A REVIEW OF SEA LEVEL RISE PROCESSES AFFECTING THE MID-ATLANTIC COAST OF NORTH AMERICA

SENIOR THESIS WRITTEN BY

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ABSTRACT

A substantial fraction of human settlements lie in coastal areas. Their proximity to the sea puts them at risk to flooding and other detrimental effects that may arise from a relative sea level rise in these locations. In public discussion, sea level rise is often presented solely through the lens of anthropogenic climate change. In actuality, some processes (such as glacial isostatic adjustment induced subsidence) operate independently of human influence. Herein I present a review of the processes behind sea level rise, with a particular focus on those operating on the Mid-Atlantic coast of North America. Additionally, I produce a series of data visualizations exploring the processes and their potential effects. These visualizations investigate novel ways of presenting data to promote accessibility of scientific data.

ACKNOWLEDGEMENTS

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INTRODUCTION

A substantial fraction of human settlements lie in coastal areas. The proximity of these settlements to the sea puts them at risk to flooding and other detrimental effects (such as salination of freshwater drinking sources due to changing water table levels) that may arise from relative sea level (RSL) rise in these locations. My thesis will review the current understanding of factors that influence sea level rise in order to present a framework for considering the causes and impacts of relative sea level rise.

In public discussion, sea level rise is often presented with anthropogenic climate change as the sole cause and context. In reality, some driving processes operate entirely independent of human influence (such as subsidence due to glacial isostatic adjustment (Peltier 1998)). Understanding the interplay of systems affecting relative sea level and where their effects might manifest will be crucial in order for communities to adapt to the changing sea level.

Increasing public understanding depends on ensuring scientific findings are accessible. I have created a series of data visualizations to explore more intuitive ways of presenting and interacting with relevant data. These visualizations complement the explanation of processes, with specific data driven examples, and highlight the possible impacts of sea level rise on coastal communities.

In order to better understand modern sea-level rise we need to place the current situation in context. As it is unrealistic to observe sea-level changes on a day-to-day basis, general assessment requires a longer timescale to situate ourselves. Tide-gauge data provides a sufficiently long record length for this purpose. Studies of tide-gauge data with record lengths exceeding 75 years have shown accelerating rates of sea-level rise (up to 0.30mm/yr^2) along portions of the North East Atlantic coast of North America (Boon 2012). However, the South East Atlantic coast has not exhibited these high rates of relative sea level rise and shows no clear evidence of acceleration, demonstrating that RSL occurs at different rates in different localities.

While record lengths of ~75 years are sufficient to establish a current understanding of RSL, the complexities of earth processes are such that tide-gauge records do not provide enough information to know whether current rates are abnormal. Determining this requires a longer record for comparison with the short-term tide gauge data. Salt-marsh sedimentary sequences from North Carolina on the US Atlantic coast have allowed the construction of a sea-level record spanning the past 2100 years (Kemp, et al. 2011). This record shows a stable sea-level from ~BC 100 until AD 950, then an increase for 400 years at a rate of 0.6mm/yr, followed by stable or slightly falling sea level until the late 19th century. Since then, sea level has risen at an average rate of 2.1mm/yr, initiated between AD 1865 and 1892 (Kemp, et al. 2011)

The record established in Kemp et al. 2011 required correction for Glacial Isostatic Adjustment in order to establish a figure for mean rather than relative sea level rise. Since ~900 Kyr ago the Earth's climate has resulted in an oscillation between glacial and interglacial conditions with a periodicity of ~100 Kyr (Peltier 1998). The formation of massive ice sheets on the surfaces of continents at high latitudes during each glacial cycle resulted in the deformation of the earth's crust; a consequence of the mass redistribution of the planet and the viscoelastic nature of its mantle. Areas under the ice sheets experienced subsidence due to the ice load, correspondingly areas further from the ice sheets experienced uplift. Since the last glacial maximum, the opposite has occurred, the crust rebounding as a result of the different mass distribution (Peltier 1998). This process continues entirely independently of anthropogenic climate change, with some areas experiencing subsidence and an accelerated rate of relative sea level rise and other areas experiencing uplift and a slowed rate of relative sea level rise.

