Impact of Sea Level Rise for the Conterminous United States. An analysis on Inhabitant Displacement and GDP Production Impediment due to Land Inundation

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An analysis on Inhabitant Displacement and GDP Production Impediment due to Land Inundation

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“All models are wrong, but some are useful" - George Box

PREFACE

This report presents the results of a half year research period in order to complete the requirements for the Master Energy and Environmental Sciences. The master is provided by the Center for Energy and Environmental Studies (IVEM), University of Groningen, the Netherlands. The research was conducted at the Department of Atmospheric and Oceanic Science (AOSC), University of Maryland, United States.

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SUMMARY

Modern recording of sea levels show that sea levels have been rising since the late 19^{th} century. Recently is has been argued by several authors that thermal expansion due to global warming is accelerating sea level rise. This report examines the impact that rising sea levels, combined with vertical land movement, will have on the coastal states of the conterminous United States. Three key indicators (land inundation, inhabitant displaced, and GDP impeded) are analyzed for three scenarios (ELT, GWC, and $GWC^{+/+}$). The ELT scenario is the extended linear trend from historic sea level rise, the GWC scenario couples sea level rise to a high-end emission scenario, and the $GWC^{+/+}$ scenario couples sea level rise to a high-end emission scenario and includes an uncertainty attribute and accelerated glacier and icecap melting.

Due to the incorporation of vertical land movement, the relative sea level rise for each state could be assessed separately. Since the vertical land movement is distinctly different for each state, this approach offers a more accurate assessment of the impact than using a uniform sea level rise. It is found that natural processes like the Glacial Isostatic Adjustment and plate tectonics are the main determinants for relative sea level rise along the Atlantic and Pacific coast. Estimates for relative sea level rise on these coasts vary per state between 0.1-0.4 meters for the ELT scenario, 0.4-1.1 meters for the GWC scenario, and 1.3-2.5 meters for the $GWC^{+/+}$ scenario. On the Gulf coast, oil extraction and groundwater withdrawal cause major human-induced subsidence, leading to high estimates for relative sea level rise. On the Gulf coast, estimated sea level rise varies for the different states between 0.2-0.8 meter, 0.6-2.5 meter, and 1.6-4.3 meter for respectively the ELT, GWC and $GWC^{+/+}$ scenario.

By use of a geographic information system (GIS), it is estimated that for the ELT scenario, a minimum of 30.000 km^2 will be inundated, 1.7 million people will be displaced, and 76 billion dollar of GDP production will be affected if no adaptive or mitigative action is taken. For the GWC and $GWC^{+/+}$ scenario this is respectively 49.000 km^2 and 76.000 km^2 inundated, 3.3 million and 7.4 million inhabitants displaced, and 130 billion and 289 billion dollar of GDP production affected. Especially Louisiana and Florida, with low-lying terrain and major cities at the ocean front see a high absolute impact on population and GDP.

Since these results are based on fairly slow inundation, it has to be realized that storm surges in combination with sea level rise can seriously increase these numbers. Furthermore, growth dynamics of population and GDP will increase the numbers even further. The results presented in this report can therefore be considered the absolute minimum impact of sea level rise under three scenarios for the conterminous United States if no adaptive and mitigative efforts are undertaken.

Concerning the significant impact sea level rise has on coastal communities, it is evidently clear that action needs to be taken. This being said, population in coastal areas continues to grows, setting the stage for either great loss, or excessive protection costs. Anticipating on sea level rise and retreating from areas at risk will greatly reduce the impact and cost of sea level rise. An optimum mix of adaptive strategies needs to be defined for each specific region depending on environmental, geophysical and socio-economic conditions. For highly developed regions it might be beneficial to protect rather than retreat. The economic value that is protected would far outweigh the cost of protection. For less developed regions, the smart option would be to accommodate and retreat since the value of protected property does not justify the cost of protection. The most sustainable strategy for future development is retreat, avoiding additional cost all together. To stop sea levels from rising, mitigative actions need to be undertaken. Due to slow mixing of warm ocean surface layers with deeper ocean layer sea levels will continue to rise by thermal expansion even after greenhouse gas emissions have been stabilized. If no mitigative action is taken today, we will pass an increasing problem on to next generations leaving the world with the legacy of excessive consumption and pollution.

SAMENVATTING

Onderzoek naar het niveau van de zee wijst uit dat de zeespiegel stijgt sinds het einde van de 19de eeuw. Verschillende auteurs beargumenteren dat de zeespiegel stijgt doordat zeewater uitzet als gevolg van het opwarmen van de aarde. In dit rapport wordt onderzocht wat voor impact een stijgende zeespiegel, in combinatie met de verticale beweging van land, heeft op de kuststaten van de Verenigde Staten. Voor dit onderzoek zijn drie indicatoren geanalyseerd (land inundatie, ontheemde inwoners, en belemmering van BNP productie) voor drie scenario's (ELT, GWC, en $GWC^{+/+}$). Het ELT scenario is een lineaire trend gebaseerd op historische data, het GWC scenario koppelt zeespiegelstijging aan een 'high-end' emissie scenario, en het $GWC^{+/+}$ scenario koppelt zeespiegelstijging aan een 'high-end' emissie scenario en gaat uit van een onzekerheidsfactor en het versneld smelten van gletsjers en ijskappen.

Doordat de verticale beweging van land wordt meegenomen in de analyse kan de relatieve zeespiegelstijging voor elke staat apart worden onderzocht. Aangezien de verticale beweging van het land anders is voor elke staat zorgt deze aanpak voor een meer accurate analyse van de impact dan wanneer er uit wordt gegaan van een uniforme zeespiegelstijging. De belangrijkste factoren van invloed op de zeespiegelstijging aan de oost- en westkust zijn de postglaciale bodemheffing/daling en plaattectoniek. In dit rapport wordt geschat dat voor de oost- en westkust de relatieve zeespiegelstijging varieert tussen de 0.1-0.4 meter, 0.4-1.1 meter, en 1.3-2.5 meter voor respectievelijk het ELT, GWC, en het $GWC^{+/+}$ scenario. Voor de staten aan de Golf van Mexico is de geschatte relatieve zeespiegelstijging tussen de 0.2-0.8 meter, 0.6-2.5 meter, en 1.6-4.3 meter voor respectievelijk het ELT, GWC, en het $GWC^{+/+}$ scenario. De hoge relatieve zeespiegelstijging aan de Golf kust kan worden verklaard door bodemdaling als gevolg van de extractie van grondwater en olie.

Aan de hand van deze schattingen is er uitgerekend dat uitgaande van het ELT scenario er 30.000 km^2 onder water komt te staan, 1.7 miljoen mensen zich moeten verplaatsen, en 76 miljard dollar aan BNP productie per jaar aangetast zal worden als er geen maatregelen worden getroffen. Voor het GWC en $GWC^{+/+}$ scenario komen deze berekeningen uit op respectievelijk 49.000 km^2 en 76.000 km^2, 3.3 miljoen en 7.3 miljoen mensen, en 130 miljard en 289 miljard dollar. Deze cijfers zullen drastisch toenemen als naast het langzame proces van zeespiegelstijging ook stormvloed in ogenschouw wordt genomen. Daarnaast zal de groei van populatie en BNP er toe leiden dat de cijfers verder toenemen. De resultaten die in dit rapport naar voren komen kunnen daarom worden beschouwd als een absolute minimale impact van zeespiegelstijging voor de Verenigde Staten.

Gezien de relatief forse impact van zeespiegelstijging is het meer dan duidelijk dat er actie moet worden ondernomen. Desondanks stijgt de bevolkingsdichtheid in kustgebieden, met als gevolg dat ofwel kustontwikkeling weer verloren zal gaan, of dat de kosten voor bescherming zullen stijgen. De kosten kunnen worden beperkt door te anticiperen op zeespiegelstijging en niet te bouwen in risicogebieden. Afhankelijk van ecologische, geofysische, en socio-economische factoren moet een optimale mix van adaptatie strategieën worden gedefinieerd. Daarnaast zal zeespiegelstijging moeten worden tegengegaan door broeikasgasemissies te beperken, zeker aangezien zeespiegelstijging ook door zal gaan nadat emissies zijn beperkt doordat warm oppervlaktewater zich blijft mengen met de diepe oceaan. Zonder actie zullen we een toenemend probleem doorgeven aan toekomstige generaties en de wereld achterlaten met een nalatenschap van excessieve consumptie en vervuiling.

1. INTRODUCTION

From the beginning of mankind, human civilization has always been drawn towards the sea. The abundance of food and the benefits of water-based transport led early humans to the coast, and still human population in coastal areas continues to increase. Currently, about 44% of the world's population is living within 150 kilometers of a coastline. Eight of the top ten largest cities in the world are located right by the sea (United Nations World Atlas, 2012). Along with great benefits also come great risks. Extreme weather conditions, storm surges and flooding pose threats to coastal infrastructure, human life and important ecological areas. With rising sea levels, these threats become more imminent, and more frequent (Solomon *et al.*, 2007). Assessing the potential impact of rising seas is an important step towards adaptation and mitigation.

1.1 Global sea level rise

Measuring sea level started as early as the beginning of the 18th century in Amsterdam (van Veen, 1945). At that time, not sea level rise but land subsidence spurred the interest in measuring changes in sea level. Modern tidal recording started in the late 19th century, with data collection from land-based tide gauges. Land-based tide gauges have since then been the primary instruments to measure the change in sea level. On August 10, 1992 the TOPEX/Poseidon satellite was launched. This satellite was the first satellite that was used to determine sea level rise from space. On December 7, 2001 the Jason 1 satellite was launched to continue the TOPEX/Poseidon mission after its decommissioning. Satellite altimetry offered a way to measure absolute sea level rise instead of relative sea level rise. Acknowledging the importance of sea level rise, the Intergovernmental Panel on Climate Change (IPCC) devoted a full chapter to sea level rise in their 2007 report (Solomon *et al.*, 2007). Figure [1] shows the recorded global sea level change from tide gauges and satellite altimetry as well as the IPCC's estimate for future global sea level rise. Sea levels are projected to continue to rise at least throughout the 21th century, and most likely beyond.

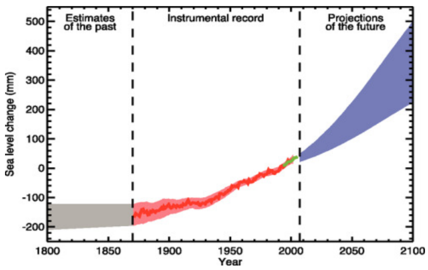

Figure [1] Global sea level rise 1800-2100. Grey shows the era previous to sea level measurements. Red shows the result from the tide gauge records. Green shows the results from satellite altimetry. Blue shows the predicted sea level rise. Source: Solomon *et al.* (2007).

The rise in sea level can be attributed to a number of causes. The best known by the public might be the melting of the polar icecaps and the melting of glaciers. Although these are indeed contributing to sea level rise, the biggest contributor to sea level rise of the last decade is the steric expansion of sea water due to global warming. It is argued that the rate of sea level rise is roughly proportional to the magnitude of warming above the temperatures of the pre–Industrial Age, linking anthropogenic warming to sea level rise (Rahmstorf, 2007). For the last decade, this volumetric expansion accounts for 1.6±0.5 mm/yr to the global sea level rise, whereas the melting of polar ice accounts for 0.21±0.35 mm/yr (Antarctica) and 0.21±0.07 mm/yr (Greenland). The melting of glaciers (and non-polar icecaps) accounts for 0.77±0.22 mm/yr (Solomon *et al.*, 2007). A recent study by Jacob *et al.* (2011) suggests that the combined contribution of Antarctica, Greenland and glaciers is higher than previously predicted, and accumulates to 1.48± 0.26 mm/yr for the period 2003-2010. Water storage also contributes to sea level change, although the absolute effects are unclear. Change in land water storage can be either climate-driven (e.g. melting of snow, drying of wetland) or anthropogenic (e.g. dams, irrigation). High uncertainty remains with estimating the contribution of change in land water storage to sea level rise. The total sea level rise for the last decade is now estimated at 3 mm/yr, and there are suggestions that it is accelerating (Church & White, 2006). Even though sea level rise is a global trend, the rate and extend of sea level rise varies greatly for different regions of the world. Local salinity, temperature, discharges of land water reservoirs (e.g. glaciers, ice caps), change in ocean circulation, and atmospheric pressure all influence local sea levels. Figure [2] shows regional sea level trends recorded by satellite altimetry, clearly showing variability of global sea level rise in different regions (Nicholls & Cazenave, 2010).

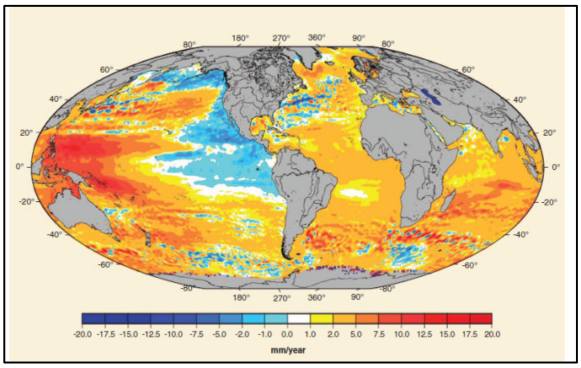

Figure [2] Regional sea level trends from satellite altimetry for the period October 1992-July 2009. Source: Nicholls & Cazenave (2010).

1.2 Relative sea level rise

Global sea level rise data is widely available, but often mistakenly used for local decision making (Nicholls & Leatherman, 1996). More important for the determination of the impact on human civilization is the difference in relative sea level rise, which is the local rise of the water with respect to the land. Relative sea level rise is co-determined by vertical land movement as is illustrated in figure [3], and can be significantly different from global sea level rise (Emery & Aubrey, 1991). Vertical land movement can have several natural and anthropogenic causes. The melting of the ice sheets that depressed the land during the last ice age causes an uplifting of the crust in those previously depressed areas, and a subsidence in adjacent regions that were not depressed by ice sheets. This process is called the Glacial Isostatic Adjustment (GIA). Other natural processes like sediment compaction contribute in certain regions to vertical land movement, and thus to relative sea level rise (Emery & Aubrey, 1991; Church *et al.*, 2001; Solomon *et al.,* 2007). Human-induced vertical land movement is also reported around the world. The extraction of groundwater and the production hydrocarbons reduce subsurface pressure causing major local subsidence (Emery & Aubrey, 1991). Whereas global sea level rise is important to determine adaptive and mitigative strategies on a global scale, determining relative sea level rise offers an insight in the possible impact on a regional level and offers local policymakers important information for the future of their state or region.

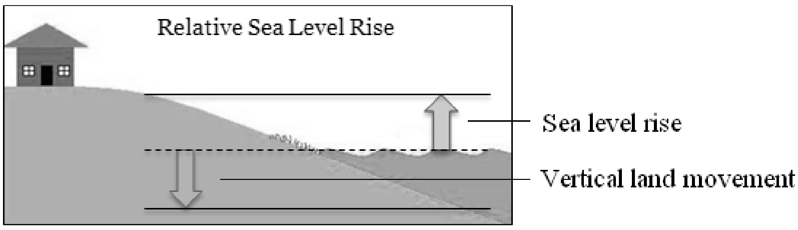

Figure [3] Illustration of relative sea level rise. Relative sea level rise is the combined effect of sea level rise and vertical land movement

1.3 Impacts of sea level rise

Although sea level rise seems to be a slowly evolving problem, the consequences are serious and a good understanding and timely response is therefore vital. With sea level rise, shoreline erosion increases, floods occur more frequently and storm damage is more severe, low-lying areas are inundated and saltwater intrudes into aquifers and surface waters (Nicholls & Leatherman, 1994; Nicholls & Lowe, 2004). Increased flooding and storm damage might be the most urgent for mankind because of high socio-economic impact (Douglas *et al.*, 2001; Solomon *et al.*, 2007; Dasgupta *et al.*, 2009). With high value capital and human life just at the sea frontier, impact can be sudden and destructive under a storm surge or a high tide flood. Coastal erosion might be a slower process, but with infrastructure and communities right by the sea, protection and tactical retreat will prove to be increasingly costly (Leatherman, 2001). Salt intrusion disrupts wildlife in brackish water and might reduce the fertility of agricultural grounds in coastal areas. The most threatened areas are deltas, low-lying coastal plains, coral islands, beaches, barrier islands, coastal wetlands, and estuaries (Nicholls & Mimura, 1998), endangering areas like the Washington metropolitan area. In addition, the socio-economic impact of rising seas are numerous, with potentially increased loss of property and coastal habitats, increased flood risk and potential loss of life, and damage to coastal protection works and other infrastructure (McClean *et al.*, 2001). Furthermore, the impact of sea level rise might cause loss of renewable and subsistence resources, loss of tourism recreation and transportation functions, loss of non-monetary cultural resources and values, and impacts on agriculture and aquaculture through decline in soil and water quality (McClean *et al.*, 2001). This research quantitatively addresses three key vulnerability issues related to sea level rise: Land surface inundated, inhabitants displaced, and affected GDP production.

1.4 Research design

The research will focus on the Atlantic, Pacific and Gulf coasts of the conterminous United States. This approach assures an analysis between three regions with distinctly different sea level rise trends observed during the last decade (fig. [2]). The research will be executed on a state level, and therefore no in-depth analysis of specific economic damage will be performed on lower aggregate levels. Instead, the three key indicators land, inhabitants, and GDP will be used to determine the vulnerability of each state to sea level rise. The research aim leads to the following main research question:

Main research question *What is the potential impact of future sea level rise (present-2100) for each coastal state of the conterminous USA?*

The research will focus on the period up till 2100. Beyond this point predictions are susceptible to very high uncertainty and are therefore not investigated. The focus on inhabitants, land and GDP is chosen to provide both common denominators for different impact categories and a measurable and quantifiable outcome.

Research question 1 *What has been the historic relative sea level rise for each state on the Atlantic, Pacific and Gulf coast of the conterminous USA during the period 1950-2010?*

The period 1950-2010 is chosen based on available sea level records. The sea level rise is determined relative to land to reflect the immediate impact for each state. This research question serves as background information for the calculation done in research question 2 and is not specifically described in this report.

Research question 2 *How can the historic relative sea level rise be projected into the future (2100) for each state on the Atlantic, Pacific and Gulf coast of the conterminous USA?*

Three scenarios will be modeled to analyze the sea level rise for each state. In appendix A, special attention will be paid to the amplitude of sea level rise to assess near-future impact by exceptional flood events.

Research question 3 *How does the projected sea level rise affect Land (inundation), Inhabitants (displacement), and GDP (impediment) for each coastal state of the conterminous USA?*

Each of the three indicators provides insight on the impact of sea level rise on a state level. By answering this research question, an analysis is provided of the impact of sea level rise for each state or region, and the different characteristics. A discussion will be added on erosion and saltwater intrusion for a more complete assessment of the impact of sea level rise.

Research question 4 *What are the general response strategies to sea level rise, and how can they be related to the projected impact on land (inundation), inhabitants (displacement) and GDP (impediment) for the coastal states of the conterminous USA*

A general overview will be provided of the potential response strategies. Those strategies will be related to the impact as found in research question 3. Note that the strategic response will vary greatly on local scale due to great differences in environmental, geophysical and socio-economic conditions. Therefore, the research question is restricted to give a broad indication of the potential benefit of using different response strategies for different states or regions.

The aim of this research is to contribute to our current understanding of the consequences of sea level rise by assessing the impact of sea level rise on a state aggregation level for the United States. The results found in this report provide a quantitative estimation of the minimum impact that different scenarios of sea level rise will have if no action is taken to prevent damage and land loss. The report provides an overview of the impact per state and discusses the causes of the differences, and thereby provides detailed information on the different impact throughout the United States.

The report contains four chapters and one appendix. Chapter 1 is the introduction. Chapter 2 and 3 answer respectively research question 2 and 3. Both chapters contain valuable information on sea level rise which can either be considered independently or related to each other. Chapter 4 answers research question 4, and describes adaptation and mitigation strategies to counteract the impact of sea level rise. Appendix A provides a case study on high water levels for the Chesapeake Bay, using extreme water level records.

1.5 Limitations

The research has two main limitations. The first concerns the complexity of the processes that cause sea levels to rise, and the high uncertainty related with predicting future sea level rise. Kettle (2012) summarizes the uncertainties involved into six categories: (1) measuring historic sea level rise can contain errors from tide gauge stations; (2) determining trends is highly influenced by the start and end period of historic measurement; (3) predicting sea level change is based on many uncertainties (e.g. what contributes to sea level rise, how is the climate going to change, and how will this effect sea levels); (4) predicting shoreline change is difficult considering the many natural and anthropological influences; (5) coastal elevation models, however accurate in general, can contain errors; and (6) impact assessment is highly dependent on the method chosen. Although shrouded by many uncertainties, it is not impossible to give a plausible assessment and at least provide a “what-if”-analysis of the impact. Throughout this research attempts are made to reduce uncertainty wherever possible. The second limitation is that the impact of sea level rise is assessed on a state resolution level. Large regional difference due to local factors can and do occur, making the prediction of future relative sea level rise difficult for states showing high variability. In those cases, the impact analysis serves more as a “what-if”-scenario.

