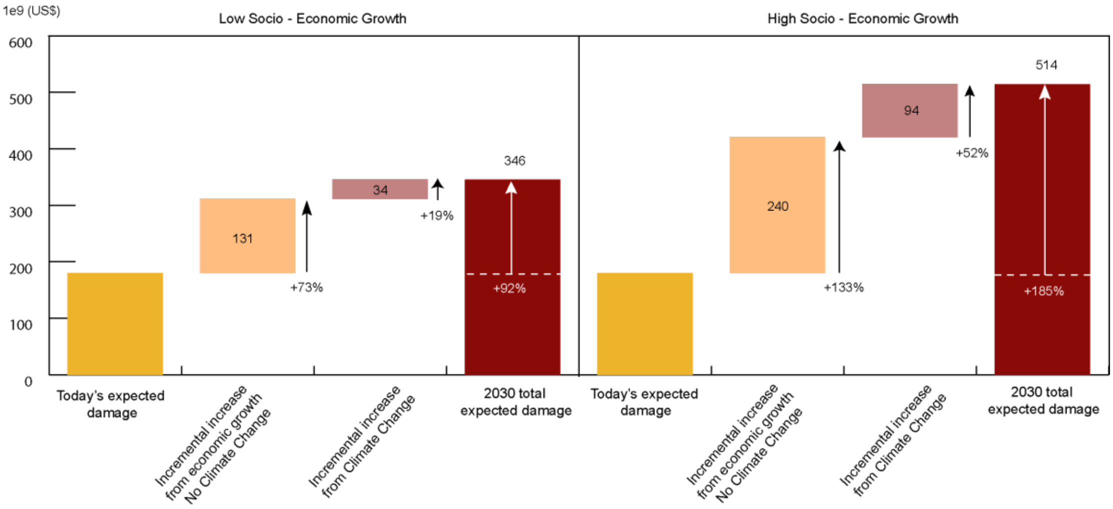

Figure 10. Wind risk waterfall across the Gulf for 2030 under the two socio-economic scenarios

3.3. Evaluating Coastal Adaptation options and residual risk

After modeling the damages from different climate scenarios, climate adaptation can be introduced in the analysis by either (a) influencing socioeconomic development (i.e. modifying future exposure) or (b) reducing the future damage by introducing coastal defenses.

Our aim is to estimate possible large-scale coastal adaptation alternatives so we modify the way we estimate damages from the damage curves when accounting for adaptation (see Figure 11). We do so by considering different types of adaptation measures. These range from structural measures such as breakwaters or floodwalls to Nature-based Defenses (NbD) such as wetland restoration (see Table 3 for a description). To assess the adaptation performance we define four different behaviors (Figure 11):

1. Hazard reduction – Structures attenuate waves or reduce flooding. . For example, wetlands reduce storm surge or reefs damp wave heights. The amount of wave attenuation or surge reduction varies by structure and depending on many factors. We used representative values based on published parameters after a literature review of available studies.
2. Flooding Level protection on the coastline (FL) – This structures provide full protection until a physical threshold is overcome, and then may offer partial reduction of the hazard. Representative cases are breakwaters or dunes that offer protection until their crest is overtopped.
3. Overtopping protection (OV) - Overtopping, represents damage only if the physical threshold is overcome at that specific area of study (calculated in blocks, aggregated to tracts). No damage

occurs if not overtopped. One representative case of this type is local house floodwalls and sandbags, only deployed and effective at each local site.

4. Elevation of structures (EL) – This mode represents the effect of the elevation of assets, which produces a translation of the damage curve (i.e. same damage requires greater water depths).