While anthropogenic climate change may be responsible for rising mean sea levels due to thermal expansion of the oceans and the addition of melting land based ice, the magnitude and rate of this rise will vary locally. The freshwater input that melting ice brings could induce changes in the thermohaline circulation (THC) as result of new salinity gradients. THC is responsible for sea surface variation and any change in ocean circulation would be followed by a regional dynamic sea level change. Modeling has shown this dynamic effect can locally reach up to ~1m in magnitude with rates of change possibly as high as 20-25 mm/yr (Levermann, et al. 2005).

The local variation in the previously discussed processes means the some localities will experience sea level rise much more rapidly than others. One such locality has been identified, a

1,000 km long hotspot on the North American Atlantic coast. It exists north of Cape Hatteras, NC. Between 1950-1979 and 1980-2009 sea level rise rate increases here were ~3-4 times higher than the global average (Sallenger, Doran and Howd 2012). Furthermore, the authors of the study found that this acceleration is consistent with models produced by the Intergovernmental Panel for Climate Change (IPCC) showing the possible results of THC weakening (specifically these rises are associated with weakening of the Atlantic Meridional Overturning Current). These same models predict sea level rise of 36 to 51cm at New York City by 2100.

METHODS

I developed visualizations that utilize real data to ensure that representations of the processes are grounded in reality and avoid misrepresentation through over-simplification.

Glacial Isostatic Adjustment Animation

I used the open source programming language and environment *Processing* to develop a visualization representing subsidence over time. Processing creates easy to use visual presentations that promote accessibility of scientific ideas through visual stimulation and understanding.

I created three visualizations based on the data gathered at Sand Point, NC (Figure 1) in Kemp et al. 2011 that plot the sea level change at this locality over time since 180 B.C. Animation 1 displays a GIA corrected curve whereas Animation 2 shows the uncorrected curve. Animation 3 plots both curves at the same time, demonstrating how GIA influences the record as land subsides.

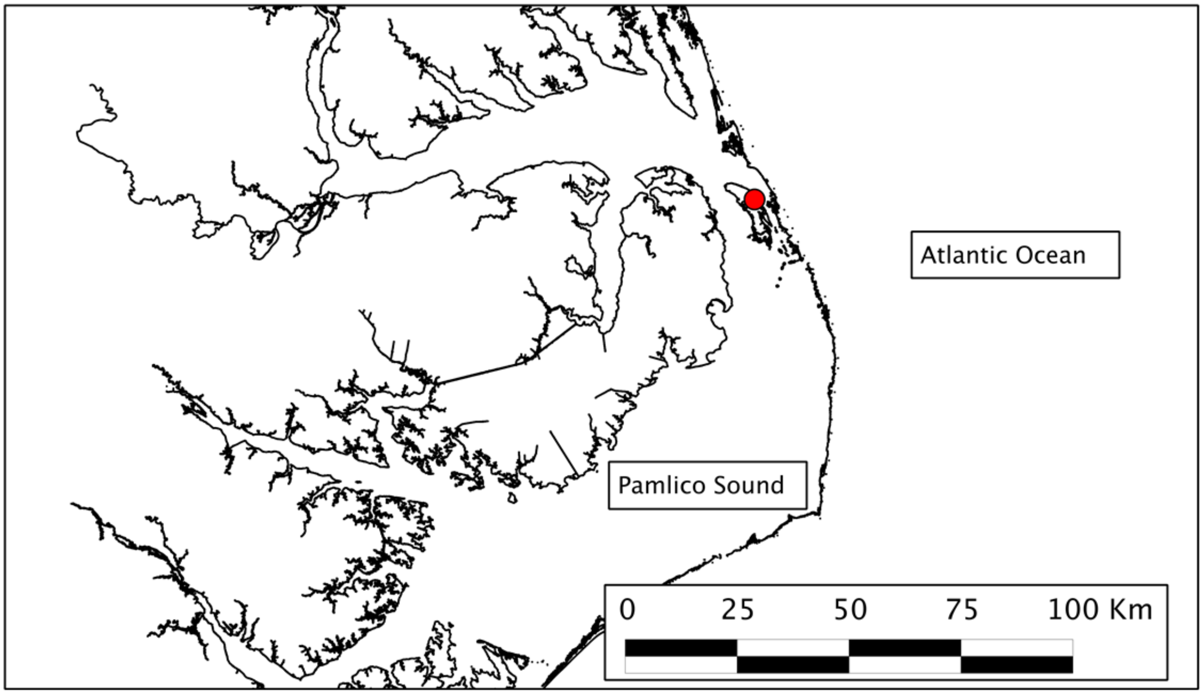

Figure 1: Location of Sand Point (marked by red dot).