2. RELATIVE SEA LEVEL RISE FOR THE US COASTAL STATES

The conterminous United States has a total shoreline of approximately 85.000 km (NOAA, 2012)[1]. Along these shores, subsidence and other regional circumstances determine how a state will be affected by global sea level rise. The relative sea level rise can be distinctly different and so will its impact be for each of the states. This chapter provides one low- and two plausible high-end scenarios based on tide gauge records, a retrospective analysis for each of the scenarios, and the results on relative sea level rise for each of the states.

2.1 Tide gauges and the historic relative sea level rise per state

Throughout history tide gauges have been used to measure sea levels. Their records provide a basis for estimating sea level rise over certain periods. The scenarios that will be discussed are therefore based on these tide gauge records. The historic relative sea level per state is derived from the tide gauge records provided by the Permanent Service for Mean Sea Level (PSMSL, 2012). Ideally, records longer than 50 years are used because shorter records are influenced by strong interannual fluctuations of sea level rise (Nicholls & Leatherman, 1996). Tide gauge records are only selected if (1) the record is relatively complete for the years 1950-2010 and (2) the record does not deviate from nearby records because of local effects. To obtain a relative sea level rise for a state, the average is taken from the selected tide gauge records. Because of the use of criteria (1) and (2) for selecting proper tide gauge records, this method provides a state level relative sea level rise from which future trends can be estimated. For a list of the used tide gauges see column "included tide gauges" of table [1].

Six states without appropriate tide gauges

For some states a different approach was required because of the lack of records satisfying criteria (1) and (2). The alternative approach for these states is described under a). For the Pacific coast and alternative approach was needed due to the regional suppression of sea level rise which is expected to change in the near future. The alternative approach for the Pacific coast is described under b).

a) New Hampshire, Mississippi and Alabama

For New Hampshire, Mississippi and Alabama there are no tide gauge records available that span the period 1950-2010. To determine the relative sea level rise for New Hampshire, the closest complete record to the south (Boston, Massachusetts, ID# 235) and the closest complete record to the north (Portland, Maine, ID# 183) of New Hampshire were selected. Since no strong regional effects are reported, the averaged result from these two tide gauges is considered to give a reasonable estimation for New Hampshire. For Mississippi the nearest tide gauge record that spans the period 1950-2010 is Grand Isle, Louisiana (ID# 526). The area where this tide gauge is located is however subject to strong regional subsidence due to groundwater withdrawal, hydrocarbon extraction, river diversion, and sedimentation processes (Emery & Aubrey, 1991). The nearest tide gauge to Mississippi and Alabama that is not subject to these regional effects and that spans the period 1950-2010 is Pensacola, Florida (ID# 246). The Pensacola tide gauge is located on the same contour level for the Global Isostatic Adjustment as the Mississippi and Alabama coast (Holdahl & Morrison, 1974). Assuming that further regional effects on relative sea level rise are minimal, the Pensacola tide gauge is therefore considered to give a good indication of relative sea level rise for both Mississippi and Alabama.

b) Washington, Oregon and California

[1] The length of the coastlines is highly dependent on which calculation method is chosen. See reference for specifics.

Due to the suppression of relative sea level rise by wind stress on the Pacific coast for the last 30 years (Bromirski *et al.*, 2011) the use of long term tide gauge records would not result in reliable future predictions. Therefore, only the two available very long term tide gauge records (<1900) were used (e.g. Seattle, Washington, ID# 127; San Francisco, California, ID# 10). For Oregon, the only available record that spans the period 1950-2010 is Astoria (ID# 265). This record is however strongly influenced by the Columbia River outflow (PSMSL, 2012) and does therefore not meet criteria (2). Since no reliable tide gauges that span the period 1950-2010 are available for Oregon, and for Washington and California only two tide gauges are selected, the results for Oregon will be estimated as the average of the outcomes for Washington and California. Note that the Pacific coast is subject to large variability in relative sea level rise due to a complex pattern of uplift and subsidence. This limits the predictability of relative sea level rise on a state level. This will be explained further during the discussion of the results.

2.2 Sea level rise scenarios

Three scenarios will be used to determine relative sea level rise on a state level. The scenarios run from 2010 to 2100. The 2100 relative sea level output for the three scenarios will be used to calculate the socio-economic impact for each state on the Pacific, Atlantic and Gulf coast of the conterminous United States. Scenario 1 is a “low-end” scenario, where scenario 2 and 3 are plausible “high-end” scenarios.

Scenario 1 - Extended Linear Trend (ELT): The ELT Scenario gives an extrapolation of the linear trend from the 1950-2010 Permanent Service for Mean Sea Level (PSMSL, 2012) tide gauge records up to 2100. The relative sea level rise for a particular state is determined by averaging tide gauge records in a state with recorded data from 1950-2010. Only tide gauges with Revised Local Reference (tide gauges set to a common datum) are used. Since sea level rise is expected to rise in an exponential non-linear fashion (Solomon *et al.*, 2007), this scenario provides a lower limit to potential sea level rise.

Scenario 2 - Global Warming Coupling (GWC): Research shows that recent sea levels seem to be proportional to the magnitude of warming above the temperatures of the pre–Industrial Age (Rahmstorf, 2007). The GWC scenario assumes a simple linear equation (1) to link the global atmospheric surface temperature to relative sea level rise (RSLR) at a certain month *n*.

$$(1) \qquad RSLR_n = \frac{1}{12}(\alpha \cdot \Delta T + \beta)$$

Where α is determined by the relation between the historic annual sea level for a state (by using tide gauge records) and the global land-ocean temperature index (Rahmstorf, 2007; Hansen *et al.*, 2010). An example of how α is determined is given in figure [4]. For the ΔT the IPCC fifth assessment (AR5) RCP8.5 emission scenario is used. The ΔT is determined by T_n - T_{n-12} to smooth annual cycles. The β represents the rebound of the earth’s crust after depression by thick ice sheets during the last ice age or subsidence due to fore-bulge collapse, also called Glacial Isostatic Adjustment (GIA). The rate of GIA can be considered constant on anthropological time scales. For a state level adjustment, the GIA data (Peltier, 2004) for the selected tide gauge records in a state are averaged. Note that since β is constant it does not influence the slope α. The RCP8.5 scenario is a so-called “high-end” scenario which depicts an upper limit of the predicted global warming. Because of the use of RCP8.5 emission scenario in the GWC scenarios, the GWC scenario is also defined as a “high-end” scenario.

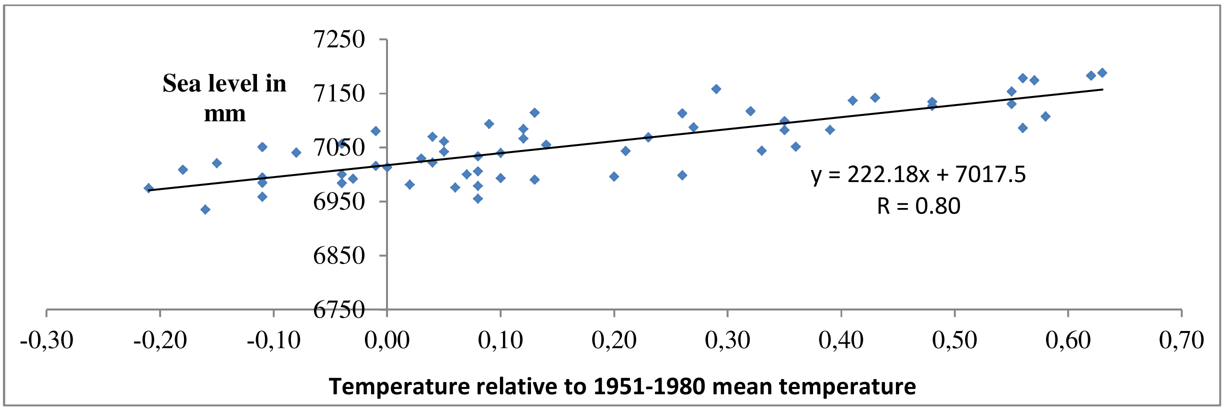

Figure [4] Determining α for the state of Maryland. The data point's represent the measured sea level rise (PSMSL, 2012) coupled to the global surface temperature (Hansen *et al.*, 2010) for each specific year for the period 1950-2010. The slope of the trend line represents the sea level rise per degree Celsius (222.18 mm/°C). For Maryland a correlation of 0.8 is found.

Scenario 3 – Global Warming Coupling & Accelerated Glacier and Icecap Melting ($GWC^{+/+}$)[2]: Recent papers suggest that the glacier and icecap melting is accelerating and that it can contribute greatly to global and regional sea levels (Meier *et al.*, 2007; Pfeffer *et al.*, 2008; Jevrejeva *et al.*, 2010). The $GWC^{+/+}$ scenario incorporates this acceleration into the GWC scenario, resulting in equation (2) for relative sea level rise (RSLR) for a given month *n*.

$$(2) \qquad RSLR_n = \frac{1}{12}(\alpha \cdot \varphi \cdot \Delta T + \beta + \gamma)$$

Where γ is the additional annual sea level rise from accelerated glacier and icecap melting. The γ is obtained by determining the annual sea level rise and averaging the prediction by Meier *et al.* (2007) and the "low1" and "high1" scenarios by Pfeffer *et al.* (2008). The contributions by glaciers and icecaps included into the IPCC assessment (or non-accelerated G&IC melting) are subtracted from γ since this was already accounted for under the GWC scenario. Again, the IPCC fifth assessment (AR5) RCP8.5 scenario is used for ΔT. The φ represents an uncertainty attribute to ΔT. The uncertainty attribute φ is 1.6 for the $GWC^{+/+}$ scenario.

The IPCC has been challenged for their apparent underestimation of global warming and sea level rise (Horton *et al.*, 2008; Grinsted *et al.*, 2009; Jevrejeva *et al.*, 2010). In the fourth IPCC assessment report, a -40% and +60% range of the model outcome was assumed to be likely (Solomon *et al.*, 2007). An φ of 1.6 represents the very upper range of this uncertainty (Solomon *et al.*, 2007) (although in the final AR5 the assumed range of likely outcomes might be smaller). Due to the use of the RCP8.5 emission scenario, the inclusion of accelerated glacier and icecap melting, and the uncertainty attribute, the $GWC^{+/+}$ scenario is classified as a high-end scenario which shows a plausible upper limit for sea level rise.

The predicted total relative sea level (RSL) for a given period n_0-n for the GWC and $GWC^{+/+}$ scenarios are obtained by summing the individual monthly relative sea level rise rates (equation 3).

$$(3) \qquad RSL_{n_0-n} = \sum_{n_0}^{n} RSLR_n$$

[2] The $^{+/+}$ describes the addition of the uncertainty attribute φ and the accelerated glacier & icecap melting.

RCP 8.5 emission scenario

The RCP (Representative Concentration Pathways) scenarios have been developed for the fifth IPCC assessment report. While the RCP6, RCP4.5 and RCP2.6 assume stabilization or decline of radiative forcing, the RCP8.5 scenario assumes a rising radiative pathway leading to 8.5 W/m^2 in 2100 (Taylor *et al.*, 2009). The RCP8.5 scenario assumes a high population and a relatively slow income growth with modest rates of technological change and energy intensity improvements (Riahi *et al.,* 2011). The effective rise in temperature would be ~4°C from 2010 until 2100.

The significance of α

As discussed, α is the relation between the historic annual sea level for a state (by using tide gauge records) and the global land-ocean temperature index. Significant correlations ($r > 0.7$) were found for 12 of the 14 Atlantic coastal states between the global mean temperature (Hansen *et al.*, 2010) and the annual mean sea level rise per state. For the Gulf coast, only Mississippi and Alabama showed lower correlations ($r = 0.69$) but are still close to significant. Note that as mentioned, the estimates for relative sea level rise for Mississippi and Alabama are based on the Pensacola tide gauge (ID# 246, Florida). All three Pacific coast state showed low correlations for the relationship between global mean temperature and the annual mean sea level rise per state ($0.4 < r < 0.6$) over the period 1950-2010. Bromirski *et al.* (2011) suggest that the sea level rise for the Pacific coast is suppressed for the last 30 years by dynamical steric response of the North Pacific eastern boundary ocean circulation to a change in wind stress curl. To assess the long term correlation for the Pacific, long term tide gauge records were examined for Washington (Seattle) and California (San Francisco). For Oregon no reliable long term tide gauge records were available. When comparing the global mean temperature with long term tide gauge records for the Pacific coast, significant correlations were found for both Seattle (1899-2010; $r = 0.79$) and San Francisco (1880-2010; $r = 0.78$). Since the suppressing effect of persisting wind stress on the sea level rise on the Pacific coast can be assumed to stop in the near future (Bromiski *et al.*, 2011), the correlation found for the long-term records is used as α for the Pacific coast. The significant correlations found between the global mean temperature and the annual mean sea level rise for each state show similarity with the correlation found by Rahmstorf (2007) for the relation between global mean temperature and global sea level rise.

Retrospective analysis

A retrospective analysis was performed for the GWC and $GWC^{+/+}$ scenarios for each of the coastal states. Note that since the ELT scenario is the linear trend of historic data, a retrospective analysis would yield perfect overlap. The analyses were benchmarked at a convergent point in 2010. The fit of the trend was analyzed by using the *confidence interval method* used by Santer *et al.* (2000). The method analyses an overlap between two time series with linear trends b_x and b_y and estimated standard errors s_{bx} and s_{by}. The overlap is defined as $b_x \pm s_{bx}$ and $b_y \pm sb_y$. Given an overlap, the null-hypothesis "*the trends are not significantly different*" is not rejected with a 95% confidence interval. For the GWC scenario it is found that for only 6 of the 22 coastal states (including Washington D.C.) the null-hypothesis needed to be rejected. An example of the *confidence interval method* for Maryland is shown in figure [5]. For the $GWC^{+/+}$ scenario, the null-hypothesis needed to be rejected for the majority of the states. This is caused by the influence of the *future* uncertainty attribute φ on the *past* sea level estimates. Since φ represents a uncertainty attribute as mentioned in the IPCC's fourth assessment report (e.g. sea level rise through other causes than thermal expansion), the $GWC^{+/+}$ scenario is still considered to be valid as a plausible future sea level scenario.

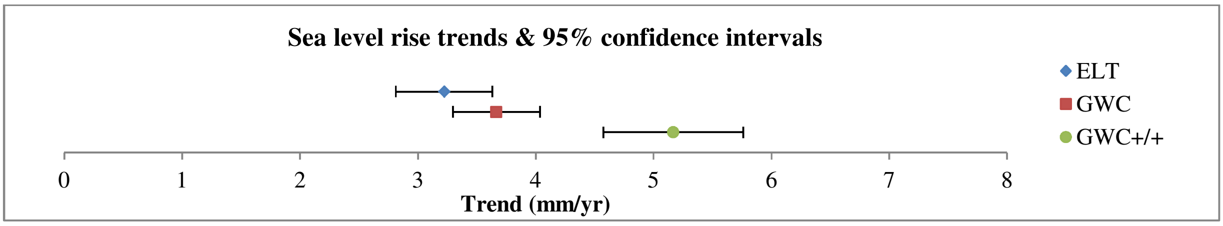

Figure [5] The confidence interval method for assessing trends and trend differences (Maryland as an example). The error bars are calculated from the estimated standard error of the residuals. Residuals are defined as the difference between the measured values and the trendline. When there is no overlap in error bars, the null-hypothesis is rejected. In this case, only for scenario 3 the null-hypothesis needed to be rejected

When the GWC scenario is derived from the long term records for Washington and California, the null-hypothesis needed to be rejected for 8 of the 22 coastal states. This is however as expected since Washington and California show suppressed sea level rise trends for the last 30 years (Bromirski *et al.*, 2011). Therefore, the results for the long term records for Washington and California are still considered valid assuming that "normal" sea level rise rates will resume (Bromirski *et al.*, 2011).

Equation (4) is used to correct the predicted sea level for 2100 for the states (excluding Washington and California) for which the null-hypothesis needed to be rejected.

$$(4) \qquad Adjusted\ RSL_{n_0-n} = RSL_{n_0-n} + \Delta\, Trend * (n - n_0)$$

The adjusted relative sea level in 2100 is calculated by adding *Δ Trend* (mm/yr) multiplied by the time period (n_0 = 2010, n = 2100) to the predicted relative sea level for 2100. The *Δ Trend* is calculated by *historic trend (1950-2010) – GWC trend (1950-2010 retrospective analysis)*. By definition, the RSL_{2100} will therefore be adjusted downwards when the trend is overestimated and upward when the trend is underestimated.

2.3 Scenario results

The results of the methodology described above are summarized in table [1]. The average relative sea level rise over all states is 0.3, 0.9 and 2.0 meter for the ELT, GWC and $GWC^{+/+}$ scenario respectively. A correction made to the estimation of the relative sea level rise for Texas is discussed in box 1. Maine and Louisiana represent respectively the lowest and highest estimates for all states for all scenarios. Due to the differences in vertical land movement, the results presented here show distinct variations of relative sea level rise for the Atlantic, Pacific, and Gulf coast.

Atlantic coast

The relative sea level rise from 2010-2100 for the Atlantic coast states ranges from 0.1-0.4 (ELT), 0.4-1.2 (GWC), and 1.3-2.5 ($GWC^{+/+}$) meters. The results show that relative sea level rise seems to steadily increase from the north to the mid-east Atlantic and steadily decrease from the mid-east to the south Atlantic, with Virginia and North Carolina being exceptions. Engelhart *et al.* (2009) constructed a database of late Holocene sea-levels for the Atlantic coast and found increasing subsidence rates from Maine (north) to Delaware (mid-east) and decreasing subsidence rates from Delaware to South Carolina (south) and attributed this to the Glacial Isostatic Adjustment. Nicholls & Leatherman (1996) found that especially in Virginia, the influence of the local component is very high, whereas in North Carolina the influence of the local component is very low (possible due to tectonic uplift of the Cape Fear Arch as mentioned by Thieler & Hammar-Klose in 1999), which explains the found deviations from the pattern found by Engelhart *et al.* (2009) for Virginia and North Carolina. The results found here (table [1]) show the same pattern as found by Engelhart *et al.* (2009) with the inclusion of the results found for Virginia and North Carolina by Nicholls & Leatherman (1996). This supports the notion that the Glacial Isostatic Adjustment is indeed the main driver for relative sea level rise on the US Atlantic coast, and causes a relatively high sea level rise on the mid Atlantic coast.

Table [1] Relative Sea Level (RSL) estimates for the year 2100, defined per state for the scenarios ELT, GWC and $GWC^{+/+}$. The table includes the used tide gauges per state. Values are given in meters.

Coast	State	Included tide gauges (ID#)	ELT RSL_{2100}	GWC RSL_{2100}	$GWC^{+/+}$ RSL_{2100}
Atlantic Coast	Maine (ME)	Portland (183); Eastport (322); Bar Harbor (525)	0.1	0.4	1.3
	New Hampshire (NH)	Boston, Massachusetts (235); Portland, Maine (183)	0.2	0.6	1.6
	Massachusetts (MA)	Boston (235); Woods hole (367)	0.2	0.7	1.9
	Rhode Island (RI)	Newport (351); Providence (430)	0.2	0.6	1.8
	Connecticut (CT)	New London (429)	0.2	0.8	2.0
	New York (NY)	New York (12); Montauk (519)	0.3	0.8	2.1
	New Jersey (NJ)	Philadelphia (135); Atlantic City (180); Sandy Hook (366)	0.3	1.1	2.4
	Delaware (DE)	Lewes (224)	0.3	1.1	2.3
	Maryland (MD)	Baltimore (148); Annapolis (311); Solomon's Island (412)	0.3	0.9	2.1
	Washington D.C.	Washington D.C. (360)	0.3	0.9	2.0
	Virginia (VA)	Sewells Point (299); Kiptopeke Beach (636)	0.4	1.2	2.5
	North Carolina (NC)	Wilmington (396)	0.2	0.6	1.6
	South Caroline (SC)	Charleston I (234)	0.3	0.8	1.9
	Georgia (GA)	Fort Pulaski (395)	0.3	0.9	2.0
	Florida (FL)	Key West (188); Cedar Key I (199); Pensacola (246); St. Petersburg (520); Fernandina Beach (112);	0.2	0.7	1.7
Pacific Coast*	Washington (WA)	Seattle (127)	0.2	1.0	2.2
	Oregon (OR)	----------------	0.2	0.9	2.1
	California (CA)	San Francisco (10)	0.1	0.9	2.1
Gulf Coast	Texas (TX)**	Galveston II (161); Port Isabel (497)	0.3	1.0	2.3
	Louisiana (LA)	Grand Isle (526)	0.8	2.5	4.3
	Mississippi (MS)	Pensacola, Florida (246)	0.2	0.6	1.6
	Alabama (AL)	Pensacola, Florida (246)	0.2	0.6	1.6

*NB: Due to large local variability of vertical land movement it is deemed impossible to give an average sea level rise prediction on state level for the Pacific coast states. The results here are based on two very long term tide gauge records (Seatlle, #127 & San Francisco, #10), and are stated to provide a basis for a "what-if" impact analysis in chapter 3.