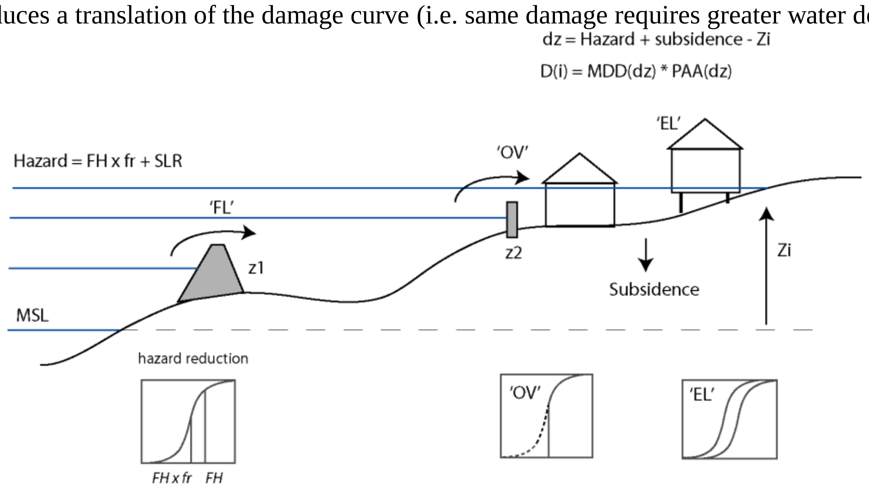

Figure 11. Sketch of the algorithm to assess adaptation. FH - Flooding Height; fr – Factor of reduction for the hazard (depending on the measure); MSL – Mean Sea Level; SLR – Sea Level Rise; MDD – Mean Damage Degree; PAA – Percentage of assets affected; Zi – elevation at each block; FL – Flooding Level, representing damage only if the physical threshold is overcome; OV – Overtopping, represents damage only if the physical threshold is overcome at that specific area of study; EL – Elevation of assets, produces a translation of the damage curve.

For each measure, we identified where measures could be used around the Gulf of Mexico, how much they would cost, and estimated their effectiveness for erosion and flood reduction. See Table 3 for a description of the measures.

Table 3. Outline of adaptation measures and main features and locations

Measure	Spatial Extent and Distribution of Measure
Wetland Restoration	6 Counties with the highest losses in assets where at least 25 miles of salt marsh could be restored by bay.
Wetland Conservation	125 miles of wetlands protected
Local Levees Priority	6 ft "hills" built to protect 532,000 existing houses on the 6 counties that experience most damages
Local Levees Remaining	6 ft "hills" built to protect 3,400,000 existing houses on the remaining 77 counties from the study area.
Sandbags	Sandbags used as barriers in 2.9 million houses for all Category 3 hurricanes across all counties in the study area.
Local Floodwalls	Concrete blocks (4 ft Structures) built to protect 1.9 million houses across all counties and parishes in the study area.
Levees	20 ft levees constructed in high risk areas around Houma, LA and New Orleans, LA covering 340 linear miles.
Barrier Island Restoration	Mississippi Coastal Counties (Hancock, Harrison, and Jackson)
Oyster Reef Restoration	Nearly 1000 miles of Oyster Reefs restored in all counties with high restoration suitability as identified by Restoration Explorer.
Beach Nourishment	All Coastal Counties in Texas.
Home Elevation Existing Homes High Priority	Elevate 481,841 existing houses by 8ft on the top 6 counties that experience the most damages
Home Elevation Existing Homes Low Priority	Elevate 3,037,869 existing houses on the remaining 77 counties from our study area by 8ft.
Home Elevation New Homes High Priority	Elevate 98,000 new houses by 10ft on the top 6 counties that experience the most damages according to our mode
Home Elevation New Homes Low Priority	Elevate 1,565,894 new by 10ft on 77 counties

The effectiveness of coastal defense measure for erosion and flood reduction depends on many factors that are not accounted for in this analysis such as: geometry, design, specific location, etc. On these grounds, we opted for stablishing a range of variation for each measure of representative designs that would provide potential reductions in the hazard (based on literature review) or provide certain protection. A description of these parameters can be found on the Appendix.

After estimating representative unit costs for each type of measure and their penetration (this parameter representing the fraction of assets that benefit from the deployment of certain adaptation measure), we obtained estimates of benefit-cost rations for avoided damages from present to 2030 for each adaptation measure. Figure 12 shows, for 2030 and under a low economic growth, the comparison of two scenarios: one with solid colors for less conservative parameters for the protection benefits from NbD (in green in the graphic) and another scenario (outlined shapes) that considers more conservative estimates of technical performance and a 20% increase in the estimated costs of the NbD options.

The results show that sandbags are the most cost-effective measure assessed (note the height of the Benefit/Cost bar). However the total amount of damaged averted by sandbags is quite low (slim bar), but they are (comparatively) a very cheap measure. Oyster reef restoration is also very cost effective and provides a decent amount of averted damages. For marshes, the cost effectiveness is high particularly if restoration occurs where people and assets are most at risk (risk reduction bar) as compared to restoration of marshes in the areas that had seen the greatest past loss (conservation scenario).

Nature-based defenses are highly cost effective in both scenarios under conservative and less conservative estimates of cost and effectiveness. Although each of these scenarios relies upon numerous hypotheses and assumptions, by modifying parameters and cost estimates (e.g. degree of risk reduction performance or cost of measures) as well as comparing different scenarios, we were able to identify that the results are robust and consistent conclusions across scenarios.

Note also that adaptation does not cover completely the climate risk and there is still a great fraction under residual risk that has to be managed by other means or internalized.