The source data is stored in an excel spreadsheet without GIA correction. Animation 2 reads in the depth and error ranges for each point and sequentially plots boxes to represent the ranges of each point. Animations 1 and 3 read in from the same data but apply GIA correction before plotting anything; Animation 1 takes the newly corrected data and sequentially plots boxes to show the ranges of each point. Animation 3 does the same as Animation 1 but adds a second series of boxes that have subsidence dynamically applied at each timestep. Animations 1 and 3 use a subsidence rate of 1 mm/yr in calculations, consistent with Kemp et al. 2011.

Hypsometric Curve

The North Carolina coastline has been identified as experiencing a hotspot of accelerated sea level rise (Sallenger, Doran and Howd 2012). In order to demonstrate the potential impact, hypsometric analysis of the 20 coastal counties of North Carolina was performed.

Digital elevation maps (DEM) of 1/9 arc second resolution were downloaded for the 20 coastal counties of North Carolina. The DEMs were acquired via the *USGS National Map* and are a part of the *National Elevation Dataset*. They are derived from LIDAR data that has been algorithmically and manually edited by the USGS to remove vegetation, buildings and other man made structures - providing a bare earth data set.

I then manually combined the DEMs using the open source GIS software *SAGA (System for Automated Geoscientific Analyses)* to produce a continuous dataset for analyses (Figure 2). The source USGS DEMs included some sectors with corrupt data; these were excluded.