**Estimates for Texas are corrected for recent policy measures that can have great influence on relative sea level rise. This is described in box 1.

Pacific coast

The relative sea level rise from 2010-2100 for the Pacific coast states ranges from 0.1-0.2, 0.9-1.0 and 2.1-2.2 meters for respectively the ELT, GWC and $GWC^{+/+}$ scenarios. The relative low variability on the Pacific coast is mostly attributed to the lack of useful data. The need for long term records because of the high impact of wind stress during the last 30 years (Bromorski *et al.,* 2011) restricted the data to two tide gauge records for the entire Pacific coast. Large difference in vertical land movement can occur over small spatial areas along the Pacific coast (Nicholls & Leatherman 1996; Thieler & Hammar-Klose, 2000a). When the medium long term records (1950-2010) are analyzed, large differences are found for records like Seattle, San Francisco, Neah Bay, Astoria (strongly influenced by the Columbia River) and Crescent City. The Pacific coast shows this great variability due to the collision of tectonic plates. In the Cascadian subduction zone, stretching from Canada to the northern part of California, the Juan de Fuca plate slides under the North American plate causing a vertical uplift in several regions along the Pacific coast of the US. As a result the Pacific coast shows a complex pattern of uplift and subsidence (Mazzotti *et al.*, 2008; Komar *et al.*, 2011). Because of this complex pattern, it is impossible to give an average relative sea level rise that conforms to the situation along the coast of either Washington, Oregon or California. Caution should therefore be taken when using these results. Concerning the focus of this research on a state aggregate level, the results given here are used as a "what-if" analysis for the Pacific coast. However, because of the geomorphology and the population density, the impact on relative sea level rise is high in the regions of the two used tide gauges as will be discussed in chapter 3, validating the impact analysis for the Pacific coast.

Gulf coast

The relative sea level rise from 2010-2100 for the Gulf coast states ranges from 0.3-0.8, 0.6-2.5 and 1.6-4.3 meters for respectively the ELT, GWC and $GWC^{+/+}$ scenario. The estimations for Mississippi and Alabama are based on the Pensacola tide gauge. The relative sea level rise for Mississippi and Alabama is considerably lower than the relative sea level rise in Louisiana. This is mainly due to regional factors in Louisiana, although the far most western tip of Mississippi might show deviating results from the state average. Both Louisiana and Texas face the problems of rapid land subsidence. The dominating process causing land subsidence in the northern Gulf of Mexico seems to be the extraction of subsurface fluids and hydrocarbons (Kolker *et al.,* 2011). Other contributing processes include deep crustal loading and the natural compaction of sedimentary deposits (Emery & Aubrey, 1991). Morton *et al.* (2006) found key indicators for the tight coupling of anthropological fluid withdrawal and subsidence in 1) the conversion of wetlands to open water in fluid extraction locations, 2) increased subsidence of wetlands after accelerated fluid withdrawal, 3) drop in subsurface pressure as a result of fluid withdrawal, 4) surface fault activity near producing fields, and 5) increased subsidence measured near producing fields than in nearby regions without producing fields. This leads us to conclude that in those regions human policy can greatly affect the rate of subsidence and that future rates will be mainly determined by hydrocarbon extraction. Depending on the necessity, it is likely that strict measures will be implemented in the face of impending submergence of land. The results for Texas are corrected in face of past and future policies to prevent land subsidence (see box 1).

The Louisiana subsidence rates seem to show a temporal pattern that compares well with the pattern of onshore oil production (Morton *et al.,* 2006; Morton & Bernier, 2010; Kolker *et al.*, 2011) and seem to show a 15 year lag between oil production and subsidence (Morton & Bernier, 2011). In 2012, the Coastal Protection and Restoration Authority of Louisiana published *Louisiana's comprehensive master plan for a sustainable coast* (Coastal Protection and Restoration Authority of Louisiana, 2012). The plan presents specific, achievable actions that aim to protect both homes and businesses and reverse the great loss of land occurring in Louisiana. The plan comprises of numerous adaptation strategies along the Louisiana coastline, but it is striking that the plan mentions subsidence only as a given factor. There is no significant notion of the potential of subsidence reduction in the 190 page report. In fact, the report specifically states that decision criteria on selecting projects are evaluated so that they would not have negative impact on the "Support for Oil and Gas". Even without effort the future subsidence due to hydrocarbon extraction could decrease because of the depletion of petroleum fields. On the other hand, continued extraction of conventional energy and the potential introduction of geopressured-geothermal fluids as an energy source could increase subsidence (Morton *et al.*, 2006) making a future prediction very dependent on policies.

Box 1: Relative Sea level Rise Correction for Texas

Historically Texas has seen great instances of land subsidence. Due to large regional differences, estimating the relative sea level rise for Texas is more uncertain than elsewhere except for Louisiana (Nicholls & Leatherman, 1996). Land subsidence has always been particularly high in the Harris-Galveston region due to hydrocarbon extraction and groundwater withdrawal (Emery & Aubrey, 1991; Nicholls & Leatherman 1996; Kolker *et al.,* 2011). Evidence for the close relation between extraction processes and subsidence was found by Morton *et al*. (2006). A decrease in subsidence was found after the formation of the Harris-Galveston Coastal Subsidence District and the implementation of extraction reduction policies (Holdahl *et al.,* 1989; Emery & Aubrey, 1991; Nicholls & Leatherman, 1996). The Harris-Galveston Coastal Subsidence District now reports that coastal subsidence has stopped due to the conversion of groundwater to surface water, and that coastal subsidence is negligible. To account for this change a new α is calculated for the Galveston tide gauge (#161). This is done by removing the residual component (mm/yr), which represents local subsidence, from the historic data and calculating the new relation for α. The residual component (mm/yr) is found by subtracting the Port Isabel residual component from the Galveston residual component as given by Nicholls & Leatherman (1996). The new α is representative for a situation in which the local subsidence has stopped. The correlation found between relative sea levels and global surface temperature shows a significance of 0.71 for the new α for Galveston. The new estimation for sea level rise is found by averaging the results for Port Isabel (#497) and Galveston (#161) resulting in 0.3, 1.0 and 2.3 meter in 2100 for respectively the ELT, GWC and $GWC^{+/+}$ scenario.

3. THE IMPACT OF SEA LEVEL RISE ON THE US COASTAL STATES

Not only is the relative sea level rise distinctly different per state, the impact that relative sea level rise has on each state differs due to differences of population distribution, land elevation, GDP per capita, and numerous other physical and anthropologic factors. Determining the impact per state offers an insight in the different consequences sea level rise has on the shorelines of the conterminous United States. This chapter provides a methodology to translate relative sea level rise to impact on inhabitants, land, and GDP and a discussion of the results. The results provides in a deeper understanding of how sea level rise could affect the United States, and which states are most in danger to suffer from sea level rise.

3.1 Impact analysis methodology

The results on relative sea level rise provided in chapter 2, table [1] serves as the input for the methodology described below. The methodology is repeated for each state and for the ELT, GWC and $GWC^{+/+}$ scenarios. The impact of relative sea level rise on the US coasts is analyzed by using a geographic information system (GIS). GIS software combines cartography, statistical analysis and database technologies. ArcMap 10, ArcGIS® software by Esri is used here to analyze the impact of sea level rise. The software provides tools to do spatial analysis on geographically referenced information.

Methodology: Inundation of land

Land along the coastal states will become inundated with rising sea levels. To allow statistical calculations, inundation maps like the map in figure [6] are created. National Elevation Data (NED) is obtained from the database of the U.S. Geological Service (Gesch *et al.*, 2002; Gesch, 2007). Seamless elevation data with a spatial resolution of 1 arc second (roughly 30 meter) is used. A single raster file for elevation is composed for each state. Inundation maps are created for the projected sea levels in 2100 for the different scenarios. An example is given in figure [6].

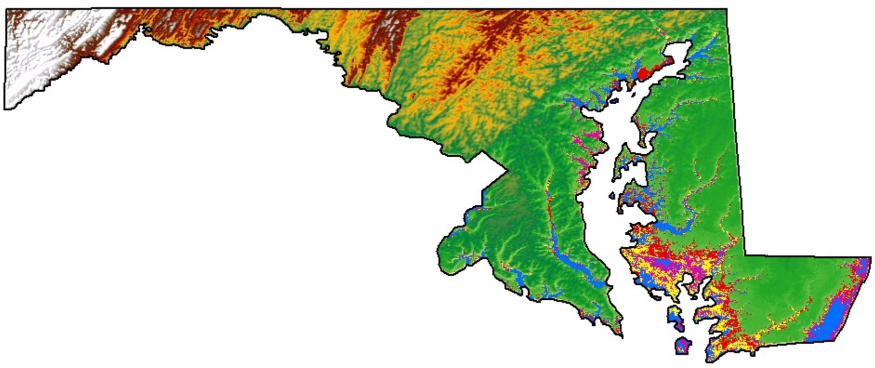

Figure [6] Inundation map for Maryland. Blue: Zero sea level rise. Purple: 0.3 meter sea level rise (ELT). Yellow: 0.9 meter sea level rise (GWC). Red: 2.1 meter sea level rise ($GWC^{+/+}$). The inundation maps are created by calculating new raster's with a specific value (1) for "elevation <= projected sea level".

The area of the inundated land is obtained by calculating the cells in each state which are covered by the inundation maps. State and county cartography is obtained from the Tiger database (*Topologically Integrated Geographic Encoding and Referencing)*. The TIGER/Line files® are public products created from the Census Bureau's TIGER database. By converting the cell size to km^2 a metric measurement of inundated land is obtained.

Methodology: Inhabitants displaced

Due to the inundation of populated areas, inhabitants will need to move if no action is taken to reduce to impact of sea level rise. To assess the number of inhabitants displaced, population distribution maps are created. Population density data (GRUMPv1) is obtained from the Center for International Earth Science Information Network (CIESIN, 2012). CIESIN provides globally consistent and spatially explicit human population information. Gridded population density of the year 2000 is used because of the availability of high resolution data (30 arc seconds). Each cell has a value *population/km*^{2}. The GRUMPv1 data is resampled to a cell size of 1 arc second to match the inundation map resolution.

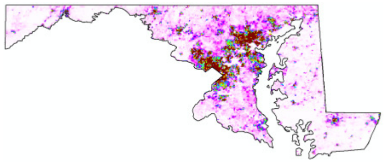

Figure [7] Population density maryland

Figure [8] Population under 0.3 m of SLR

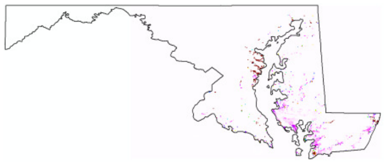

Figure [9] Population under 0.9 m of SLR

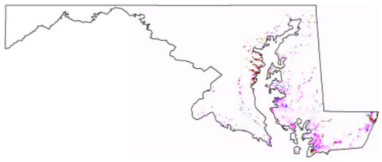

Figure [10] Population under 2.1 m of SLR

The population under sea level rise (SLR) maps are computed by raster calculations, where *population under X meter of SLR = inundation x population density* (inundated cells are given a value of 1). The population under sea level rise is calculated by summing the cell values and multiplying the cell count with the cell size in km^2. The resulting maps are shown in figure [7]-[10]. The error is obtained by calculating the total population for a state with the population density map, and comparing it to the actual population in 2000 (CIESIN, 2012). It is found that the value obtained deviates ≤ 7% from the reported population in 2000 for the US coastal states.

Methodology: GDP affected

With the inundation of land and the displacement of inhabitants, production will be affected impeding GDP. To assess the impact, a GDP distribution map is created for each state. The GDP distribution maps are created by calculating *cell value = GDP per capita per county x population density*. Both GDP per capita and population density are resampled to 1 arc second, so the resulting GDP distribution maps match the resolution of the inundation maps. GDP per capita per county is calculated by adding population per county and GDP per county to the county file in ArcGIS and calculating a new field containing GDP per capita per county to the tigerline files. The process is shown in figure [11].

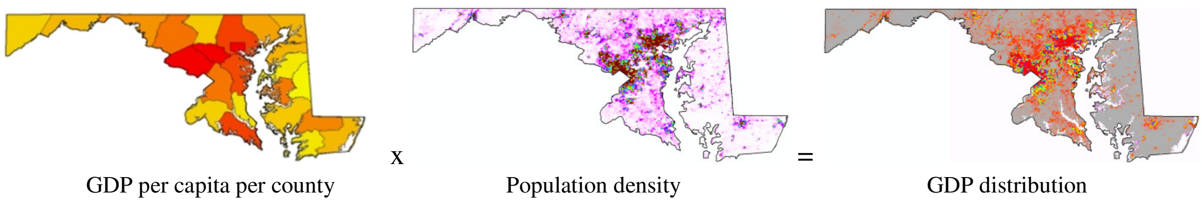

Figure [11] Calculating the GDP distribution for the state of Maryland. GDP per capita per county is rasterized and multiplied with the population density raster to create GDP distribution.

This approach assumes that GDP is produced where people live. In general, this assumption is correct although it might not hold on a very small scale. Since the GDP distribution is based on the population density the same error of 7% is assumed. Data on GDP per county and total population per county is obtained from the Spatial Trends in Coastal Socioeconomics (STICS)[3] database of the National Oceanic and Atmospheric Administration (NOAA). STICS derives its information from the Census Bureau.

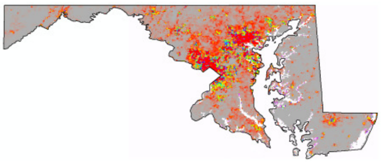

Figure [12] GDP distribution Maryland

Figure [13] GDP under 0.3 m of sea level rise

Figure [14] GDP under 0.9 m of sea level rise

Figure [15] GDP under 2.1 m of sea level rise

The shapefile is converted to a raster and multiplied with the population density raster to obtain the GDP distribution map. The GDP under sea level rise maps are computed by raster calculations, where *GDP under X meter of SLR = inundation x GDP distribution* (inundated cells are given a value of 1). The results for Maryland are shown as an example in figure [12]-[15].

3.2 Impact results

The results on the impact of relative sea level rise on inundated land, inhabitants displaced and GDP are summarized in table [2]. The values given are considered good estimates of the impact if no adaptive or mitigative measures are taken to counteract the threat of (relative) sea level rise. The absolute values of inundation are mainly determined by the elevation of the terrain, the relative sea level rise and the length of the coastline. Subsequently, the absolute values on inhabitants displaced and the GDP affected are determined by a combination of the area inundated, the population density distribution and how the GDP distribution is divided over the coastal counties. The results are explained in the following paragraphs. The implications of the results for adaptive and mitigative policies are described in chapter 4.

NB: The results on the Pacific coast are based on a "what-if" analysis that does not take into account the great variability of vertical land movement along the Pacific coast. However, the relatively high impact in the Pudget Sound and San Francisco Bay area account for the largest share for the total impact on the Pacific coast for each of the three indicators. Since these are also the areas where the calculations for the relative sea level rise are based on (Seattle and San Francisco tide gauges), the results are considered to give a good indication of the overall impact.

[3] http://coastalsocioeconomics.noaa.gov/download/download2.html

Table [2] Impact of relative sea level rise on the inundation of land, inhabitants displaced and GDP production affected for the US coastal states. State abbreviations are given as well as the length of the coastline per state, which are based on calculation by NOAA (2012).

Coast	State	Coastline (km)	**Inundated land (km2)**			**Inhabitants displaced (x 1000)**			**GDP affected (USD x billion)**		
			ELT	GWC	$GWC^{+/+}$	ELT	GWC	$GWC^{+/+}$	ELT	GWC	$GWC^{+/+}$
Atlantic Coast	ME	5597	366	470	706	12	16	28	0.21	0.32	0.63
	NH	211	29	36	62	4	4	10	0.05	0.06	0.25
	MA	2445	26	83	246	15	48	115	0.89	3.39	6.73
	RI	618	48	80	126	21	32	53	0.50	0.77	1.23
	CT	995	10	40	78	5	18	36	0.29	0.94	1.91
	NY	4225	154	260	496	131	228	550	2.93	5.37	14.95
	NJ	2884	665	1157	1907	157	262	536	4.08	7.93	18.96
	DE	613	30	266	584	3	11	34	0.16	0.50	1.66
	MD	5130	711	1568	2455	71	106	177	1.17	2.06	4.00
	D.C.	-	2	4	6	2	5	8	0.41	0.78	1.32
	VA	5335	886	1757	2724	58	132	347	1.32	3.78	11.80
	NC	4432	1432	3939	6501	32	65	128	0.59	1.43	3.09
	SC	4628	662	1300	2764	34	55	129	0.93	1.72	4.88
	GA	3772	592	1347	2219	9	27	69	0.28	0.90	2.55
	FL	13,576	2585	6662	13655	349	722	2823	7.31	18.19	98.20
Pacific Coast	WA	4870	31	132	532	7	15	46	0.18	0.18	0.93
	OR	2270	10	54	254	2	4	14	0.00	0.03	0.27
	CA	3427	1026	1281	2300	29	83	241	0.80	2.96	11.52
Gulf Coast	TX	5406	400	1315	6163	15	31	210	0.55	1.19	8.29
	LA	12426	20329	27000	31048	925	1391	1764	53.43	77.74	94.62
	MS	578	28	152	548	1	11	36	0.02	0.20	1.20
	AL	977	129	237	881	4	6	13	0.03	0.07	0.26
	Total	**84415**	**30150**	**49140**	**76256**	**1885**	**3272**	**7367**	**76**	**130**	**289**

Considering the timespan of the scenarios, population growth and growth of GDP will have a profound influence on the results. Determining how population growth and growth of GDP will develop is however extremely difficult. Not only do the normal uncertainties with growth play a role, the actual effects of relative sea level rise will determine for a large extent how this growth will occur. Numerous factors related to sea level rise will determine how population and GDP will grow in a certain area which is presently at the seashore. Because of this great uncertainty, growth of population and GDP are *not* considered in the results presented in table [2], and figure [18] and [19]. Including them is considered to reduce the validity of the results. Again it is therefore stressed that the results presented are the absolute *minimum* impact under a scenario with no adaptive or mitigative action. Here, a short discussion is provided on how growth might take place in those region threatened by sea level rise.

If no adaptive measures are taken, population and GDP growth in a certain area is likely to follow a path of normal growth, decreasing growth, slow decline and rapid decline when the impact of sea level rise become more and more apparent and habitation becomes less and less possible (fig. [16]). During normal growth, the effects of relative sea level rise are not directly threatening inhabitants. The seashore might migrate but no frequent inundation takes place. During decreasing growth the effects become more visible, with more frequent inundations and a migrating shoreline. Inhabitants might become more aware of the structural problems caused by relative sea level rise. People might not be moving into the area and the normal outward migration slows down growth. During slow decline the effects of sea level rise might become a real threat, with storm height increasing (see also appendix A). In addition to normal outward migration, inhabitants are now actively leaving the region. The last phase of rapid decline is a phase in which the shoreline has migrated significantly inland and structural damage is frequent. Inhabiting the region becomes near impossible, and no other option is left than migrating from the area. The duration of each of the phases is depending on many physical factors (e.g. land elevation, storm frequency) and socio-economic factors (e.g. risk awareness, reduced tourism). Note that the curve will be significantly different for each coastal state in the United States, with different regions showing different population/GDP growth.

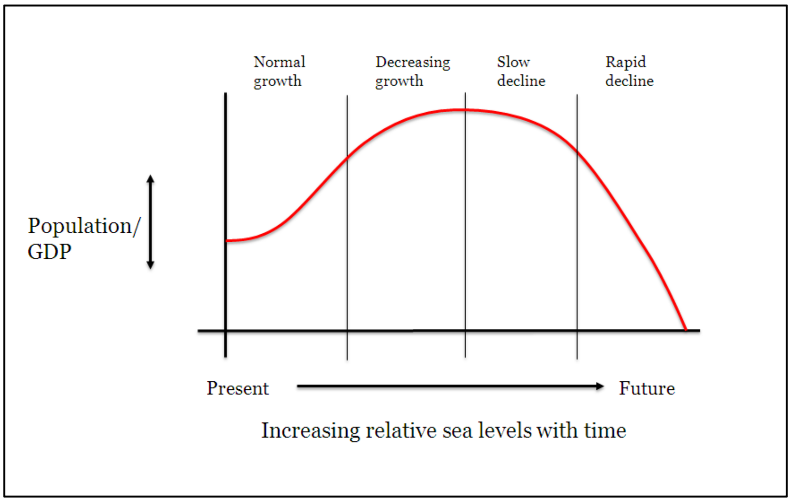

Figure [16] Illustration of a possible growth path of population/GDP growth and decline near shore regions under threat of relative sea level rise.