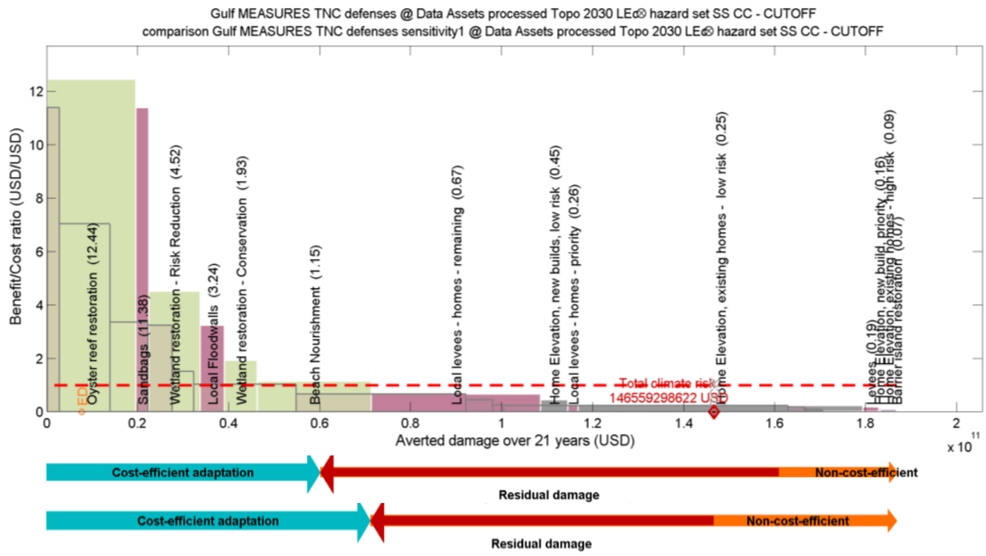

Figure 12. Benefit-cost ratio of adaptation measures across the Gulf Coast. Comparative cost effectiveness of the different measures and the likely amount of damages averted in billions of dollars.

4. Discussion and Conclusions

Coastal communities are increasingly vulnerable to flooding (Woodruff et al. 2013). The need to reduce risks from coastal storms has given rise to efforts to make greater use of integrated ecosystem-based approaches, such as NbD (e.g. Van Slobbe, et al., 2013). Such approaches leverage the capacity of wetlands, beaches and dunes, reefs, and other natural features to reduce the impacts of storm surge and waves (Temmerman et al. 2013). While the potential to apply NbD to flood risk management will depend on the physical, geomorphological, and ecological context, examples of the importance and application of such approaches are increasing worldwide (Temmerman et al. 2013 and references therein). Further, these services can stand alone, but can also be incorporated into hybrid engineering solutions.

Natural and nature-based defenses can be used to enhance the resilience of coastal areas threatened by sea level rise (Borsje et al. 2011) and coastal storms (e.g. Gedan et al. 2011, Lopez, 2009). For example, beaches are natural features that can provide coastal storm risk reduction and resilience where their sloping nearshore bottom causes waves to break, which dissipates wave energy over the surf zone. In turn this dissipation helps to stabilize the shoreline and allows the development of dunes and a green buffer behind. These breaking waves often form offshore bars that help to dissipate waves farther offshore. Dunes that back a beach can also act as physical barriers that reduce inundation and wave attack to the areas behind the dune.

Nature-based defenses are likely to provide their most important benefits for high frequency, low intensity events from daily to events of intermediate frequency and intensity. They thus can make the coastal zone more resilient to frequent storms (i.e. higher potential to sustain impacts). However, for less frequent more intense events other defenses will be required in addition to NbD to provide defense (Figure 13). The selection of measures, as sketched in Figure 13 should be such that benefits from the high-frequency of delivery of NbD services (i.e. coastal defense and others), its low-cost of implementation and plan for rare high events that cannot be covered by other type of defenses. Looking at how the different measures can contribute in reducing risk for the different events (risk spectra), in terms of cost and intensity efficiency, can provide quantitative understanding to build a resilient and more sustainable portfolio for coastal adaptation.