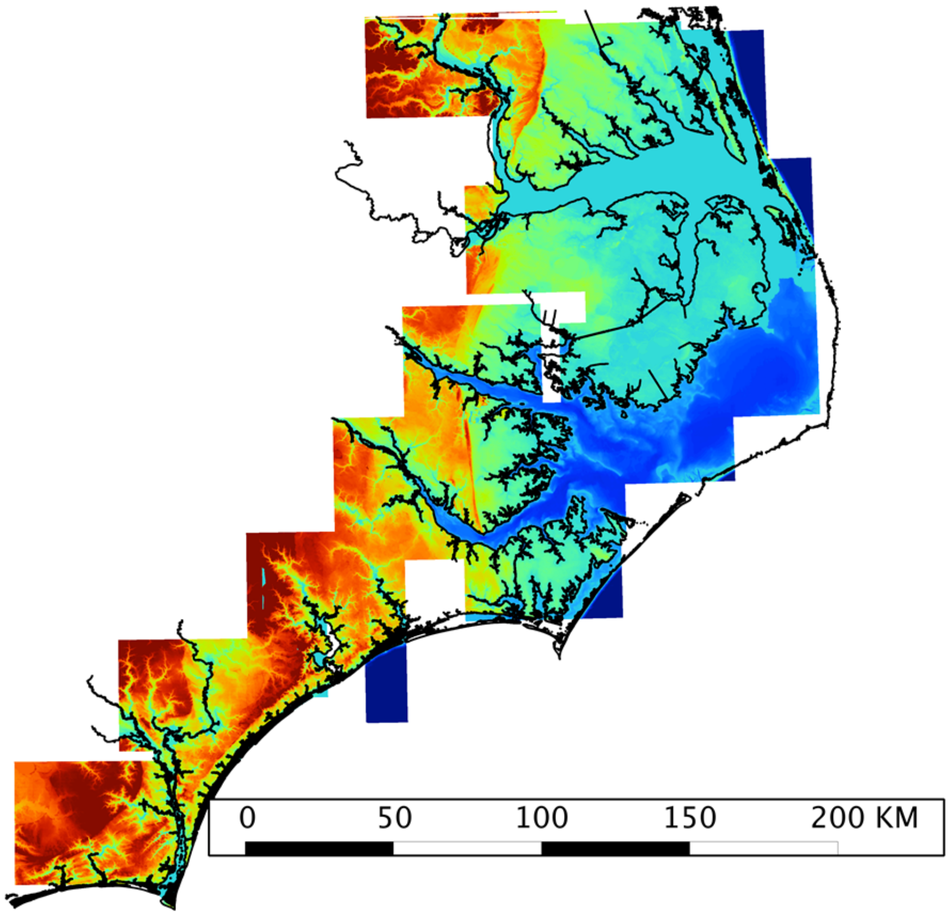

Figure 2: Combined elevation map of area surveyed with overlaid North Carolina estuarine coastline.

The combined DEM was subjected to hypsometric analysis using *SAGAs* morphometry tools to create a hypsometric curve of the area with 100 bins. The hypsometric curve was limited to values above sea level as the source data handled bathymetric values inconsistently; some sectors provided continuous topobathy surfaces while others provided only topography or topobathy with approximated depth values.

RESULTS

Glacial Isostatic Adjustment Animations

The produced animations are available as standalone applications for all major operating systems but are unable to be embedded in this document. In lieu of this I have produced a series of representative screenshots. Links to download the applications are available in the appendix.

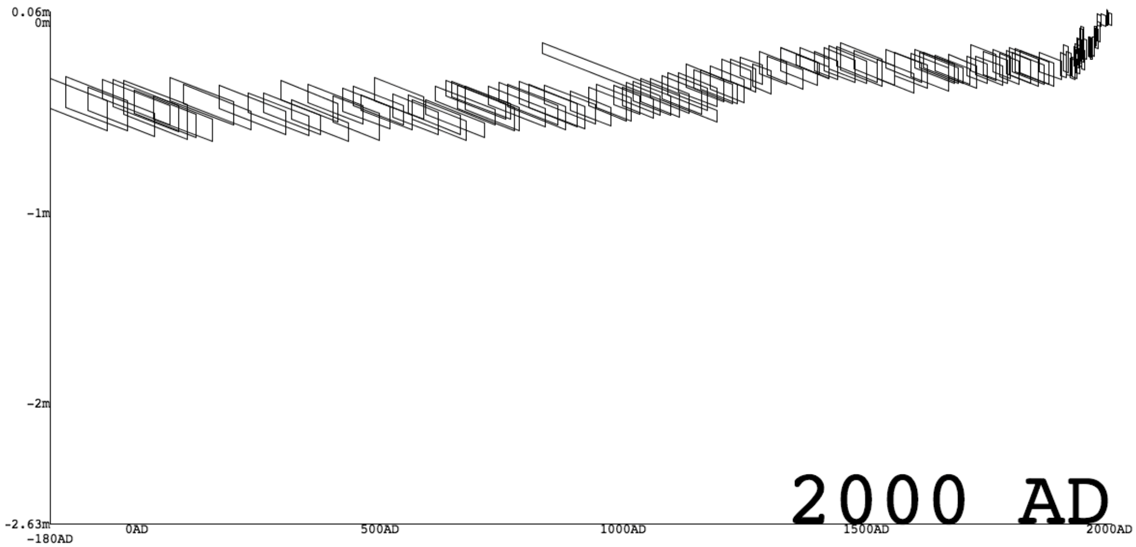

Figure 3: Screenshot of Animation 1 (GIA corrected values) after completion.