Further research on population and GDP dynamics in face of sea level rise are desirable and will contribute greatly to our understanding of the potential impact on the United States coast. As shown in table [2], the minimum impact on population and GDP is already profound. As a sensitivity analysis, a calculation is done for population assuming a 20 year normal growth period and 30 year of decline to zero growth for the ELT scenario, a 15 year normal growth period and 25 year of decline to zero growth for the GWC scenario, and a 10 year normal growth period and 20 year decline to zero growth for the $GWC^{+/+}$ scenario. Furthermore, it is assumed that growth distribution is proportional to the current population distribution. Growth rates per state for the period 2000-2010 (U.S. Census Bureau, 2011) are given in table [3]. Under these arbitrary assumptions, impact on population would increase with 28% to ~2.4 million people displaced under the ELT scenario, with 24% to 4.1 million people displaced under the GWC scenario, and with 24% percent to 9.1 million people displaced under the $GWC^{+/+}$. Since GDP is linked to population density, roughly the same percentual increase would be seen for GDP, although inflation will have some effect. The impact on state level would change to some respect in accordance to the growth rates as shown in table [3]. This shows that impact could increase significantly, depending on growth dynamics.

Because of the high uncertainty of how population and GDP will grow in face of sea level rise, and the arbitrarily chosen assumption, these calculations will not be used for further impact assessment. Instead, the more accurate results given in table [2] that represent the absolute minimum impact if no action is taken are used throughout the remainder of the report.

Table [3] Population growth in % over the period 2000-2010 for the coastal states of the conterminous United States. Source: U.S. Census Bureau (2011).

State	Growth '00-'10	State	Growth '00-'10	State	Growth '00-'10	State	Growth '00-'10
ME	4.2%	NJ	4.5%	SC	15.3%	TX	20.6%
NH	6.5%	DE	14.6%	GA	18.3%	LA	1.4%
MA	3.1%	MD	9.0%	FL	17.6%	MS	4.3%
RI	0.4%	D.C.	5.2%	WA	14.1%	AL	7.5%
CT	4.9%	VA	13.0%	OR	12.0%		
NY	2.1%	NC	18.5%	CA	10.0%		

Inundation of land

The total estimated area of inundated land is ~30.000, ~49.000 and ~76.000 km^2 for respectively the ELT, GWC and $GWC^{+/+}$ scenario. The inundation in Louisiana accounts for approximately 60%-40% (ELT-$GWC^{+/+}$) of the total inundated land in the conterminous United States and the inundation in Florida accounts for approximately 8-18% (ELT-$GWC^{+/+}$). Together with North Carolina (ELT-$GWC^{+/+}$: ~5-8%) and Texas (ELT-$GWC^{+/+}$: ~1-8%) these states make up for 74% of the estimated land inundated. Louisiana shows extreme levels of inundated land. The large area of inundated land can be attributed to 1) the high rate of relative sea level rise due to high rates of subsidence caused by hydrocarbon extraction and 2) the large areas of low-lying wetlands stretching along the entire coast of Louisiana. Note that the relatively large absolute impact on the coast of Florida and Louisiana is partly caused by the sheer length of the coastline for these states as is shown in Table [2].

To gain a better perspective on the vulnerability of the different coastlines, the impact is calculated as a ratio of inundated land/1000 km shoreline and is shown in figure [17]. The lengths of the coastlines are obtained from NOAA (2012). Washington D.C. is excluded since no information on coastline was available. The average result of the $GWC^{+/+}$ scenario is presented as a dotted line to highlight those states which see above average impact. As with the absolute values, impact per 1000 km shoreline is highest in Louisiana, Florida, Texas and North Carolina. There is no distinction between dryland loss and wetland loss. Note that wetlands are dynamic systems that can respond to sea level rise. However, development of dryland will prevent wetlands to migrate and are thus squeezed out (Titus *et al.*, 2009). Furthermore, rapid sea level rise coupled with subsidence prevents wetlands to regenerate through sediment loads, submerging them which eventually lead to the conversion to open water (Kolker *et al.*, 2011).

The impact of sea level rise is different for each state due to different coastal characteristics. The North Atlantic coast is highly variable in coastal landforms, but is mainly dominated by rocky coastline and cliffs (Hapke *et al.*, 2010). The North Atlantic coast was for a large part covered under ice sheets during the last glacial period. With the retreat of the ice sheets, a rugged, rocky terrain was left behind. Since this region also sees low relative sea level rise, the impact on land inundation is moderate. Still, there are several (low-lying) mainland beaches, like in the Boston area and popular tourist centers, which are more vulnerable to inundation. For the North Atlantic, this means that inundation of land is low, as shown in figure [17], but because populated areas are located at beach and ocean front, impact is relatively high on population as shown in figure [18]. This is further discussed in the paragraph "*Inhabitants displaced*".

The Mid-Atlantic coast is characterized by a chain of barrier islands backed by estuaries and lagoons (Thieler & Hammar-Klose, 1999; Morton & Miller, 2005). The South Atlantic coast shows the same characteristics, but also has long stretches of linear beaches and extensive marshes (Morton *et al.*, 2004; Morton & Miller, 2005). Wetlands are common along the mid-Atlantic coast and the South Atlantic coast (see Stedman & Dahl, 2008, for an analysis of wetland density for the United States). Since these coasts are naturally low lying areas with little or no slope, they are therefore very vulnerable to inundation due to relative sea level rise. On top of that, chapter 1 shows that the mid Atlantic coast sees the highest relative sea level rise along the Atlantic. This is shown in figure [17]. Especially North Carolina and Florida have large areas of coastal wetlands and show the largest impact on inundation per kilometer. Considering that North Carolina has a low predicted relative sea level rise (table [1]) the vulnerability to inundation due to sea level rise seems particularly high.

The Gulf coast shows similar features as the mid and south Atlantic coast and is in general is characterized by barrier islands, lagoons and marshes that run along the Gulf coast (Thieler & Hammar-Klose, 2000b; Morton *et al.*, 2004). However, differences in coastal formations are seen in each state. Alabama only has a small stretch of coast, which mainly consists of sandy barrier islands. The Mississippi coast has widely spread barrier islands, and long stretches of exposed mainland beachfronts (Morton *et al.*, 2004). The Texas coast is characterized by many barrier islands and Louisiana is characterized by large delta's (Morton *et al.*, 2004). Most regions are low lying terrain (Morton *et al.*, 2004), which in combination with the extreme high relative sea level rise (due to subsidence) makes Louisiana extremely sensitive to inundation as shown in figure [17].

The Pacific coast shows low result for inundation per km coastline despite the moderate relative sea level rise found in chapter 1. On the Pacific coast, the Juan de Fuca plate slides under the North American plate which causes the land to show a steep elevation from the coastline inlands, reducing vulnerability to inundation. California shows higher results on inundated land because of the geography of the San Francisco Bay area and a more gradual slope of the land along the coast in southern California (Thieler & Hammar-Klose, 2000a). While northern California has an irregular coast with steep cliffs and offshore islands, southern California has long stretches of beachfronts (Hapke *et al.*, 2006), making it more vulnerable for inundation.

From the results presented here, it is clear that the impact of relative sea level rise differs greatly per state. The values found are in good agreement with the knowledge on coastal geological characteristics (Thieler & Hammar-Klose, 1999; Thieler & Hammar-Klose, 2000a; Thieler & Hammar-Klose, 2000b). Highest (absolute) impact on land is seen in Louisiana, Florida, North Carolina and Texas. The combination of low-lying terrain and high relative sea level rises causes fast land surface areas to be inundated. The response to relative sea level rise will therefore vary among states. The strategic response will however be determined to a large extent by the impact on inhabitants and GDP, since extensive inundation does not per se signal a high impact on socio-economic factors.

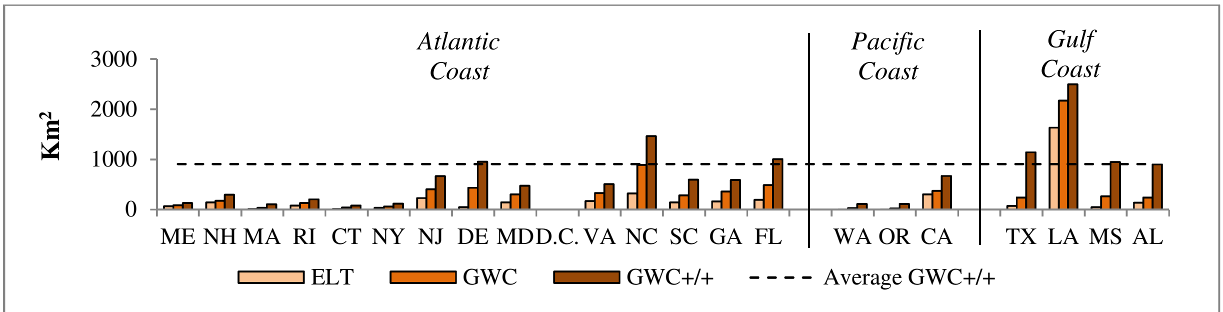

Figure [17] Area inundated in km^2 per 1000 km of coastline. ELT: Extended Linear Trend. GWC: Global Warming Coupling. $GWC^{+/+}$: Global Warming Coupling and accelerated Glacier and Ice Cap Melting under a high uncertainty scenario. The average of the $GWC^{+/+}$ scenario is presented as a dotted line.

Inhabitants displaced

The total number of inhabitants displaced is ~1.9, ~3.2 and ~7.4 million inhabitants for respectively the ELT, GWC and $GWC^{+/+}$ scenario. Louisiana would see the largest number of inhabitants displaced under the ELT (~49%) and GWC (~42%) scenario. Florida would see the largest number of inhabitants displaced under the $GWC^{+/+}$ (38%) scenario. Together with New York (ELT-$GWC^{+/+}$: ~7-7.5%) and New Jersey (ELT-$GWC^{+/+}$: ~8-7%) these states account for ~83-77% (ELT-$GWC^{+/+}$) of the impact. The high impact of relative sea level rise is mainly caused by the location of major cities near ocean fronts. Eight of the top ten nationally ranked cities for largest total population below 4 feet above mean sea level are located in Florida (Strauss *et al.*, 2012). New York, also low above sea level, ranks second on this list. New Orleans (Louisiana), of which two thirds is built on reclaimed land, is vulnerable to low levels of relative sea level rise. The impact of inundation became apparent when hurricane Katrina hit, breaking through levees and inundating large sections of the city.

To show the vulnerability of the coastlines the impact on inhabitants is shown as inhabitants' displaced/1000 kilometer shoreline and is shown in figure [18]. The average result of the $GWC^{+/+}$ scenario is again presented as a dotted line, and again highlights those states that would see an above average impact per 1000 kilometer shoreline. Note that the presented results are an average for the whole state. The impact varies greatly on local scales. Inundation in urban areas has a far greater impact on inhabitants displaced than inundation in rural and uninhabited areas. This becomes apparent when figure [17] is compared to figure [18]. States with a relatively low density of coastal wetlands and with large cities located at the sea front show a high number of inhabitants displaced despite of low inundation levels due to relative sea level rise. This is especially true for a large part of the northeast Atlantic coast states Massachusetts, Rhode Island, Connecticut, New York and New Jersey. New Jersey shows particularly high impact which is due to the development of all but one of its barrier islands and the tendency to fill coastal marshes for development (Titus *et al.*, 2009). In Massachusetts, the Boston area is most vulnerable to sea level rise due to beachy shores. This coincides with the fact that the Boston area is heavily developed, with large population centers (Hapke *et al.*, 2010). Therefore the impact on inhabitants is relatively high with only low levels of inundation. The same is seen in Rhode Island and Connecticut. The state of New York faces the ocean at long island, which is moderately to densely developed (Hapke *et al.*, 2010). However, closer to New York City, development increases. New York City itself is one of the most densely populated cities in the world. Sea level rise impact on inhabitants is therefore large despite of low levels of inundation as is obvious when comparing figure [17] and [18]. The results show that future action to prevent the impact of sea level rise depends heavily on the combination of land inundated and population density. Even small levels of inundation as seen in the New England region can cause relatively high impact on population. With respect to policy, this could mean that protecting a small area by adaptive measures will have significant benefits. Chapter 4 discusses the implications for future policies in further detail.

The majority of the states on the mid and south Atlantic coast that have a relatively high density of coastal wetlands show a low impact on inhabitants displaced per 1000 kilometer of coastline. This is attributed to the fact that states like Virginia, North Carolina, South Carolina and Georgia have most of their developed land further inland from the coast (Titus *et al.*, 2009). On a state level, sea level rise is more a threat to wetlands in these states than it is to population. For the mid and south Atlantic coast the strategic response on state level should therefore differ from the New England region in order to address the impact in the most sustainable matter (Chapter 4). NB: locally the impact on population can be significant.

Figure [18] shows that Florida sees a significant impact on population. The Florida coast is flat, and large cities are located near shore. Florida is well known for its popular beachfronts, and there are numerous tourist centers located at the seafront. Considering absolute impact as shown in table [2], Florida is one of the most vulnerable states due to its extreme long coastal border. Careful planning for future sea level rise is therefore of utmost importance here.

Compared to the Atlantic coast, the impact on the Pacific coast is small, except for southern California. Along the Pacific coast California sees the highest impact on inhabitants. This is partly attributed to the fact that California sees the highest level of inundation as shown in figure [17]. Besides higher levels of inundation, southern California is the most densely populated part of the Pacific coast with communities right by the sea (Hapke *et al.*, 2006). The northern part of California and the coast of Oregon and Washington are rugged an inaccessible and there sparsely populated. Impact on population in those regions is therefore very low.

Along the gulf coast, impact on inhabitants is moderate for Texas, Mississippi, and Alabama, and is especially high in Louisiana as shown in figure [18]. This is somewhat mitigated by the fact that Louisiana has a long stretch of coast which is characterized by wetlands. If the absolute impact is considered as shown in table [2], it is clear that Louisiana is under great threat. This stems mainly from the fact that New Orleans is already below sea surface, and that Louisiana is subsiding fast. Louisiana faces serious problems that need to be addressed with urgency.

From figure [17], [18] and table [2] it can be concluded that the impact of relative sea level rise on inhabitants is significantly different from the impact on land. This will greatly determine how states need to react to sea level rise. States like Maine, Washington, Oregon and Alabama, which show very low impact on inhabitants can adopt softer measures, while states like New York need to revert to hard protection. As mentioned previously, chapter 4 will handle this issue in more detail.

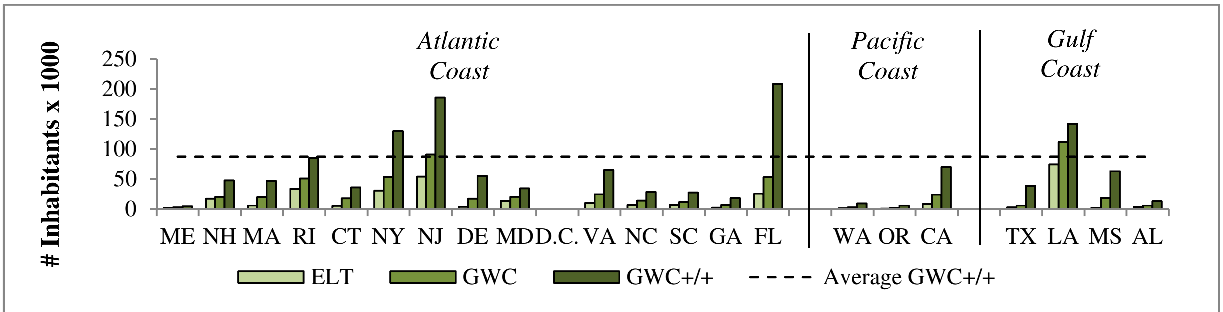

Figure [18] Inhabitant displacement per 1000 km of coastline. ELT: Extended Linear Trend. GWC: Global Warming Coupling. $GWC^{+/+}$: Global Warming Coupling and accelerated Glacier and Ice Cap Melting under a high uncertainty scenario. The average of the $GWC^{+/+}$ scenario is presented as a dotted line.

GDP affected

The total GDP production affected is ~76, ~130 and ~289 billion USD/year (~0.5-1.9% of the GDP of the whole United States in 2010). Louisiana would see the largest impact on GDP production under the ELT (~70%) and GWC (~60%) scenario. Florida would see the largest impact on GDP production under the $GWC^{+/+}$ (34%) scenario. Together with New York (ELT-$GWC^{+/+}$: ~4-5%) and New Jersey (ELT-$GWC^{+/+}$: ~5-7%) these states account for ~78-89% of the impact on GDP production depending on the different scenarios. Since GDP is calculated based on population density, approximately the same division of percentages seen on inhabitants displaced can be seen for GDP as shown in figure [19]. The causes of the differences per state are therefore the same as provided above for inhabitant displacement. However, the results deviate slightly because of differences in GDP per capita for the different counties per state. States which have a relative low GDP in coastal counties show a drop with respect to the inhabitants displaced (e.g. Rhode Island; Maryland) while the opposite is true for states with relative high GDP in coastal counties (e.g. Massachussets; Florida; New Orleans, Louisiana).

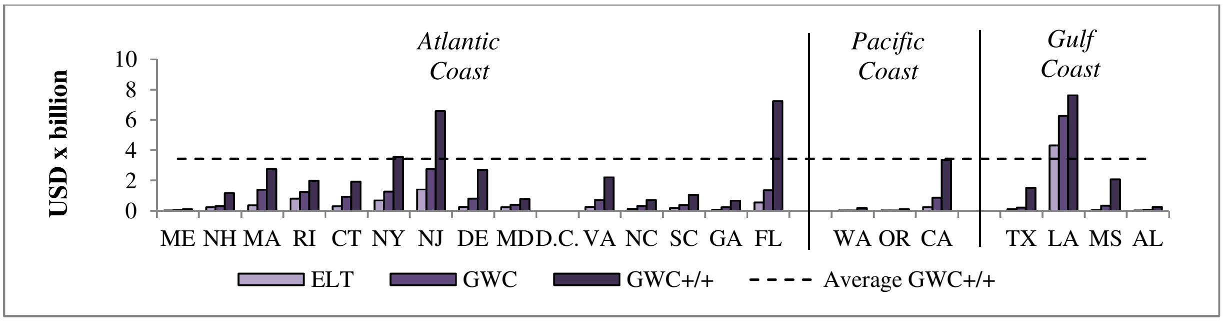

Figure [19] GDP production affected per 1000 km of coastline. ELT: Extended Linear Trend. GWC: Global Warming Coupling. $GWC^{+/+}$: Global Warming Coupling and accelerated Glacier and Ice Cap Melting under a high uncertainty scenario. The average of the $GWC^{+/+}$ scenario is presented as a dotted line.

GDP production is used here as an economic indicator of the impact of relative sea level rise. Determining the economic impact is however extremely difficult. Normal depreciation of production facility/capacity might lead to a natural response to progressive seashores even under scenarios of no adaptive measures. On the other hand, GDP produced in seashore tourism and the GDP associated with wetlands could have a more rigid and negative response to relative sea level rise. Several studies have attempted to determine the economic impact of sea level rise for the United States (Nordhaus, 1991; Titus *et al.*, 1991; Yohe, 1991; Fankhauser, 1995; Yohe *et al.*, 1996; Yohe & Schlesinger, 1998). Neumann *et al.* (2000) summarize the results and come to an economic impact between 20 billion (with efficient adaptation) and 150 billion (if vulnerable areas are inundated) for the developed coast of the United States if sea levels rise uniformly with 0.5 meter. The cost of wetland loss is especially hard to determine due to gaps in knowledge on the response and the value of wetlands, but could significantly increase the cost for the United States (Neumann *et al.*, 2000). These economic assessments do however not serve a purpose on state level. Without the use of high resolution elevation maps and relative sea level rise these studies only give a very broad generic estimation of the economic impact. Furthermore, difference in land value, infrastructure, development, land use, and socio-economics make generic estimations of damage less useful. Darwin & Toll (2001) state that many analyses that focus on the economic impact of sea level rise are imperfect, using rough and incomplete databases, and crude methods. Furthermore, most studies ignore the dynamic response of economic value of land and the market response due to sea level rise. Bosello *et al.* (2007) performed an analysis taking into account such dynamic responses. Unfortunately they too used a uniform sea level rise of 25 cm in 2050, which does not represent reality. Furthermore, the economic crisis that occurred in 2008 devaluated property and land, making previous estimates on value obsolete. More specific analyses of economic impact are done on a local scale (Ayyub *et al.*, 2011; Heberger *et al.*, 2011) and are presumably more successful in giving an adequate assessment of the economic impact of sea level rise.