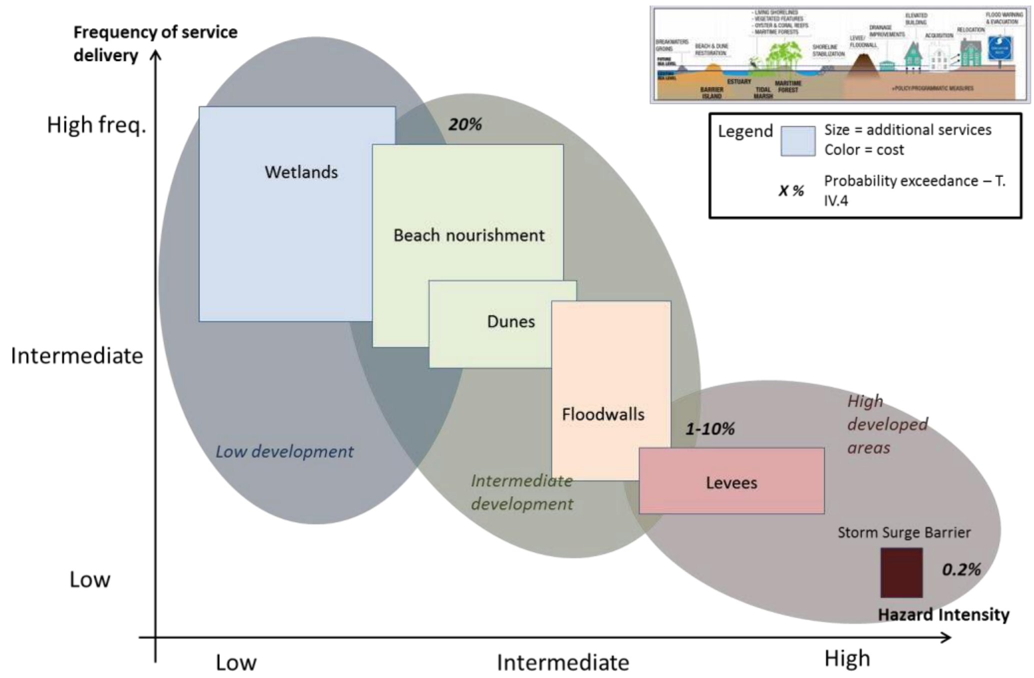

Figure 13. The conceptual role of NbD in the coastal risk reduction spectra.

Assessment of the role and cost efficiency of adaptation measures is increasingly demanded and so it has been acknowledged. We have applied the ECA methodology to quantify the costs and benefits of disaster risk reduction solutions with special emphasis on (1) nature based measures, (2) on a spatially explicit basis for the US Gulf Coast, and (3) using fully open source models. Swiss Re, the second largest global re-insurer, and The Nature Conservancy (TNC), a pioneer in habitat restoration for hazard mitigation, are working together to make these approaches more accessible and spatially explicit. We have advanced an approach that is able to quantitatively assess and compare natural and artificial defenses as well as policy options for risk reduction,

A significant gain from having developed these models is that we are able to fully explore many risk reduction options. We can also consider the sensitivity of the results to many reasonable changes in the underlying parameters. By changing these parameters across scenarios we can assess what creates the most variation in risk and more importantly in the cost effectiveness of risk reduction measures. By modeling many scenarios, we know for example that:

- Economic growth is more likely than climate change to create the greatest risks in the near term;
- Oyster reef and marsh restoration will be particularly cost effective in comparison to most other measures under any likely scenario of costs and benefits;

- The cost effect effectiveness of oyster reef and marsh restoration depends significantly on the location of the restoration projects, which should have significant influence on our priorities;
- Adding other ecosystem services such as fisheries does not greatly affect the cost effectiveness of marsh or oyster restoration;
- Habitat loss (or not considering habitats in current models) appreciably increases the costs from damages;
- The combination of major oyster reef and marsh restoration can avert billions of dollars in future damages, which should factor in to how one assesses and prices risk.

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APPENDIX

Table 4 outlines the range of variation for each measure depending on whether they contribute to wind waves (short waves) or long waves (storm surge) as well as if they provide a physical threshold for inundation.

Table 4. Adaptation performance parameters in the adaptation module. Developed based on bibliography review and Coastal Engineering Manual.

DEFENSE	Hazard reduction factor		Elevation Threshold (m)	Mechanism of defense in the model
	Wind Waves (%)	Storm Surge (%)		
Local Levees (homes)	10 -20%	-	1.8	Overtopping (local)
Levees (shoreline protection)	80-90%	-	7.5	Overtopping (shoreline)
Sandbags	-	-	0.5	Overtopping (local)
Beach Nourishment	75-90%	-	-	Hazard reduction
Local floodwalls	-	-	1.2	Overtopping (local)
Home Elevation	-	-	3	Elevation
Wetland restoration	30-50	10-30	-	Hazard reduction
Barrier island restoration	30-60	5-10	-	Hazard reduction
Oyster reef restoration	20-50	0-5	-	Hazard reduction

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