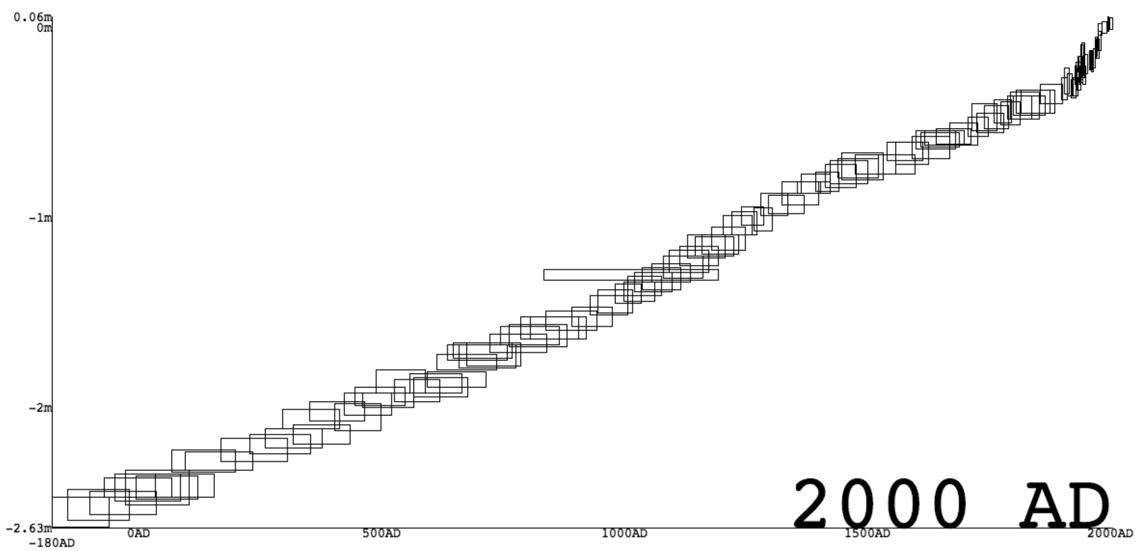

Figure 4: Screenshot of Animation 2 (uncorrected values) after completion.