The results presented in this study focus on the production of GDP per year linked to population density. Because of the high aggregate state level and the effort to obtain a simple indicator on state level, it excludes the cost of damage to infrastructure, buildings, ecosystems etcetera. To assess the cost of direct economic impact it is recommended to perform detailed analyses on local levels, since generic results would not provide the accuracy needed. The use of GDP does provide a general indicator of what the impact of sea level rise could mean for coastal state economies. Keeping the above in mind, this research gives an absolute minimum economic impact under a no action scenario for each state.

The results on land inundated, population displaced and GDP give an overview of the impact of sea level rise per state. The impact is explained above, and shows for each state or region what they would face in the year 2100 if no action is taken. Chapter 4 discusses the implications of this impact for determining a timely response strategy.

3.3 A brief discussion on other impacts

The choice of examining the issues above is made to provide an assessment of simple key indicators for the impact of sea level rise on a state resolution. As introduced in chapter 1, the impacts of sea level rise are numerous. Damage can occur on infrastructure and buildings, tourism could decline, and soil could be contaminated. These are just some examples of the different impacts of sea level rise. Two of the most often mentioned impacts that are not discussed as indicators in this research are erosion and saltwater intrusion. Here, a discussion is given for both to provide a more complete overview of the impact of sea level rise.

Erosion

Coastal erosion is the permanent or temporary loss of sand from beaches and dunes. Coastal erosion can mainly be attributed to waves, currents, and tides. Although all shorelines are affected by erosion, the rate is very different depending on the (geo-)morphology of the coast. Shorelines tend to erode and deposit the sand in the direction of the current, a process that is called longshore drift. Human interference like the construction of bulkheads can hinder the natural erosion, causing regions further down-current to erode faster than they would under natural conditions. Increasing sea levels increase erosion by enabling high-energy, short period storm waves to reach farther up the beach (Leatherman, 2001). Coastal retreat is determined by the combined effect of inundation and erosion (Leatherman, 2001). Erosion rates increase due to sea level rise, and the impact on the set indicators can be more significant since inundation and erosion both impact the developed and natural shorelines of the United States.

Figure [20] provides a map showing the vulnerability to erosion for the conterminous United States. The map is created in ArcMap 10 by Esri, using data on erosion obtained from Hammar-Klose & Thieler (2001). The largest part of the United States is at moderate risk of coastal erosion, which is defined by Hammar-Klose & Tieler (2001) as a stable shoreline. Especially the Pacific coast, with large cliffs due to tectonic uplift, shows stable shorelines. However, Allan & Komar (2006) show that increased wave height might increase erosion along the Pacific coast, and future climate change might cause this pattern to persist throughout the coming decades. Furthermore, yearly average erosion obscures that the crumbly sedimentary rocky shorelines are subject to periodic large scale erosion due to extreme weather events like El Niño (the Heinz Center, 2000). Along the Atlantic coast the erosion risk is in general high or very high from New York to South Carolina due to the large areas of wetlands, sandy beaches and barrier islands. The northern part of the Atlantic coast consists mainly of rocky coasts and cliffs from glacial deposits and is therefore relatively stable. Along the Gulf of Mexico, erosion and accretion are relatively balanced for the largest part of Texas and the Florida peninsula (Davis, 1997). Strong rates of erosion along the Louisiana and Mississippi coast can be attributed to the diminished sand supply from the Mississippi and Atchafalaya rivers, which cause the rapid loss of wetlands and barrier islands (Davis, 1997). If this is compared to the results on inundation (fig. [17]) it is clear that areas with high inundation in general also are subject to high erosion rates. The link can be explained by the characteristics of low-lying areas (e.g. wetlands, sandy beaches) and the strong response of these areas to erosion.

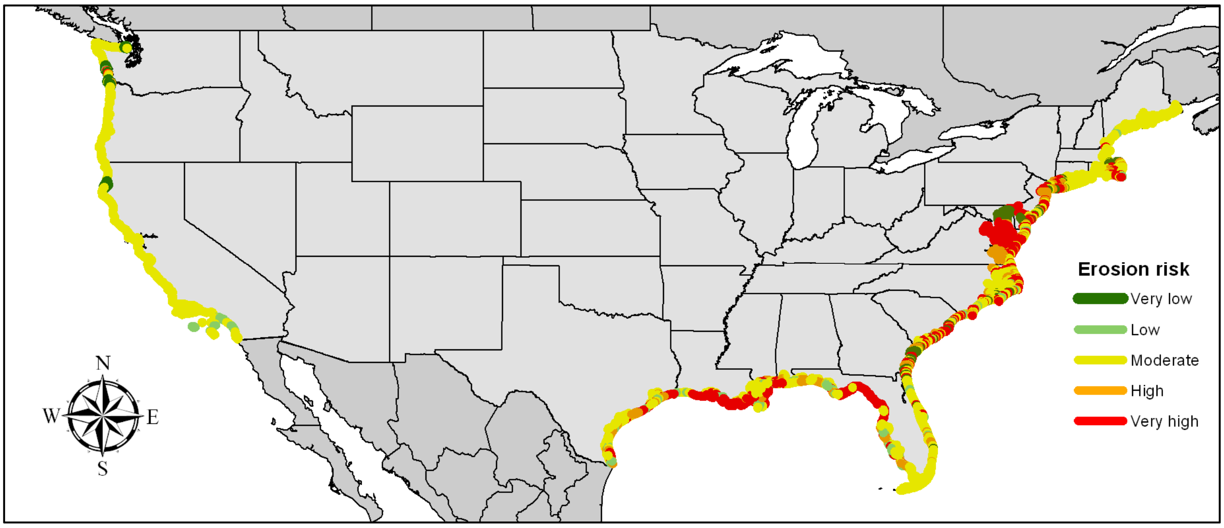

Figure [20] Erosion along the shores of the conterminous United States. Source of erosion data: Hammar-Klose & Thieler (2001). Using ArcMap 10 by Esri, the erosion risk is shown in polygon format. Very low: 2> m/yr accretion. Low: 1.0-2.0 m/yr accretion. Moderate: -1.0-+1.0 m/yr accretion/erosion. High: 1.0-2.0 m/yr erosion. Very high: 2.0 m/yr erosion.

The effects of erosion of the coast on socio-economics can be significant. Below are some key findings relevant for this study from "*The evaluation of erosion hazard*" conducted by The Heinz Center (2000) under contract of the Federal Emergency Management Agency (FEMA).

- Home owners close to shore are under as much risk from erosion as they are from flooding.
- Approximately 1500 homes and the property they are built on will be lost annually for the coming several decades.
- The cost of property loss due to erosion may be up to 500 million US dollar per year.
- Total value of property in areas along the coast which are most vulnerable to coastal erosion has decreased 10%.
- Most erosion damage will occur in low-lying areas which are also most susceptible to flooding.

As is clear, the impact of erosion can be significant. An analysis done by Leatherman (2001) predicts that "future sea level rise will cause retreating beaches to continue to erode, accelerated sea level rise will increase the rate of erosion along such coasts, and stable to slightly accretional shorelines should begin to erode in the future unless additional, excessive sediment supplies are locally available". If true, this will shift the map shown in figure [20] towards high and very high erosion for the majority of the United States coastline, and will most likely increase the impact as stated by the Heinz Center.

Saltwater intrusion

Intrusion of saltwater due to sea level rise and groundwater pumping in coastal aquifers can cause the salinization up to several kilometers inland depending on the type of aquifer (Werner & Simmons, 2009). Saltwater intrusion causes the contamination of groundwater sources which are used for water supply, forcing closure of groundwater wells. This has both an impact on the water supply for humans and feedstock, as well as on the watering of crops. Furthermore, the saltwater intrusion under agricultural land has negative effects on the crops that have low salt tolerance. The rate at which saltwater intrudes in aquifers is dependent on multiple factors, including the groundwater withdrawal rate, the geological structure of the aquifers, the hydraulic properties, confining units and the proximity to discharge and saltwater sources (Barlow & Reichard, 2010). The area affected by saltwater intrusion can therefore range between very local to large regional saltwater intrusion. Barlow & Reichard (2010) give many examples of saltwater intrusion in the United States to show the complexity of the problem: Lateral encroachment of saltwater in New Jersey, vertical migration along fractures in southeastern Georgia and northeastern Florida, intrusion due to large-scale pumping and drainage in southeastern Florida and regional intrusion in central and southern California. Barlow & Reichard (2010) conclude that the most important cause of saltwater intrusion is groundwater extraction. However, they did not focus on saltwater intrusion due to sea level rise. Ferguson & Gleeson (2012) conducted a research to determine what factor (sea level rise vs. groundwater extraction) had the highest impact on saltwater intrusion. They used a Geographic Information System (GIS) synthesis of coastal aquifers with hydrogeological and population density (as a water extraction indicator) information and combined this with an analytical model that simulates changes in sea level and groundwater extraction. From their analysis, they conclude that groundwater extraction has a far more significant impact on saltwater intrusion into aquifers than sea level rise for a wide a range of hydrogeological conditions and population densities. The same influence of human water use on saltwater intrusion was found by Payne (2010), who investigated saltwater intrusion in South Carolina. This leads to the conclusion that even though sea level rise has some impact on saltwater intrusion, it is less significant than groundwater withdrawal and can be mitigated by a change in groundwater use. Given the fact that coastal areas largely depend on groundwater use for potable water, this is easier said than done. Barlow & Reichard (2010) categorize the response to saltwater intrusion in three categories; (1) scientific monitoring and assessment, which serves as early warning systems and provide information for management purposes, (2) engineering techniques, including moving wells inland, recharging wells, desalination, and (3) regulatory or legislative approaches, including reduce pumping rate and restricting the construction of new wells. Although sea level rise seem to play a minor role in saltwater intrusion, it will increase with rising sea levels. Continued monitoring of the effects of sea level rise on saltwater intrusion is therefore recommended.

4. STRATEGIC RESPONSE TO SEA LEVEL RISE

Although bound by a high degree of uncertainty, there is a broad general consensus that sea levels will rise in an increasing, non-linear fashion throughout the next century. A strategic response to limit the negative effects of sea level rise as given in chapter 3 is therefore required. The two broad possible responses to sea level rise are 1) adaptation – adjustment of natural or human systems as a response to sea level rise and 2) mitigation – reducing the greenhouse gas emissions and increase sinks (Nicholls & Lowe, 2004). Adaptation and mitigation are executed at different aggregate scales. Mitigation is by its nature a global-scale response while adaptation is a local or regional response (Nicholls, 2011). Although the threat of sea level rise on the United States coast is very real, it is not impossible to overcome the loss of land and the displacement of inhabitants. Throughout history mankind has seem to become increasingly capable of adapting to change. The negative impacts of sea level rise are not inevitable, although the costs are likely to become increasingly higher (Nicholls & Cazenave, 2010).

4.1 Adaptation

Strategies for adaptation to sea level rise can generally be categorized into three different categories (Nicholls & Leatherman, 1996; Parry *et al.*, 2007) which are visualized in figure [21].

- Protecting - Increase robustness. Construction of dikes, dams, levees etc.
- Accommodation - Increase flexibility. Adopting land use to rising water levels (e.g. Raising buildings, converting to salt tolerant crops)
- Retreat - Increase adaptability. Retreat and abandonment of land prone to inundation due to sea level rise and associated hazards.

The appropriate measure varies greatly with differences in land use, coastal morphology, value of land and property, socio-economics and so forth. Selecting the right measure depends on 1) the associated time frame of the potential hazard, 2) the additional costs of the different measures, and 3) the implications of the selected measure (Nicholls & Leatherman, 1996).

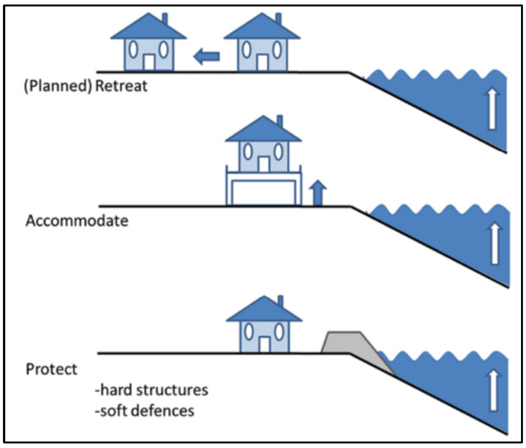

Figure [21] Adapting to sea level rise. The three general categories are shown: (1) planned retreat, (2) accommodation, and (3) protection. Source: Nicholls (2011)

Note that a fourth coastal strategy is *advancing* through land reclamation as is done in for instance Singapore, Hong Kong, New Orleans, and the Netherlands. This strategy is however rarely an act of defense against rising sea levels, but is spurred by space constraints (Nicholls, 2011).

Protection

Protection is by far the most commonly implemented form of adaptive strategy. Natural processes that would impact coastal zones are limited (Nicholls, 2011). Protection strategies include hard structural protection, soft structural protection and indigenous options like wetland restoration and afforestation (Klein *et al.,* 2001). Table [4] shows the possible protection strategies. Hard protection like tidal barriers and sea walls are well-known measures, with the capability of protecting large areas from sea level rise. However, maintenance and construction can be expensive, and with rising sea levels the solution is only short-term (Tam *et al.*, 2011). Hard protection can furthermore have negative adverse effects on natural ecosystems by reducing it capacity to respond to changing conditions. During the last decades, protection of the coast by beach nourishment has been preferred over hard protection techniques because of the more positive effects on natural processes and ecosystems (Neal *et al.*, 2005).

Table [4] Protection as adaptive response to sea level rise. Table based on information from Klein *et al.* (2001) and Neal *et al.* (2005)

Strategy	**Subtype**	**Description**
Hard stabilization	• Shore-parallel • Shore-perpendicular	Seawalls, bulkheads, revetments, offshore breakwaters Groins, Jetties
Soft Stabilization		Adding sand to beach, beach replenishment, beach scrapping, increased sand dune volume, adding vegetation, wetland restoration, afforestation, living shorelines

London *et al.* (2009) show that both hard stabilization and soft stabilization are used by all coastal states of the conterminous United States. Each states shows a mix of different stabilization methods that are reported to be implemented and each regions shows its own mix of preferred measures. Neumann *et al.* (2000) summarize several reports and conclude that protection by dikes and levees of the United States coast for 1 meter of sea level rise costs 450.000-2.400.000 US$/km. Protection by seawalls and bulkheads against 1 meter of sea level rise costs 450.000-12.000.000 US$/km. Protecting the American coastline against the impact found in this report would be extremely excessive, running in the hundreds of billions of dollars. In the IPCC fourth assessment report, the study by Neumann *et al.* (2000) is shown in conjunction with a study on costs for England and Wales and a study for New Zealand (Parry *et al.*, 2007). These two studies show that soft protection is generally more economically efficient than hard protection. In the United States there are an increasing number of states that prohibit to some extent the use of hard stabilization (Morton *et al.*, 2004; Morton & Millar, 2005; London *et al.*, 2009). This is partly due to cost, partly due to public preference of soft stabilization versus the less appealing hard stabilization (London *et al.*, 2009).

The results provided chapter 3 give some insight in those states that could benefit most from protective strategies. This becomes evident when the ratio *inhabitants displaced/inundated land* (or *GDP affected/inundated land*) is considered. A high ratio signals low inundation, but high impact. This means that a relatively small area needs protection to prevent the impact on inhabitants or GDP. The states with the highest ratio are Massachusetts, Rhode Island, Connecticut, New York and New Jersey. Note that this certainly does not mean that in other states there are no specific areas with a high ratio. Cities are built along the coast in most states, which all deserve protection. It does however show that for these five states, protection is a very interesting adaptive strategy on a state level. In those places where population density is very high along the coast, relative little protection is needed to prevent impact on a large populated area. Take for instance the Boston area, with heavy urbanization along the shore, or New York City, which is a clear example of a situation in which the gain of developing & protecting can be significantly higher than the cost of protection. Considering the risings seas, for large parts of the New

England (north-east Atlantic) region protection would therefore be the recommended choice based on socio-economic considerations.

The opposite can also be concluded. The remaining states show a (relatively) low ratio *inhabitants displaced/inundated land* (or *GDP affected/inundated land*). From this, it is argued that protection is not a state-wide option. This is for instance true for those state that have fast stretches of wetlands, like Maryland, North Carolina, Florida, and Louisiana. Furthermore, this is true for states that have both low impact on land, and low density population in inundated land. This is for instance true for the Pacific coast (excl. south California) and Maine. Even though protection is still vital on a local scale, the results of this research show that for these states retreat and accommodation strategies should get more attention on a state level than protection because of the low socio-economic gains of protective strategies. It has to be kept in mind that although the ratio *inhabitants displaced/inundated land* (or *GDP affected/inundated land*) is low for such states, this does not mean that there are no densely populated regions under threat of sea level rise that are in need of protection. Therefore, it is *not* stated here that protection is *not* an option for states with low impact, but that on the higher aggregate level, protection could be minimized.

As shown, protection is an expensive option (Neumann *et al.*, 2000; Parry *et al.*, 2007; Tam *et al.*, 2011). Furthermore, because of sea level rise protection (especially hard protection) is a short-term solution that needs updating frequently, and therefore costs will continue to rise with rising seas. This research shows that even under the most conservative scenario, a large land surface area will potentially be inundated. Protecting all this land is economically undesirable. Determining those regions that need protection and those that could be managed with other strategies is therefore vital for sustainable coastal management. An overall indication is given here for which state protection could potentially benefit from extensive application of protection (mainly the southern New England region), and which state should lean more towards retreat or accommodation (Pacific coast excl. South California, Maine).

Accommodation

Under accommodation strategies, natural processes are allowed to occur without interference. The impact for the coastal population is kept at a minimum by changing the use of the coastal region (Nicholls, 2011). A summary of strategies is given in table [5]. Accommodation encompasses a broad spectrum of different strategies. Innovative building techniques like floated or floodable development can assure a habitable coastline despite of rising seas. However, many of such techniques require specific geographic conditions like a sheltered bay with low wave intensity (Tam *et al.*, 2011). Accommodation is furthermore a medium to long term solution. If global warming continues, sea levels will eventually rise to unmanageable levels for accommodation.

Table [5] Accommodation as adaptive response to sea level rise. Table based on information from Klein *et al.* (2001) and Neal *et al.* (2005)

Strategy	**Subtype**	**Description**
Communication	• Emergency planning	Early warning systems, evacuation systems
Regulation		building codes, insurance eligibility requirements, Low-density development, hazard zoning
Modification	• Land use • Development	Salt resilient crops, aquaculture Retrofit homes, Elevate homes choose elevated building sites, Curve and elevate roads, Block roads terminating in dune gaps, Move utility and service lines into interior or bury below erosion level, improved drainage , desalination

Due to the wide range of possible option for accommodation, and the specific requirements for each option, it is not possible to directly relate the results found in this report to show if accommodation would be useful for specific states. In general there will always be regions in a state where some form of accommodation is possible. This being said, the research of London *et al.* (2009) does show that accommodation is a strategic response option that is used in more states than retreat. Building elevation is widely used along the coast of the conterminous United States, with only two of the 22 coastal states reporting not to use building elevation as an option. Hazard zoning is implemented in 16 of the 22 coastal states. In the southeast only one state used hazard zoning. As mentioned, development in those states is typically further inland, reducing the need of hazard zoning along the coast. London *et al.* (2009) report that only eight of the 22 coastal states consider low-density development as an accommodation strategy. Especially in the mid-Atlantic and the Gulf coast, low-density development is reported not to be implemented by many states. This is interesting, since these are the regions that see the highest impact of sea level rise. Low-density development here would reduce future impact tremendously, and would help to adapt to sea level rise.

Accommodation strategies allow for a more flexible response to sea level rise than protection does. Accommodation offers coastal management strategies which greatly reduce the impact of flooding related to storms and sea level rise (see also appendix A). However, as with protective strategies, accommodation is still a relative short term solution and will need frequent 'updating'. This implies increasing costs with increasing sea levels. Even though accommodation should be considered versus protection wherever possible, retreat is potentially the most cost efficient and durable strategic response.

Retreat

Managed retreat is moving existing and planned development away from shorelines to restore the natural ocean and coast processes like erosion and sedimentation flows (Neal *et al.*, 2005; Nicholls, 2011). Retreat is a viable option when protection or accommodation would imply excessive economic costs which exceed the benefits, now or in the future. In chapter 3, it is shown that sea level rise causes increasing problems on existing population. A sensitivity analysis based on some arbitrary assumptions on population dynamics show that if development in coastal areas continues, impact (or cost of protection) will be significantly higher.