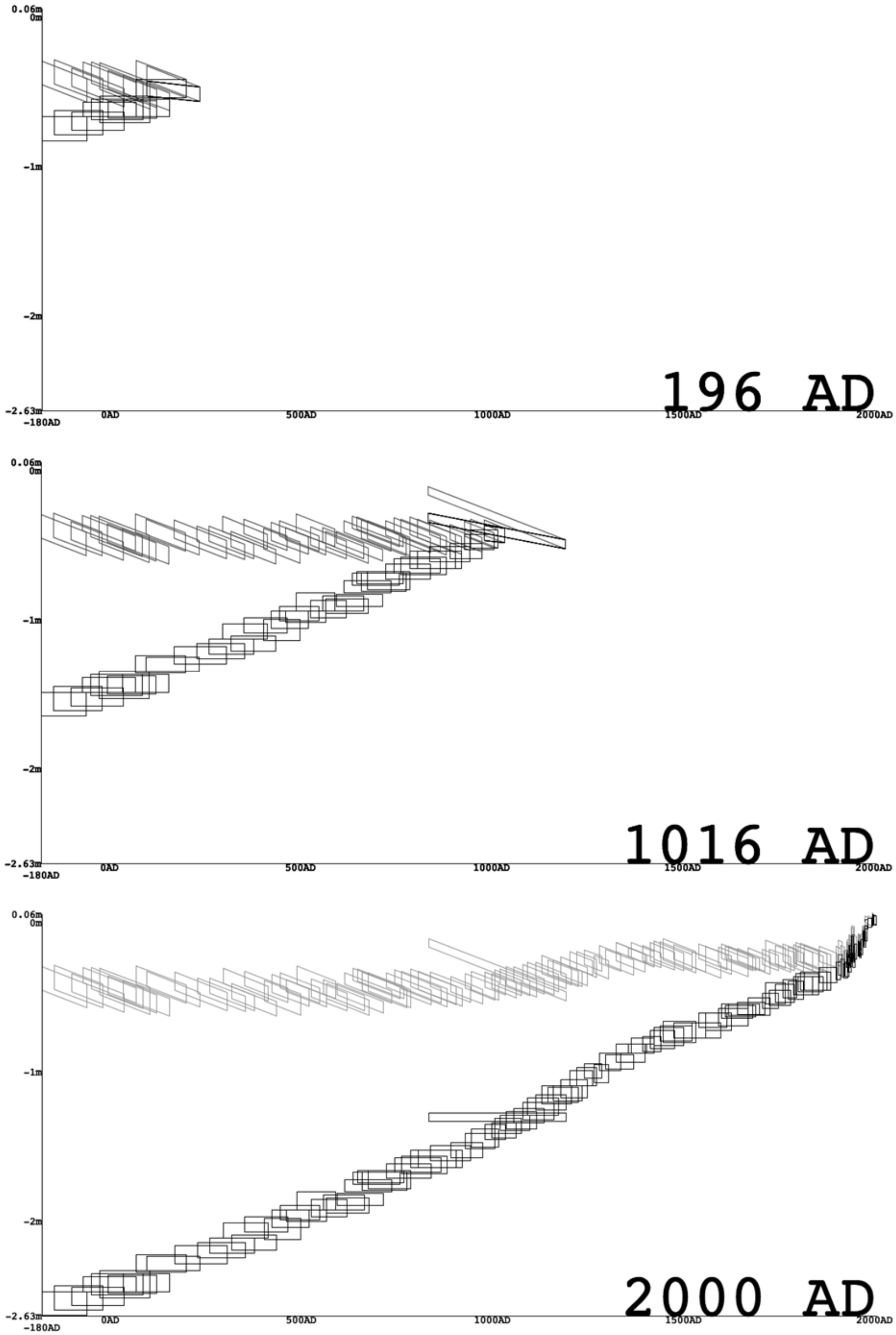

Figure 5: Demonstrative screenshot series of Animation 3 (combined GIA corrected and uncorrected values).

Hypsometric Curve

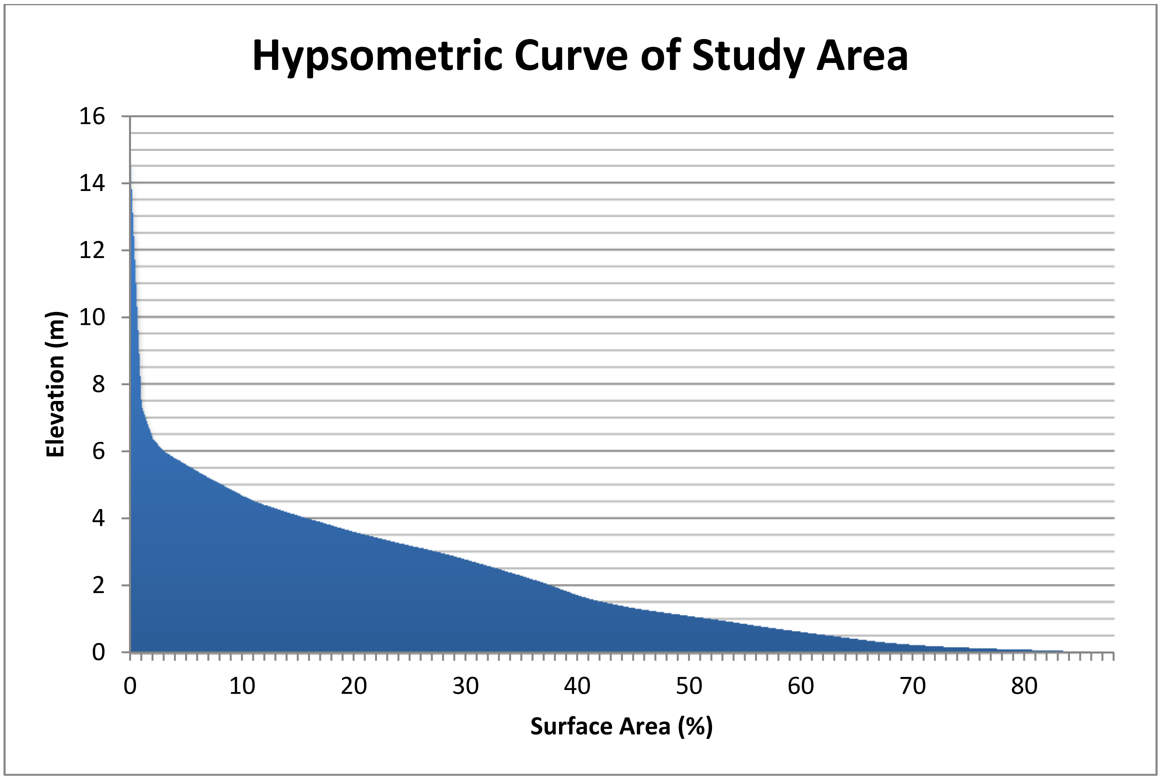

Figure 6: Hypsometric curve of study area with elevation above sea level. Surface Area percentage is of entire study area shown in Figure 2.

Table 1: Percentage of entire study area affected by Sea Level Rise Extent

SLR extent (m)	Area Affected (%)
0.1	8
0.2	16
0.3	20
0.4	22
0.5	25
0.6	27
0.7	29
0.8	31
0.9	33
1	35

DISCUSSION

Glacial Isostatic Adjustment Animations

Comparison of Animation 1 (Figure 3) and Animation 2 (Figure 4) shows a substantial difference. Without correcting for GIA the recent acceleration of sea level rise since the late 19th century would not seem to be a significant deviation from the existing pattern, however with GIA corrected for this acceleration becomes much more obvious.

Although subsidence rates of 1mm/yr may not seem like much, these animations show that they have substantial impact over time and should not be ignored. While some groups in public discussion dismiss human responsibility for recent climate change, subsidence operates independently of human activity and needs to be considered regardless of one's beliefs on anthropogenic climate change. As the magnitude of GIA induced subsidence varies depending on the locality it is important to consider sea level rise not just as a single global process. Coastal communities around the world will be affected differently and will have to plan their responses according to their particular situation.

Hypsometry

The produced hypsometric curve (Figure 6) shows that much of the study area has relatively low elevation. A large portion of North Carolina is at risk from the effects of sea level rise, with a majority of the area below 2 meters in elevation. Sea level rise of just 0.2 meters would place 16% of the study area below sea level while a rise of 0.5 meters would place 25% below sea level (Table 1). While sea level rise itself presents a direct risk, it also makes the area much more vulnerable to storm surges associated with storms and hurricanes which would further elevate the sea level (albeit temporarily).

Possibilities for Future Work

The animation format I have presented here could be used for data from other localities to provide an interesting comparison of how different subsidence rates effect the relationship between global sea level rise and local relative sea level rise. Comparison with localities experiencing uplift as a result of GIA might be particularly useful.

The hypsometric analysis could be improved with a more complete data set; full topobathy data would be ideal. Should DEMs be obtained that provide full coverage of the NC coastal area, the method could be used on a county-by-county basis to identify those counties that would be most affected by sea level rise. This process would work for any location for which sufficient DEMs can be obtained and could be a useful tool for communities worldwide.

APPENDIX

Animation Download Links

Animation 1 (GIA corrected values):	http://www.mediafire.com/?t0bgb67exr9xngz
Animation 2 (Uncorrected values):	http://www.mediafire.com/?ag3b09la8rd41ny
Animation 3 (Combined Values):	http://www.mediafire.com/?crhb9icc14cyyll

Each download is 38 MB in size and includes the source code for that particular animation.

Data Sources and Software Used

Data Sources

Digital Elevation Maps - National Elevation Dataset: http://ned.usgs.gov/

Acquired via the USGS National Map: http://nationalmap.gov/index.html

DEMs were acquired for the following counties:

Beaufort	Hertford
Bertie	Hyde
Brunswick	New Hanover
Camden	Onslow
Carteret	Pamlico
Chowan	Pasquotank
Craven	Pender
Currituck	Perquimans
Dare	Tyrell
Gates	Washington

Coastal North Carolina Estuarine Shoreline shapefiles (used in figures):

North Carolina Department of Environment and Natural Resources, Division of Coastal Management: http://dcm2.enr.state.nc.us/maps/chdownload.htm

Software

Processing: http://processing.org/

XlsReader Processing Library by Florian Jennet: http://bezier.de/processing/libs/xls/

System for Automated Geoscientific Analysis (SAGA GIS): http://saga-gis.org/en/index.html

Quantum GIS (QGIS) (used in figure construction): http://www.qgis.org/

A Note on Figure Construction

Figure 1 and Figure 2 were created in QGIS, they employ EPSG:3631 for their Coordinate Reference System: http://spatialreference.org/ref/epsg/3631/

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