Klein *et al.* (2001) and Neal *et al.* (2005) give several strategies for managed retreat. These strategies are summarized and explained in table [6]. The advantage of managed retreat is that it minimizes hazard impact due to severe weather events. Natural sedimentation processes allow for a better response to wave energy intensification and shorelines naturally replenished by sediments from eroding coast. In areas with low development or uninhabited regions the cost of managed retreat is relatively low. Even more important, not building in threatened regions means future costs will be kept at a minimum. However, in densely populated or developed areas the cost of managed retreat is particularly high due to loss of abandonment of structures (Tam *et al.,* 2011). Besides the high cost, managed retreat may be deemed socially unacceptable by stakeholders in the area (Parry *et al.*, 2007).

The study by London *et al.* (2009) examined the use of retreat strategies for the US coastal states. The use of retreat strategies differs greatly among regions. In the northeast region, fixed setbacks and land acquisition are used by every state, while relocation is only implemented by two states. In the Mid-Atlantic, land acquisition is used by every state, while abandonment and relocation are each only used by one state. In the Southeast, three states used fixed setbacks, two states use land purchase and relocation, and only one state has options for abandonment. London *et al.* (2009) furthermore found that among the Gulf coast states, retreat options were differently used, with each state favoring different strategies. Along the Pacific coast, relocation is the most used strategy. Interestingly, most states along the US coast favor fixed setbacks. Rolling setbacks are not an often adopted option. This reduces the dynamic response to sea level rise. Of course one should wander if an ever rolling setback is desirable, or that costs should be allowed to rise to protect against sea level rise after a certain line is crossed.

Unfortunately, London *et al.* (2009) do not specify by state, but only by region. This makes relating their results to the results found in chapter 3 difficult. However, general conclusions can be found in connection with this research. Figure [18] and [19] show that on the Atlantic coast, the upper northern region and the southern region (excl. Florida) show low impact on population/GDP while the mid-Atlantic coast shows high impact. London *et al*. (2009) show that those two regions have more states adopting abandonment and relocation than the mid-Atlantic region (although options are adopted by not more than half the states in the region). This indicates that as discussed here, those approaches might indeed be recognized as plausible retreat options. The Gulf coast shows a mixed response. The report here also finds a large mixed impact, which would also be suggested when making the simple conclusions based on the mixed results in figure [18] and [19]. Again, in accordance with the very low impact found on population/GDP here on the Pacific coast, London et al. (2009) show that retreat options are adopted by most Pacific coast states. These results are not surprising, since the economic gain of protection is low, and so are the cost of retreat. This shows that the high aggregate state level results found in this research can give at least some indication for which state retreat would be a state-wide option. Again, to stress the fact, it must be noted that it is still largely a case-by-case assessment of whether or not to retreat at some points.

Table [6] Managed retreat as adaptive response to sea level rise. Table based on information from Klein *et al.* (2001) and Neal *et al.* (2005)

Strategy	**Subtype**	**Description**
Abandonment	• Unplanned • Planned	Abandonment after storm damage Abandonment at preset end-of-life of structures
Relocation	• Active • Passive	Relocate before damage Rebuilt after damage
Relocation planning	• Zoning, land use planning	Long term plans with designated areas are assumed to be relocated in the future
Setbacks	• Fixed • Rolling	Setback line at fixed distance from reference line Setback line at fixed distance from migrating shoreline
Acquisition	• Land acquisition	Purchase (voluntary or involuntary) by the government
Avoidance	• Avoid hazard areas	No construction in areas like tidal inlets, swashes, permanent overwash passes, wave velocity zones

The results presented in chapter 3 offer some insight in those states for which retreat would be a viable option for current development. Figure [18] and [19] show the impact of sea level rise on population/GDP per 1000km coastline. Those states where the impact is low, retreat might be interesting on a state level. On the Atlantic coast, those states are for example Maine, North Carolina, South Carolina, and Georgia. In North Carolina, South Carolina and Georgia we find high levels of inundation (fig. [17]) but still the impact on population/GDP is low. In these states, coastal development is low, with most developed regions and larger cities further inland. For those states, the benefit of retreat strategies would outweigh the cost of protection or accommodation. The same is true for Alabama on the Gulf coast. On the Pacific coast, there is low impact on population/GDP for the states Washington and Oregon, which have very little development along the shoreline due to the rough terrain. Note that even with low impact on population/GDP, retreat might not be an option. Valuable ecosystems might be at risk, which deserve protection rather than erosion or inundation. The low impact might be in coastal cities and towns, where retreat options are difficult, and perhaps socially undesirable. In contrast, states with heavily developed areas still would have large areas in which retreat is more beneficial than protection or accommodation.

States like New York and Florida have high impact on population/GDP (table[2], figure [18] and [19]), but also have large uninhabited or scarcely populated areas where retreat might be the best (economic) choice.

Concerning the ongoing impact as shown in this report, retreat is of major importance as a strategy for future development. Chapter 3 showed a short analysis based on some arbitrary assumptions of population growth under threat of sea level rise. It showed that without retreating planned development, the impact given in this report could be far greater than if future sea level rise is considered in development planning. Because retreat is based on planning into the future, it could proof to be one of the most durable strategic responses. The impact of sea level rise is minimized by thinking ahead, and planning accordingly. The benefits of not developing in regions that would otherwise need protection in the near future are clear. The result presented in this research should be a sign that attention needs to shift to retreat wherever possible. Especially considering the high-end scenarios, states need to focus on the potential impact, and if possible minimize it through pre-emptive actions and not developing in regions that would see high impact. There is not one specific state for which this is true, since it is true for all states. Whether the impact is high (e.g. Louisiana, Florida), or whether the impact is low (e.g. Oregon, Maine), all states should consider sea level rise in their future development, and minimize the impact through careful selection of retreat options.

Klein *et al.* (2001) did found that that there is a trend towards recognition of the advantages of soft stabilization, managed retreat and accommodation strategies, and that there is a higher awareness of the importance of allowing nature to follow natural paths through the right choice of adaptation strategies. Besides physical (e.g. geographic, geologic) factors and public demand, the decision of which strategy to follow will be greatly influenced by socio-economic needs (Parry *et al.*, 2007). Local stakeholders are more likely to prefer protection strategies, while national environmental policy makers are more likely to prefer retreat or accommodation. The best strategy to follow will in most cases by a hybrid strategy that fits the local circumstances for both humans and nature (Nicholls, 2011). On a state level, the followed strategy will be a mix of all three strategic response options. The mix of relative use of each strategic response will be different per state depending on environmental, geophysical and socio-economic factors. As discussed above, states with a high *inhabitants displaced/inundated land* ratio (or *GDP affected/inundated land* ratio) will benefit from more protective strategies in this mix, and states where this ratio is low will benefit from a mix that holds more accommodation and retreat as options. To limit future impact of sea level rise, all states should lean towards retreat strategies to limit future impact. The right mix of strategic response would ideally consist of protection of high developed regions, accommodate and retreat where possible, and not plan for future development in regions at risk of inundation due to sea level rise. Note that this is true in general, but on a local scale circumstances might lead to significantly different strategies.

4.2 Mitigation

Mitigation as a strategy is a far broader approach to the problems related to sea level rise. If global warming continues at an accelerated pace, sea level rise is far from the only problem that mankind faces. Climate zones will shift away from the equator, and more severe weather and extreme weather phenomenon's such as hurricanes will pose a threat to humans and nature alike. Scientist agree that global warming is one of the great drivers of sea level rise with thermal expansion accounting for over 50% of the total global sea level rise for the last decade (Solomon *et al.*, 2007). At current emission rates, global warming could be ~4^{o}C in 2100, which is well above the 2^{o}C which is often regarded as the upper limit to prevent dangerous impact on the environment (Metz *et al.*, 2007). The IPCC reports that if no additional policies are implemented, greenhouse gas emissions will raise between 25% and 90% between 2000 and 2030 and even a relative increase of 250% with high dependency on fossil fuels (Metz *et al.*, 2007). For an extensive discussion on greenhouse gas emissions and mitigations, see the IPCC assessment reports.

The problem of greenhouse gas emissions with respect to sea level rise is that sea level rise could continue even if greenhouse gas emissions are reduced. Nicholls & Lowe (2004) state that even if "greenhouse gas concentrations were (hypothetically) stabilized today, sea level would still eventually rise by more than 1 meter due to thermal expansion alone, although this would take more than 1000 years". They argue that sea level expansion shows a lag-phase of decades or even centuries with respect to global warming due to the slow mixing of warm surface water with deep ocean water. This is confirmed in a recently published research by Meehl *et al.* (2012). In their research, Meehl *et al.* (2012) investigated future sea level rise under a scenario of aggressive mitigative efforts. A world in which aggressive mitigative efforts are taken are represented in the RCP2.6 scenario. The RCP2.6 scenario has negative CO2 emissions in the year 2070. Meehl *et al.* (2012) show that even under a scenario of decreasing global temperature (+0.83 °C at 2100, to +0.66 °C at 2200 and +0.55 °C by 2300) sea level rise due to the mixing of warm surface water with deeper ocean water would cause a rise in sea level from +14.2 cm at 2100 to +20.7 cm at 2200 and +24.2 cm at 2300. Although Meehl *et al.* (2012) do note that large uncertainties might influences the exact outcomes, the mechanism of continued sea level rise even with global mitigative efforts is evidently clear. Even if global warming is halted by the reduction of greenhouse gas emissions, the oceans will continue to rise long after the temperature has stabilized.

Furthermore, it is still unclear how glaciers and icecaps will respond to continued global warming. It is argued that global warming can cause the accelerated breakdown of the Greenland and Antarctic ice sheets (Solomon *et al.*, 2007). Evidence of this process is already found by authors like Meier *et al.* (2007) and Pfeffer *et al.* (2008). This acceleration of glacier and icecap melting could raise sea levels even further, aggravating the impact on coastal societies and emphasizing the need for mitigation.

A global effort is therefore needed to reduce greenhouse gas emissions to prevent further negative impact. Even with stabilizing measures, the oceans will continue to rise, impacting coastal nations worldwide. If no drastic measures are taken, the sea level rise will be worse, and will continue for centuries. Although the international community has ratified several climate conventions like the Kyoto protocol, it is more than often a weaker agreement than deemed necessary. Recently, developing countries do not want to comply with strict regulations opposed by developed countries, deeming the measures unfair considering the immense polluting in the past of developed countries. Strong polluters like the United States block important international measures to protect the national economy. This will without a doubt prove to increase the consequences on the United States coast as shown in this report. Based on the economic consequences alone, the economic trade-off should tip in favor of implementing mitigative strategies now, rather than accepting future adaptive strategies in face of rising seas. Fact is that if no extensive mitigative actions are taken, sea levels will continue to rise, either disrupting life at the coast or exponentially increasing the cost of coastal protection.

5. CONCLUSION AND DISCUSSION

This research investigated the impact of relative sea level rise for the conterminous United States by answering the main research question "*What is the potential impact of future sea level rise (present-2100) for each coastal state of the conterminous USA?*". For the first time, this research presents a quantification of the impact of sea level rise for the entire conterminous United States on land inundation, inhabitant displacement and GDP impediment on basis of *relative* sea level rise per state. By using relative sea level rise per state, a more accurate and precise view is gained on the consequences of rising seas. The scenarios in this report are based on a simple relation of global warming and relative sea level rise inspired by the semi-empirical relation between global surface temperature and global sea level rise found by Rahmstorf (2007). The GWC scenario is especially interesting since this scenario seem to agree with the expected sea level rise given by several authors in the recent years (Rahmstorf, 2007; Horton *et al.*, 2008; Pfeffer *et al.*, 2008; Jevrejeva *et al.*, 2010). The results show significant relations between relative sea level rise and global surface temperatures, even though there are no complex mathematics behind the scenarios. Furthermore, when performing a retrospective analysis on the trend lines, the simple mathematical relationships seem to hold. The results found on relative sea level rise are in agreement with the available knowledge on coastal geological circumstances and knowledge on subsidence and uplift and therefore do give plausible results.

The total land at risk of inundation is found to be between ~30.000 km^2 for the most conservative relative sea level rise scenario (ELT), ~49.000 km^2 for the GWC scenario, and ~76.000 km^2 for the extreme, but not impossible, high-end $GWC^{+/+}$ scenario. In 1991, Titus *et al.* (1991) performed an analysis of the total area of land inundated for 50cm, 100cm and 200cm sea level rise. These three measures are somewhat proportional to the values used here, with an average relative sea level rise (over all states) of 0.3, 0.9 and 2.0 meter for the ELT, GWC and $GWC^{+/+}$ scenario respectively. The results found in this research can therefore on some level be compared and validated with the study by Titus *et al.* (1991). In general, it can be stated that, although the results found by Titus *et al.* (1991) are based on a solid methodology, using relative sea level rise is a more valid and a more accurate approach, since it is clear that relative sea levels will not uniformly rise. Titus *et al.* (1991) found a combined loss of dry and wetland of ~14.000-34.000 km^2 for 50 cm of sea level rise. For 100 cm of sea level rise they found a combined loss of dry and wetlands of ~22.000-49.000 km^2. For 200 cm of sea level rise Titus *et al.* (1991) found ~31.000-66.000 km^2 of lost land. The results found in this report overlap (on the high end) for the 50 cm and 100 cm analysis, and are found to be considerably higher for the 200 cm analysis. Due to the use of relative sea level rise per state, some states in this research show lower levels of sea level rise than posed by Titus et al. (1991), while other states show higher levels of relative sea level rise. Especially the (more realistic) results found here for Louisiana cause the assessment in this report to be on the high end of the assessment done by Titus *et al.* (1991). If Louisiana is taken out of the results, the estimations in this report are ~10.000 km^2 inundated land for the ELT scenario, ~22.000 km^2 inundated land for the GWC scenario, and ~45.000 km^2 inundated land for the $GWC^{+/+}$ scenario. This put the results found in this report right in the middle of the Titus *et al.* (1991) projections, validating the results found in this research. However, because of the use of relative sea level rise, this research provides a far more accurate assessment, approaching reality by defining inundated land per state.

For inhabitant displacement, calculations made in this research show that under the ELT scenario ~1.9 million people are at risk of being displaced, under the GWC scenario ~3.3 million people are at risk of being displaced, and under the $GWC^{+/+}$ 7.4 million people are at risk of being displaced. Note that this is under the assumption that no action is taken. A report by Strauss *et al.* (2012) notes that in the United States there are approximately 3.7 million people living below ~1 meter above current sea level, 5 million below ~1.5 meter above current sea level and 6 million below ~1.8 meter above current sea level. This could roughly compare to the results found here, although again, since relative sea level rise estimation are used the results found in this report are considered more accurate for a national assessment. It must be noted that the results found in this report are not representative for the real life situation, since adaptation measures will be taken to combat the effects of sea level rise. It does however show the urgency of the problem, and the need to act. Even under the most conservative estimate, 1.9 million people need to be protected. With a growing population, and a tendency of migration towards the sea, this number will continue to increase.

Furthermore, this research gives an estimation of the GDP production that will be affected by rising sea levels and inundation of land. The GDP is coupled to the population density to be able to calculate what part of the GDP production will be affected. As discussed, the assumption that GDP is produced where people lives holds in general, but might not be accurate on a very local scale. The total GDP production affected is ~76, ~130 and ~289 billion USD/year for the ELT, GWC, and $GWC^{+/+}$ respectively. Referred to the 2010 benchmark, this would be ~0.5-1.9% of the GDP of the whole United States in 2010. This is considered a minimum estimation, since the physical damage to land and property is not taken into account. Several authors have tried to give an estimation of economic damage related to sea level rise (Nordhaus 1991; Titus *et al.*, 1991; Yohe, 1991; Fankhauser, 1995; Yohe *et al.*, 1996; Yohe & Schlesinger, 1998; Darwin & Toll, 2001; Bosello *et al.*, 2007). However, in general they use uniform sea level rise, which is inaccurate, and the value of land and structures is obsolete, especially after the 2008 crisis. For a realistic assessment of economic damage, a local in-depth analysis needs to been performed like done by Ayyub *et al.* (2011) for Washington D.C. and Heberger *et al.* (2011) for California.

A more in-depth conclusion based on the results can be given for each of the three coasts and their different regions. For the Atlantic coast, it is found that the Glacial Isostatic Adjustment is the main determinant of relative sea level rise per state, with the exception of Virginia (subsidence due to groundwater pumping) and North Carolina (no vertical land movement due to the stability of the Cape Fear Arch). The impact of the relative sea level rise on land inundation shows significant differences. The rocky northeastern region shows low levels of inundation, but the mid and south Atlantic region show high levels of inundation due to low-lying terrain and long stretches of wetlands and barrier islands. The impact on population and GDP does not follow the same pattern. Even though land inundation levels are low in the north Atlantic region, impact on population is high per km^2 of land inundated. This is attributed to the fact that development in this region occurs at those stretches of coast that are low-lying and characterized by beaches. A lower impact on inhabitants and GDP per km^2 inundation is seen on the mid and South Atlantic coast. This is either caused by the fact that (1) development is usually further inland, or (2) besides impact on developed land, there is also a large impact on undeveloped land. This means that there will be a significant difference on state level on how to adapt to sea level rise. Note that the response will always be a mix between protection, accommodation, and retreat. This is especially true for current development. For those states which show high impact on population and GDP per km^2 of land inundated (mainly in the northeast region), on a state level protection will prove to be the most cost efficient solution and should therefore get more priority when defining the mix of adaptive strategies. Relative short stretches of coast could be protected to reduce the impact on many inhabitants. For the other states, the mix will need to be more divers, leaning towards accommodation and retreat in those states with development further inland North Carolina, South Carolina, Georgia), and a uniform mix for those states that have both developed and undeveloped regions under threat (e.g. Maryland, Florida). To reduce impact in the future, more attention needs to be paid to accommodation and retreat strategies. By staying clear of areas at risk, damage and loss of property can be prevented potentially saving billions of dollars. Furthermore, if sea level rise is taking into account for future development, costs for adaptation are reduced by limiting the need for hard or soft protection.

For the Gulf coast, it is found that subsidence is the main contributor to the large impact of sea level rise. Will subsidence rates are low for the largest parts of Mississippi and Alabama, they were high for the coast of Texas, and continue to be (extremely) high for the coast of Louisiana. Texas implemented regulations and measure and now shows normal subsidence rates along the shore. Louisiana is continuing to subside, without proper regulations to stop the process. The relative sea level rise for Louisiana is therefore significantly larger than anywhere else in the United States. This is reflected in the results on relative sea level rise found in this report. The impact on inhabitants and GDP follows this pattern. This means that adaptive strategies for Texas, Mississippi, and Alabama are comparable to what is discussed for the Atlantic coast. Louisiana however faces more serious problems. To counter the effect of relative sea level rise on its low-lying lands, Louisiana should focus on reducing subsidence. The recently released master plan does however not provide options to combat land subsidence. Here it is clear that socio-economic needs outweigh the cost of adaptation, since the Louisiana economy is built on oil extraction and production. The solution is therefore not as easy as stopping production to limit subsidence. For Louisiana, it is more important than elsewhere to focus on accommodation and retreat strategies for future development. Relative sea level rise undoubtedly will cause major problems for Louisiana in the near future. If protection by hard or soft stabilization is adopted as main strategy, and development is allowed to take place in areas at risk, the cost will become excessive. On the other hand, a timely response and careful planning of development away from risk areas can reduce the cost tremendously.

For the Pacific coast, relative sea level rise over the last 30 years has been low, if not declining, due to wind stress patterns that influence cold water upwelling. However, it is suggested that relative sea level rise will return to relative sea level rise rate as it was before those 30 years. Estimations for sea level rise are therefore based on very long-term records. Due to lack of data the results for long-term relative sea level rise are based on the San Francisco Bay Area and the Pudget Sound. The results in this report do not show the complex pattern of uplift and subsidence occurring along the Pacific coast, but since the impact is significantly larger in the San Francisco Bay and Pudget Sound than elsewhere along the Pacific coast, it gives a relative good indication on the impact on land, inhabitants and GDP. Inundation levels are generally low along the Pacific coast due to steep cliffs and rocky shores. Population density is low near shore due to the rough conditions at the coastline. Impact on population and GDP is therefore low along the Pacific coast, with the exception of South California. The San Francisco Bay area is densely populated, so low levels of inundation can cause higher levels of impact on population and GDP. Along the southern shore, development usually occurs at the beach front. This means that especially in the San Francisco bay, protection would be a sound option. Because the location of development in the bay, a relative large area can be protected by engineering the bay mouth. Furthermore, the area lends itself to accommodation strategies due to its enclosed space, which shelters it's from wave and storm impact. In Washington and Oregon, impact is low on inundation, population and GDP. Managed retreat will therefore be the least costly option. As for the other coasts, future adaptive strategies need to lean toward anticipating on sea level rise through accommodation and retreat. However, because impact is highest in the Pudget Sound and San Francisco bay, protection will not prove to give excessive costs, and the decision to develop and protect in those regions might be desired concerning socio-economics benefits.

The conclusions above are based on the impact of land inundation caused by relative sea level rise. Appendix A shows that the results found in this report could be significantly higher if not inundation, but flooding due to storm events is taken into account. Although the effects of a storm are short term impacts, the disruption it causes on coastal societies can be immense. With rising sea levels, even small storms surges rise to a height that can flood and damage developed regions. Furthermore, a short study on potential population growth shows that allowing development to occur in regions at risk will increase impact along the United States coast. These two effects combined emphasize the results found in this research, leading to the conclusion that a timely response is vital to reduce both the impact and costs of sea level rise.

In general, it can be concluded that careful consideration in coastal management can significantly reduce the impact for seafront societies. This is true for both existing development, and future planning. It is estimated that adaptation strategies can reduce the impact by a factor 10 to 100 (Parry *et al.*, 2007).

Choosing the right mix of adaptive response strategy per state will determine whether cost will proof to increase exponentially, or that they will remain manageable. For future planning, this means that accommodation, and especially retreat strategies should be considered over protection. As discussed, specific region might still benefit more on a socio economic level from protection, but allowing sea levels to rise and not developing those regions would reduce greatly the impact and cost associated with the problem. Policy makers and local coastal managers play an important role in choosing the right adaptive strategy to limit negative effects (Tribbia & Moser, 2008). The question is if local and national policymakers pay enough attention to the threat of sea level rise. The costs of reacting to sea level rise will be greater or smaller depending on how well the sea level rise was anticipated, and how measures were taken. A timely long term plan of action will considerably reduce the need for hard protection, which is costly to build and to maintain. This being true, Titus *et al.* (2009) note that along the US Atlantic coast property owners and land use agencies do not incorporate sea level rise in decision making. This results in 60% of coastal dryland along the Atlantic coast to be developed without planning for future impact of sea level rise. Only 9% of the dry land has been designated as conservation area (Titus *et al.*, 2009). This lack of long term vision will eventually lead to increasing costs as more land and development needs to be protected.

Although only shortly discussed in this report, mitigation of global warming is of utmost importance if we as humanity are to limit sea level rise that impacts our coastal societies. With the steric expansion of sea water due to global warming, it is clear that if temperatures rise increasingly, so will the sea level. Besides the known effects of global warming on sea level rise, there are still large unknowns, the biggest of which is the unclear response of glaciers and icecaps to global warming. A collapse of the Greenland and Antarctic combined could lead to a sea level rise of 70 meters (note that a full collapse would take millennia). Furthermore, due to the slow mixing of warm surface water with cooler deep ocean waters, steric expansion will continue long after the atmospheric temperature has stabilized or even declines (Nicholls & Lowe, 2004; Meehl *et al.* 2012). Considering mitigative action, this momentum of sea level rise needs to be taken into account if the impact of sea level rise on the long term is to be limited (Metz *et al.*, 2007). This emphasizes the need to undertake international efforts to limit our greenhouse gas emissions. Although the importance of reducing these emissions is evident, a somber prospect looms with repeated failure to take adequate decisions by countries worldwide. Due to the lag phase of mitigation and sea level rise, the response to reduce the impacts of sea level rise should be a combination of adaptation and mitigation. Concerning a world with scarce resources, an economic trade-off might be foreseen between mitigation and adaptation since investing in one removes resources from the other (Tol, 2007; Parry *et al.*, 2007) increasing the need for finding a right mixture between the two strategies. Finding the optimum balance has yet to be researched (Nicholls, 2011).

To conclude, this report shows the potential impact of relative sea level rise per state for three different sea level rise scenarios. The report emphasizes the need for anticipating measures, which need to be a mix of adaptive and mitigative strategies. Adaptive strategies will remain important due to the commitment to sea level rise as result of the lag phase of global warming and sea level rise. Mitigation is however the solution to the cause of the problem, and if we want to limit the impact of sea level rise and prevent costs to rise incrementally due to the need for coastal protection, than reducing greenhouse gas emissions is the path that needs to be taken.

RECOMMENDATIONS FOR FURTHER RESEARCH

The impacts discussed in this report are only part of the problems related to rising sea levels. The choice was made to analyze the indicators to a high level of accuracy, which meant attention was diverted from other problems. This research mentioned, but does not include in the results, the growth of population and GDP. Growth of population and GDP are left out because any simple extrapolation would not do justice to the complexity of growth in face of sea level rise, and would therefore undermine the validity of the impact analysis. It is however highly recommended to include an in-depth analysis in this growth, to gain a better insight in the minimum impact sea level rise might have. Furthermore, Mclean (2001) summarizes several other problems related to sea level rise like increased loss of property, potential loss of life, damage to coastal protection and infrastructure, loss of renewable and subsistence resources, loss of tourism, recreation and transportation function, loss of non-monetary cultural resources and values and impact on agriculture and aquaculture. Furthermore, the contribution of glacier and ice cap melting under a warming atmosphere is still shrouded by uncertainty. Some attempts have recently been made to assess this contribution for the near future (e.g. Meier *et al.*, 2007; Pfeffer *et al.*, 2008), but ongoing research is needed to determine the additional impact melting will cause. The fact of the matter is that sea level rise will cause increasing problems for coastal regions. Over the course of the last decades, the scientific community has paid more and more attention to the problem of sea level rise. Continuing this effort is paramount to gain a better understanding of what we face. Additional research is needed on the best strategies for adaptation. The right option to choice will be different for each region and for a wide set of circumstances. Concerning the mentioned economic trade off with mitigation effort, research on how to strike the right balance between the two will become more valuable for policy makers now and in the near future.

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APPENDIX A: EXTREME HIGH WATER ANALYSIS FOR THE CHESAPEAKE BAY

In this appendix two key issues related to sea level rise are investigated for the Chesapeake Bay. First, the height of extreme water levels above the mean sea level is investigated. As noted in the report, inundation is a gradual process. But flooding due to storms cause a major imminent problem. It is therefore important to assess the storm height with respect to the rising seas to gain a clear view of the combined effect of extreme water level and sea level rise. Second, it is investigated here if extreme water levels show a greater increasing trend than sea level rise. It is sometimes indicated in literature that storms and flooding may become more frequent with sea level rise, and storms more violent with global change. This could potentially cause extreme water levels to increase above the sea level rise trend. Both issues are addressed here, with a focus on hurricanes due to the extreme water levels associated with these events.

Hurricanes in the Chesapeake Bay

The Chesapeake Bay experience hurricane and tropical storm events yearly. Throughout the bay's history, such storms are often related with both local and widespread flooding in the Bay. The focus of this appendix is therefore put on hurricanes. The hurricane season starts at June 1 and ends on November 30. Hurricanes form around the equator under influence of warm, moist rising air. Because of the rising air, an area of lower pressure is created at the bottom of the system. Air moving in this area of low pressure heats up and gathers moist causing it to rise as well. This process fuels the formation of hurricanes. Over open ocean, hurricanes can grow to immense storms, fed by air sucked in at the bottom of the system. Near shore and over land, hurricanes die out because of the lack of warm moist air. Hurricanes are scaled in five categories (1-5) with wind speeds between 119-154 km/hour for a category 1 and wind speeds over 250 km/hour for a category 5 hurricane. Category 1 hurricanes typically cause storm surge heights of 1.2-1.6 meters and Category 5 hurricanes can cause over 5.4 meters of storm surge heights. Most extreme water levels occur when a storm surge coincides with astronomical high tide. Storm surges are a complex phenomenon and are determined by many different factors like wind speed, wind direction, coastal layout etcetera. The slope of the continental shelf also has a profound influence. A gradual sloped coastal region can set up a relatively high storm surge, whereas a quickly dropping coastal region would see only minor storm surge heights. The impact of hurricanes is different for the Chesapeake Bay depending on the characteristics of the storm, as will be discussed. Here, an analysis is given of the average extreme water levels in the Chesapeake Bay, with a special focus on hurricanes. The analysis is performed using tide gauge water level data.

Tide Gauges

The calculations made in this appendix are based on NOAA tide gauge records (NOAA, 2012). Tide gauge records for this analysis are selected on (1) being located in the Chesapeake Bay and (2) having a full record length of minimal 50 years. The length of the records is often considered as the minimum length to provide trustworthy results on sea level rise (Nicholls & Leatherman, 1996). The tide gauge records are obtained from NOAA, since NOAA also provides the highest measured extreme water level per month. The selected tide gauges are Baltimore, MD (8574680), Annapolis, MD (8575512), Solomons Island, MD (8577330), Washington D.C. (8594900), Sewells Point, VA (8638610), and Kiptopeke, VA (8632200). Figure [A-1] shows their location in the Chesapeake Bay. Baltimore, Annapolis, Washington D.C. and Solomons Island can be considered upper-bay records. Sewells Point and Kiptopeke can be characterized as lower-bay records.

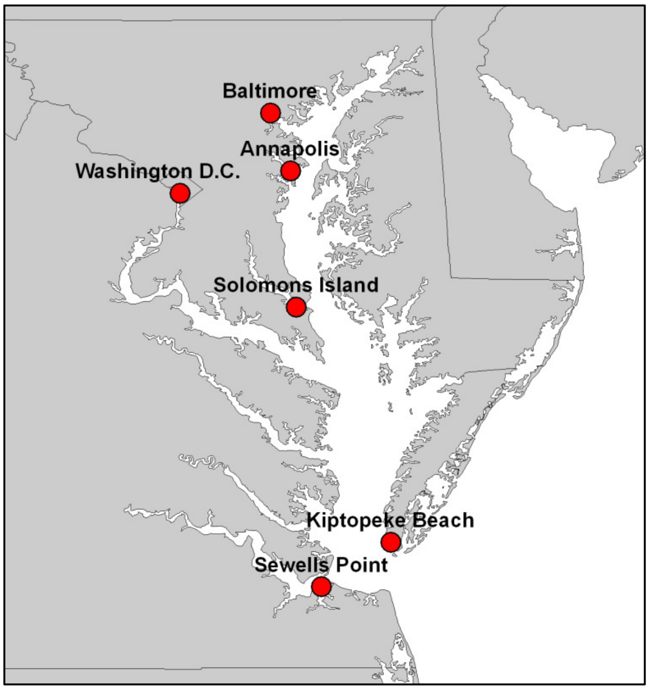

Figure [A-1] Map of the selected tide gauge locations in the Chesapeake Bay. The tide gauges are located in Maryland, Virginia, and the District of Columbia. The tide gauges in Baltimore, Annapolis, Washington D.C., and Solomons Islands are classified as upper-bay tide gauges. The tide gauges Sewells Point and Kiptopeke Beach are classified as lower-bay tide gauges.

Extreme storm height

By taking the mean sea level trend out of the extreme water level records, the extreme water level above mean sea level is obtained. The results for the selected records are shown in figure [A-2]. Figure [A-2] highlights the year of hurricane events that caused storm surges over a meter above the mean sea level trend for each record. Table [A-1] provides the names of the hurricane events, and the measured extreme water level at each station. Washington D.C. shows the highest results on the measured extreme water level above mean sea levels. Because of its location along the Potomac River, Washington D.C. is also vulnerable to flooding caused by high precipitation associated with hurricanes. The combined effect of storm surge from the Chesapeake Bay and heavy rainfall filling the Potomac and Anacostia river cause extreme high water levels for Washington. Furthermore, Washington D.C. is vulnerable to high precipitation and ice melting in winter not related to hurricanes. In 1936, melting of ice and snow caused flooding in the city and in 1942 floodwater caused by high precipitation reached the steps of the Lincoln Memorial (NCPC, 2008). The storm of Ash Wednesday in 1962 is also visible in the records, and mainly seem to have affected the records further down the bay (Sewells Point, Kiptopeke). Cho *et al.* (2012) modeled the storm surge development in the Chesapeake Bay for Floyd ('99) and Isabel ('03). Their model shows good agreement with the observed effects on water height. Cho *et al.* found that the storm surge is first set up by remote winds, and then develops further under local winds. The first stage is similar for both storms, but the second stage is different. Isabel was followed by upper-Bay winds, while Floyd was followed by down-Bay winds. This can be traced back in figure [A-2], where it is shown that Floyd caused water levels to rise >1 meter above mean sea level at Sewells Point and Kiptopeke, but is not reflected in the upper-bay records. Isabel caused >1 meter above mean sea level for all records, but had a more profound rise in the upper-bay record of Baltimore and the Washington record (see also table [A-1] for recorded heights for Floyd and Isabel). The difference can be explained by the trajectory and character of the storm. Floyd travelled parallel to the coast, characteristic for an eastern-type storm, while Isabel travelled perpendicular to the coast, characteristic for a western-type storm (Cho *et al.*, 2012). Due to its path, western-type storms push water up the bay causing flooding in the northern part of the bay. Eastern-type storms that travel along the coast cause a maximum storm surge height in the southern part of the bay. Due to the complexity of wave, wind and precipitation patterns, storms with similar paths show different flooding patterns. The path of hurricane David ('79) showed a trajectory further inland instead of along shore or perpendicular on the bay. Figure [A-2] and table [A-1] show that hurricane David affected the upper-bay with water levels higher than one meter above sea level rise, but did not significantly affect the lower bay. Hurricane Frances ('11) also showed a trajectory further inland, but caused a more significant effect in the lower bay. Table [A-2] shows an inter-comparison between the correlations of extreme water level for the selected records. The correlation of extreme water level is high between the upper-bay records Baltimore, Annapolis, Solomons Island and Washington, except for the Solomons Island-Washington relation. The correlation is again high for the lower-bay records Sewells point and Kiptopeke. The correlation between upper-bay and lower-bay records is low. This is in accordance with the different types of storms hitting the bay and causing high impact in different regions depending on their trajectory.

The average extreme water level over the available record length is 0.61 meter for Baltimore, 0.54 meter for Annapolis, 0.51 meter for Solomons Island, 0.85 meter for Washington D.C., 0.84 meter for Sewells Point, and 0.81 meter for Kiptopeke. Widespread flooding has occurred over the events given in table [A-1]. The average height of such storm floods is above 1 meter. If we take into account the three scenarios for sea level rise given in the main report, the most conservative (linear) prediction will result in raising the *average* extreme water level above 1 meter for Washington D.C., Sewells point and Kiptopeke, and bring the average from Baltimore, Annapolis and Solomons Island close to 0.9 meters. This conservative assessment is the absolute minimum sea level will rise. Even with this very conservative estimate, the impact of a hurricane event will become increasingly worse due to sea level rise. Not only that, average monthly measured extreme water levels would rise to levels where a normal storm would cause major impact. The chance that sea level rise will follow a linear path is however very unlikely (Solomon, 2007; Rahmstorf, 2007; Nicholls, 2011). This research assumes two high-end scenarios to assess the sea level rise for the Chesapeake Bay which result in 0.9-1.2 meters (Maryland and Virginia differ in relative sea level rise due to different subsidence rates) rise for the GWC scenario and 2.1-2.5 meters rise for the $GWC^{+/+}$. The GWC scenario results are well within the range of several assessments on global sea level rise (Rahmstorf, 2007; Horton *et al.*, 2008; Pfeffer *et al.*, 2008; Jevrejeva *et al.*, 2010). The $GWC^{+/+}$ scenario is above the range, but it must be noted that *relative* sea level rise is considered in the scenario rather than *global* sea level rise. Since vertical land movement is negative for Maryland and Virginia, this could explain the higher range of results. If sea levels rise follows a path given here and by several other authors, the rise of sea level alone would rise to levels that are currently associated with massive flooding. A storm like Isabel would add a storm surge to a height that would wreak havoc over the entire stretch of the Chesapeake Bay. Even if adaptive measures are taken to defend against sea level rise, the potential failure of the protective structures would cause disaster since the land behind the measures is now lower with respect to the ocean. Flooding is thus expected to become more frequent, and more severe because of rising sea levels

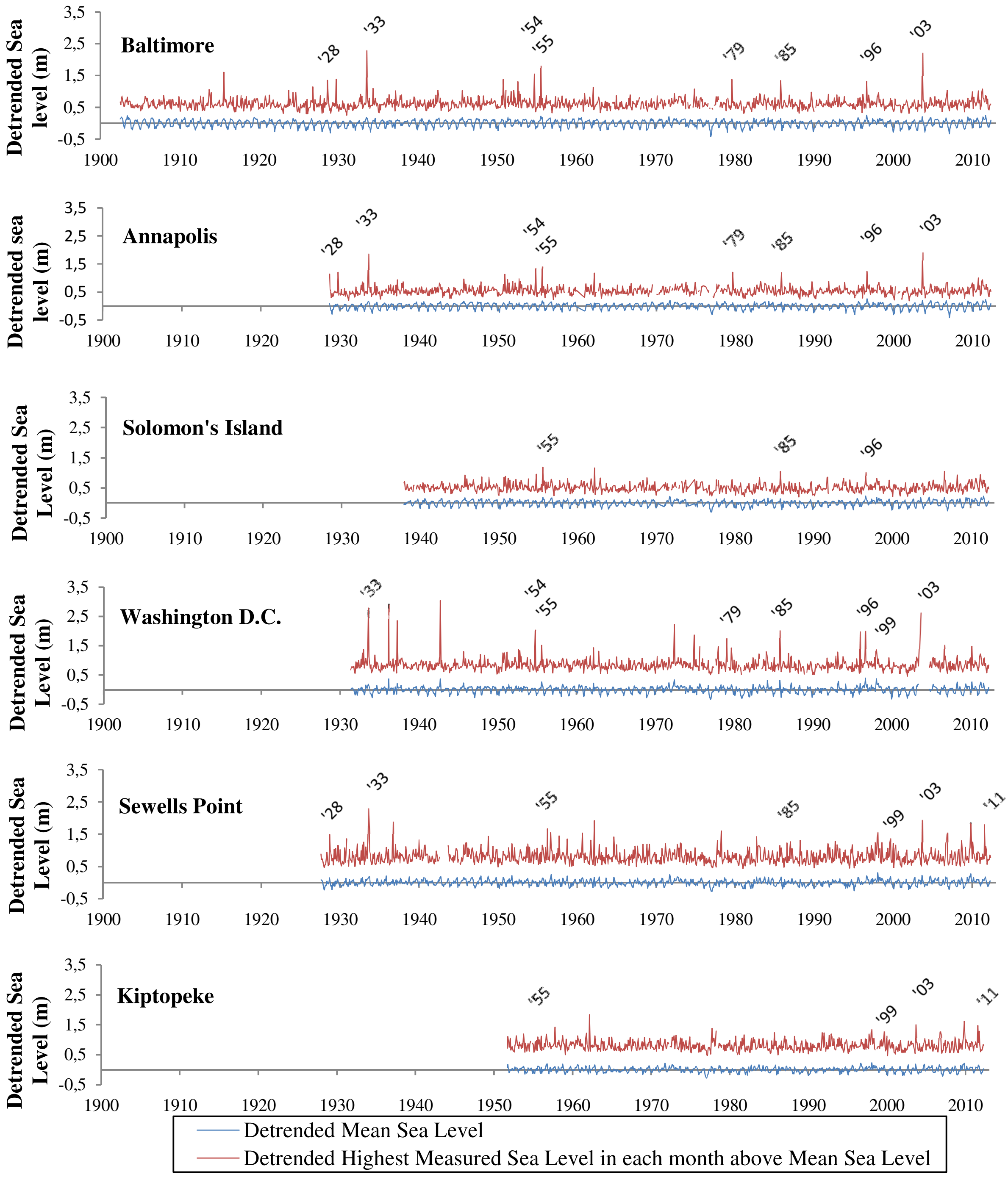

Figure [A-2] Detrended Mean Sea Level and detrended Highest Measured Sea Level per month for selected long term records (in meters) in the Chesapeake Bay. For both records the Mean Sea Level Trend is removed. The years mark hurricane events that affected the Chesapeake Bay. The years of Hurricanes that caused Sea Levels to rise one meter above the Mean Sea Level trend are highlighted. Note: there was no data point for '03 Isabel for the Solomons Island record.

Table [A-1] Extreme Water Level above Mean Sea Level Trend for the selected record length. N/R: No Record due to the length of the data. N/V: No Value due to error. Values are in meters.

year	Month	hurricane	Baltimore	Annapolis	Solomons island	Washington	Sewells point	kiptopeke
1928	Aug.	(Tropical cyclones)	1.35	1.15	N/R	N/R	1.49	N/R
1933	Aug.	Chesapeake-Potomac	2.28	1.86	N/R	2.80	2.30	N/R
1954	Oct.	Hazel	1.55	1.37	0.95	2.04	0.92	N/V
1955	Aug.	Connie & Diane	1.82	1.42	1.19	1.52	1.16	1.09
1972	Jun.	Agnes	0.93	0.79	0.69	2.23	0.73	0.78
1975	Sep.	Eloise	0.79	N/V	0.67	1.48	0.86	0.83
1979	Sep.	David	1.37	1.21	0.78	1.42	0.94	0.85
1985	Sep.	Gloria	1.34	1.19	1.05	2.03	1.15	0.96
1996	Sep.	Fran	1.31	1.24	1.03	2.00	0.82	0.82
1999	Sep.	Floyd	0.78	0.72	0.76	1.09	1.37	1.29
2003	Sep.	Isabel	2.20	1.92	N/V	2.62	1.94	1.52
2011	Aug.	Frances	0.68	0.59	0.76	0.83	1.80	1.48
2011	Sep.	Lee (tropical storm)	0.87	0.64	0.65	1.04	0.83	0.90

Table [A-2] Correlations for the water levels found in table [A-1] for the selected records. Grey cells show significant correlations (>0.7).

Tide gauge	Baltimore	Annapolis	Solomons Island	Washington D.C.	Sewells Point	Kiptopeke Beach
Baltimore	1.0	0.99	0.85	0.77	0.53	0.25
Annapolis	--	1.0	0.83	0.81	0.47	0.18
Solomons Island	--	--	1.0	0.40	0.08	0.05
Washington D.C.	--	--	--	1.0	0.33	-0.09
Sewells Point	--	--	--	--	1.0	0.98
Kiptopeke Beach	--	--	--	--	--	1.0

Extreme storm height trend

To determine if there is an increasing trend of extreme water levels, the mean sea level trends and extreme water level trends are determined over three periods: (1) the available length of the record, (2) 1950-2012, and (3) 1975-2012. The available record length is from 1902-2012 for Baltimore, 1928-2012 for Annapolis, 1937-2012 for Solomons Island, 1931-2012 for Washington D.C., 1927-2012 for Sewells Point, and 1951-2012 for Kiptopeke beach (table [A-1]). Note that for Kiptopeke Beach, period (1) and (2) are the same due to the relatively short record length.

To analyze if there is a significant difference in the trend of mean sea levels and extreme water levels, the *confidence interval method* of Santer *et al.* (2000) introduced in chapter 2 paragraph 2 is used. The null-hypothesis is again "*the trends are not significantly different*", and the alternative H_1-hypothesis is "*the trends are significantly different*".

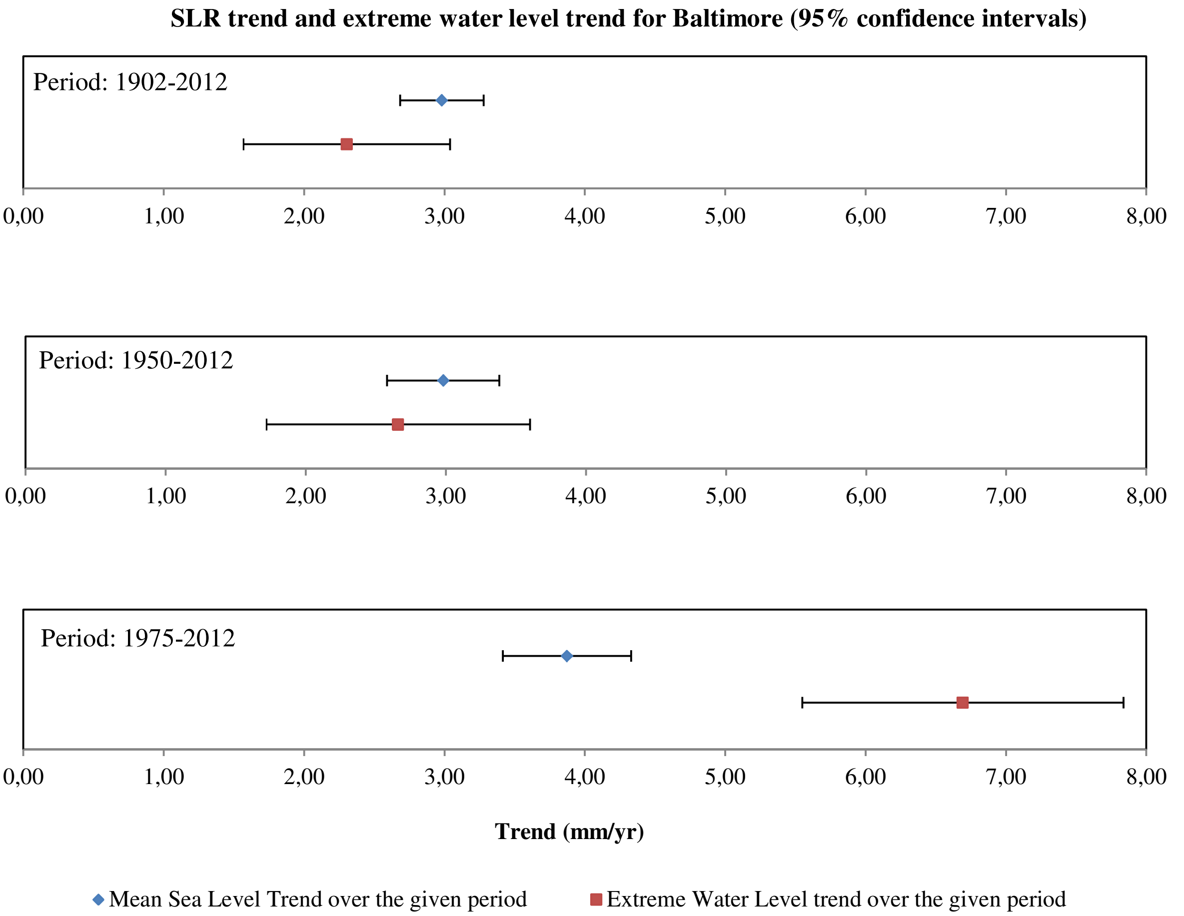

Figure [A-3] The confidence interval method for assessing trends and trend differences (Baltimore as an example). The trendlines are defined for a specific tide gauge record over the (1) the length of the record, (2) 1950-2012, and (3) 1975-2012. The error bars are calculated from the estimated standard error of the residuals. Residuals are defined as the difference between the measured values and the trendline. When there is no overlap in error bars, the null-hypothesis is rejected. In this case, only for the 1975-2012 trendlines the null-hypothesis needed to be rejected.

The method analyses an overlap between two time series with linear trends b_x and b_y and estimated standard errors s_{bx} and s_{by}. The overlap is defined as $b_x \pm s_{bx}$ and $b_y \pm sb_y$. At an overlap, the null-hypothesis "*the trends are not significantly different*" is not rejected with a 95% confidence interval. If there is no overlap, the null-hypothesis is rejected and the H_1-hypothesis is accepted, meaning that if there is no overlap it can be stated that the trends are significantly different with 95% confidence. This method is performed for the three periods as shown in figure [A-3] for the Baltimore tide gauge.

Table [A-3] shows the results for the six selected records and for each of the three periods. The values stated are the *extreme water level trend – the mean sea level trend*, effectively stating how the extreme water level trend deviates from the mean sea level trend. In table [A-3], a positive value means that extreme water level has a higher trend than mean sea level; a negative trend means that the mean sea level trend is higher than the extreme water level trend. For the trends of the complete record and the trends for the 1950-2012 period the null-hypothesis could not be rejected. This means with a 95% confidence interval it could not be rejected that the trends are the same. Over the period 1975-2012, the null-hypothesis could be rejected for the Baltimore, Solomons Island, Washington D.C. and Sewells Point record. For the Annapolis and Kiptopeke Beach record it could not be rejected, with a 95% confidence interval, that the trends are the same. Although the null-hypothesis could not be rejected for Annapolis and Kiptopeke Beach for the 1975-2012 period, they do seem to be much larger than the trends from the complete record period and for the 1950-2012 period.

Table [A-3] Difference between Extreme Water Level trend with respect to the Mean Sea Level trend. Grey cells show values where the trend difference is significantly different.

Tide Gauge	Record length	Δ trend (Extreme Water Level trend – Mean Sea Level trend)			Δ trend (1975-2012) extrapolation to 2037
		Complete record	1950-2012	1975-2012	
Baltimore	1902-2012	-0.07 mm/yr	0.38 mm/yr	1.77 mm/yr	44.25 mm
Annapolis	1928-2012	0.02 mm/yr	0.36 mm/yr	0.87 mm/yr	21.75 mm
Solomons Island	1937-2012	-0.22 mm/yr	-0.18 mm/yr	1.44 mm/yr	36.00 mm
Washington D.C.	1931-2012	-0.68 mm/yr	-0.32 mm/yr	2.82 mm/yr	70.50 mm
Sewells Point	1927-2012	0.48 mm/yr	-0.06 mm/yr	1.30 mm/yr	32.50 mm
Kiptopeke Beach	1951-2012	0.09 mm/yr	0.09 mm/yr	1.51 mm/yr	37.75 mm
				Average	40.46 mm

The same methodology was applied on the Mean Highest High Water (MHHW) records provided by NOAA. The MHHW shows average of all the high tides measured in a month. If diurnal tidal heights occur, the highest is included. Those records typically are available from 1979 for the six selected records. No significant deviations were found. This could mean that either there is no difference, or that extreme water levels show a rising trend that has no significant impact on the average highest high water measured over the whole month. Due to the complexity of the system such linear extrapolations do not portray long term reality. However, it is interesting to see how sea level rise and a persisting higher trend of extreme water levels would affect the Chesapeake Bay. Here, we put a focus on the state of Maryland. For this analysis, the average linear trend from the six selected tide gauges is projected 25 years in the future (from 2012), resulting in a +0.04 meter water level as shown in the last column of table [A-3]. Note that this is only small compared to both the hurricane height and the sea level rise. Furthermore, the average height of Isabel over the six tide gauges is assumed, resulting in an additional +2.04 meter water level. Finally, the results are added to the ELT, GWC and $GWC^{+/+}$ (see main report) water heights for 2037, resulting in an overall water height of respectively 2.10, 2.40 and 2.60 meters in the year 2037. The flood map in figure [A-4] shows how far the water might reach (for methodology, see main report). Note that different from sea level rise, a storm surge will dissipate over land, and might not inundate the whole area.

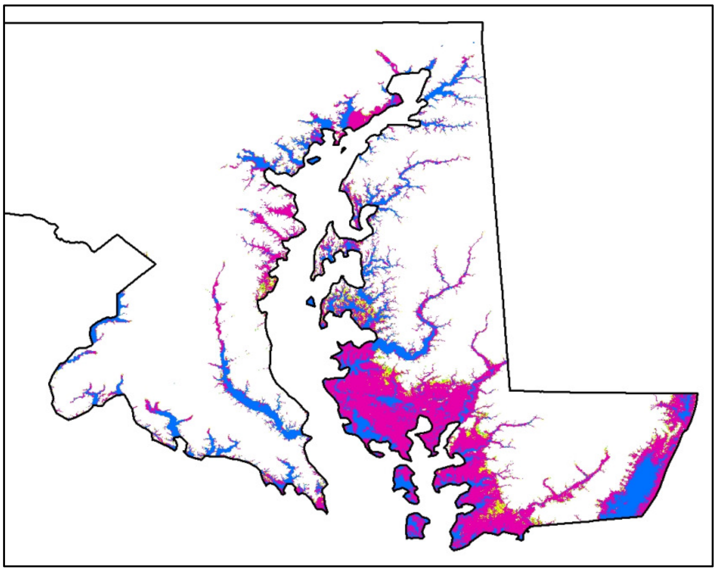

Figure [A-4] Flood map for Maryland in 2037 under (1) rising extreme water level trend, (2) two meter hurricane storm height, and (3) relative sea level rise. Blue: Zero sea level rise. Purple: 2.1 meter sea level rise (ELT). Yellow: 2.4 meter sea level rise (GWC). Green: 2.6 meter sea level rise ($GWC^{+/+}$). The flood maps are created by calculating new raster's with a specific value (1) for "elevation <= projected sea level". Not that due to geographic slope, the difference between 2.1, 2.4 and 2.6 meter is small, and difficult to visualize in the figure.

By using the methodology for land inundation in the main report, it is calculated that the land surface area at risk of flooding is 2455, 2646, 2759 km^2 for the ELT, GWC and $GWC^{+/+}$ respectively. If a hurricane would hit under condition of (1) no sea level rise, and (2) no increased extreme water level trend, the area under flood risk would be 2386 km^2. This means that sea level rise and an extreme water level trend above mean sea level trend would result in ~3-16% more land under flood risk from a hurricane that produces two meter storm surges. Applying the same methodology for inhabitants results in ~177.000, ~194.000, and ~207.000 inhabitants for the ELT, GWC and $GWC^{+/+}$ respectively for the risk of being in a flood. If a hurricane would hit under condition (1) and (2) stated above, the inhabitants at risk would be ~171.000. This means that sea level rise and an extreme water level trend above mean sea level trend would result in ~3-21% more inhabitants at risk from a hurricane that produces two meter storm surges. Again applying the same methodology for GDP results in impeded GDP production of 4.00, 4.56, and 4.97 billion US dollar/year for the ELT, GWC and $GWC^{+/+}$ respectively. Note that different from inundation by sea level rise, the effects of a hurricane would not last for a year. If a hurricane would hit under condition (1) and (2) stated above, the affected GDP production would be 3.83 billion US dollar/year. This means that sea level rise and an extreme water level trend above mean sea level trend would result in ~5-30% more inhabitants at risk from a hurricane that produces two meter storm surges. Note that these percentages only count for these specific conditions, and only for the state of Maryland. Due to large geographical and socio-economic differences, the results will be different for different storm heights and different states. The question still remains if storms like hurricane Isabel would occur more frequent due to global warming. There are several authors that report on the intensification of tropical cyclones. Webster *et al.* (2005) used satellite data to show a positive relation in the last 30 years between tropical cyclones and rising sea surface temperatures (SST's). Rising sea surface temperatures is associated with global warming (Solomon *et al.*, 2007), but Webster *et al.* (2005) do note that the record they used is essentially too short to relate an increasing trend in tropical cyclones directly to global warming. Chan (2006) noted that the results found by Webster *et al.* (2005) are faulty because of the use of satellite data and exclusion of records before the satellite era. According to Chan (2006) the recent increase in tropical storm is more likely to be part of a large inter-decadal variability related to similar temporal fluctuations in the atmospheric environment. In response to the comments made by Chan

(2006), Webster *et al.* (2006) noted that the database used by Chan (2006) had data that was in need of reprocessing. After careful reassessment, Webster *et al.* (2006) conclude that if "SSTs continue to rise under anthropogenic forcing, it is reasonable to expect […] that there will be an associated increase in the intensity of typhoons". Hoyos *et al.* (2006) analyzed the intensification of hurricanes, and found that the increase in category 4 and 5 hurricanes is directly linked to the increasing trend of SSTs over the period 1970-2004. These papers support the significantly increasing trend found here with simple linear calculations (table [A-3]). However, extrapolating these results into the future with predicted global warming is not as simple. Knutson *et al.* (2008) report that although the increase of SSTs in the recent decades is most likely the cause of an intensification of hurricanes in the Atlantic, it might not continue, even under face global warming. Their dynamic model shows that the relative strong rise of SSTs with respect to other ocean basins might be the cause of the intensification of hurricanes in the Atlantic. They argue that since the SSTs in the Atlantic are not expected to increase more rapidly than other tropical basins, no intensification of hurricanes is expected in the North Atlantic for the 21th century. The research by Emanual *et al.* (2008) found an increase in tropical storm frequency for the Western North Pacific, decreased frequency on the southern hemisphere, and left he frequency undetermined for the Northern Atlantic. Coughlin *et al.* (2009) summarize several studies which use dynamical models, and found that they predict a range of 5–7% increase in maximum wind speeds 12–26% increase in the precipitation rate within 100 km of the storm center. However, a mixed range in storm frequency was found Coughlin *et al.* (2009) for the 21th century (+2.2% to -25% change in tropical cyclone frequency; +40% to -18% change in the number of Atlantic hurricanes) which shows there is still disagreement among scientist on future storm frequency. In their 2010 review, Knutson *et al.* (2010), state that the frequency of tropical cyclones is most likely to decline under global warming. They do however note that the frequency of high impact hurricanes is expected to increase. This is highly relevant since these are the storms that cause the intensive flooding in the Chesapeake Bay. This conclusion is supported by Bender *et al.* (2010). They produce a model which focuses specifically on category 4 and 5 hurricanes. Bender *et al.* (2010) conclude that although overall frequency of tropical cyclones decreases, it is likely that the most intense storms see an increase due to anthropogenic warming at the end of the 21th century, potentially doubling the current frequency. If correct, the Chesapeake Bay will increasingly be affected by extreme flooding events.

Conclusions

Extreme water levels in the Chesapeake Bay are related to extreme hurricane and tropical storm events. There is an ongoing disagreement among scientists about the intensity and frequency of tropical cyclones. But even without increasing frequency and intensity the storm water level height will increase with increasing sea levels. If the intense tropical cyclone events indeed intensify as suggested by several authors, the Chesapeake Bay would not only see very high sea levels due to the combined effect of sea level rise and hurricane events, it would also see the frequency of the most intensive storms increase. The added effects of these factors would mean increased damage and an increased risk of loss of live for the Chesapeake Bay. It is found here that with rising sea levels, and with an increase of extreme water levels with respect to the mean sea level trend for the next 25 years, the impact on land surface inundation could be between 3-16% greater than under conditions of no sea level rise and no increasing trend of extreme water levels for the state of Maryland. The effect on inhabitant displacement is calculated to be between 3-21% higher for respectively the most conservative and the most extreme sea level rise scenario. For GDP a range of 5-30% increased impact is found. Note that hurricanes have wreaked havoc in the Chesapeake throughout history. It is very likely that, taking into account sea level rise and a potential increased frequency of high category storm, the Chesapeake Bay is up for a century of increased flooding and storm damage. Even if the anthropogenic warming were to be stopped, the sea levels will continue to rise (Nicholls & Lowe, 2004; Meehl *et al.*, 2012), and storm surge height will therefore continue to rise with it despite efforts to stop global warming. This emphasizes the importance of adaption and mitigation efforts to prevent global warming and related sea level rise for the near and far future.

The study performed in this appendix is a case study for the Chesapeake Bay, with a focus on Maryland. The general conclusion must however be extrapolated to the results found in the main research. Clearly, every coast has its own geophysical conditions and storm characteristics. For each of the coastal states of the conterminous United States, it is however clear those extreme water levels will increase with sea level rise. Even if storm intensity does not increase, extreme water levels will still be elevated with minimally the sea level rise. This has implication for the results found in the main research, which only focused on permanent inundation. Figure [17] shows the land inundated with sea level rise. These values are considerably higher if extreme water levels are taking into account, as shown in this appendix for the state of Maryland. The definition of impact will not be land inundated, but land potentially at risk of flooding. This means the impact is not permanent, but with extreme water levels increasing, the frequency of flooding events increases, making habitation more difficult. Consequently, larger areas are at risk. Especially regions with relatively gradual coastal slope like the Gulf coast and mid and southeastern Atlantic would see more flooding due to higher water levels. As shown in figure [17], those are the areas that are already the regions which see the largest impact due to sea level rise.

The impact of this extreme water level would also significantly increase the values found for inhabitant displacement and GDP affected (fig. [18] and [19]). Again, the impact is not permanent, but because of the abrupt nature of extreme water levels the consequences might be more extreme. Loss of life and sudden loss of property will more frequently occur and disrupt life in coastal communities. As shown here in this appendix, the *average* extreme high water will already increase to levels at which extensive flooding occurs. This will be true for all of the coastal states. The impact will of course vary, with high impact on those states that already show high impact (fig. [18] and [19]) due to either low-lying terrain or high coastal population densities.

In the main research it is noted that adaptive strategies against inundation due to sea level rise are not impossible, but will become more costly. Attention has to be paid to future development through retreat and accommodation strategies. Extreme storm levels add an extra dimension to these conclusions. First, adaptive strategies have to encompass not only areas at risk of inundation, but further beyond, to the end of flood maps. Those areas that are not at risk at this point might be found in a risk zone due to retreating and eroding shorelines. Second, it is mentioned in the main research that a breach of protective measures leaves more people at risk because sea levels are relatively higher with respect to the developed land. Such a breach is more likely to occur with a high frequency of extreme water levels. Great care should therefore be taken in choosing adaptive strategies, selecting the right mix of options, and paying attention to maintenance and the state of protective measures.

To conclude, this appendix is considered a vital addition to the main research, showing the potential effects of storms in combination with sea level rise. Neither inundation due to sea level rise, nor flooding due to a combination of sea level rise and storms, is more important than the other. Both cause disruptions, the first slowly but progressively, the other sudden and abrupt (and increasingly frequent). It is therefore of great importance to keep our focus on both issues, and respond through adaptation and mitigation to reduce the impact of storms and sea level rise.

Appendix A references

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