Climatic Change (2011) 107:129–146
DOI 10.1007/s10584-011-0080-2

Assessment of sea level rise impacts on human population and real property in the Florida Keys

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Received: 3 June 2010 / Accepted: 31 March 2011 / Published online: 15 May 2011

Abstract The potential impacts of sea level rise (SLR) on 95% of the land areas of the Florida Keys were estimated through analysis of a digital elevation model (DEM) derived from airborne light detection and ranging (LiDAR) measurements in a geographic information system. The topographic detail of the LiDAR DEM allowed projections of land, population, and property inundation in 0.15 m increments across a broad range of SLR scenarios for the next century. The results showed that a 0.6 m SLR by 2100 would inundate about 70% of the total land surface, but smaller percentages of the population (17%) and real property (12%). A 1.5 m rise in sea level during the same period would inundate 91% of the land surface, 71% of the population and 68% of property in the study area. Comparison of inundation dynamics indicates that the Lower Florida Keys are more susceptible to SLR than the Upper Florida Keys. The inundation dynamics exhibit non-linear behavior and demonstrate tipping points in inundation processes beyond which the inundation of land, population, and property speeds up. Acceleration of SLR will amplify the non-linear inundation, causing tipping points to be reached sooner.

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1 Introduction

One of the most obvious and certain consequences of global warming is an increase in sea level. According to tide gauge records, global sea level rose at a rate of 1.8 mm/year in the twentieth century, with most of the rise attributable to thermal expansion and the melting of glaciers (Douglas 2001). Based on synthetic global sea level time series from tide gauge records and satellite altimeter measurements, Church and White (2006) concluded that sea level rise (SLR) accelerated from 0.7 mm/year during the period 1870–1935 to 1.8 mm/year from 1936 to 2001. In 2007, the Intergovernmental Panel on Climate Change (IPCC) projected a global SLR of 0.18–0.59 m by 2100 as a result of climatic change (IPCC 2007). However, recent studies on ice disintegration dynamics suggest that the IPCC report may have greatly underestimated SLR, because the role of acceleration in the melting of the Antarctic and Greenland ice sheets was not accounted for. Rahmstorf (2007) linked the global SLR rate to the increase in global mean surface temperature from 1880 to 2000 using a simple linear equation, resulting in a projected SLR in 2100 of 0.5 to 1.4 m above the 1990 level. Recently, Vermeer and Rahmstorf (2009) extended the method by adding an instantaneous item into the Rahmstorf (2007) equation, thereby deriving an updated SLR projection of 0.75–1.9 m by 2100. Pfeffer et al. (2008) indicated that a 0.8–2.0 m global SLR by 2100 was likely by including the dynamics of Antarctic and Greenland ice sheets into the estimate of SLR. Bamber et al. (2009) estimated that the rapid collapse of the West Antarctic ice sheet would lead to a 3.3 m rise in global mean sea level, with regional variations that indicate the U.S. Atlantic and Pacific coasts would experience 25% additional SLR beyond the global mean. Hansen (2007) argued that the acceleration of ice sheet disintegration may cause a 5 m SLR by the year 2100.

Such large SLR rates in this century would threaten millions of people and developed as well as natural environments in coastal areas. Potential SLR impacts have been studied extensively around the world to address adverse effects on low-lying ecosystems, property, critical infrastructure, and population (Leatherman 1984; Nicholls 2004; Nicholls et al. 1995; Schneider and Chen 1980; Titus and Richman 2001; Titus and Wang 2008; Zhang 2010). Additionally, several papers over the past 20 years have specifically analyzed the impact of sea level changes on the Florida Keys. Titus and Richman (2001) examined the SLR-induced inundation of the U.S. East coast, including the Florida Keys, using a one degree digital elevation model (DEM) produced by the U.S. Geological Survey (USGS) based on 1, 2, 3, and 5 m SLR scenarios. Harrington and Walton (2007) estimated the values of impacted property in Monroe County, which includes the Keys, to be approximately \$3.3 and \$5.8 billion if sea level rises 0.31 and 0.65 m, respectively. Recently, The Nature Conservancy (2009) estimated potential ecological and economic consequences of rising sea level for the Florida Keys, especially Big Pine Key, based on the 2007 IPCC projections of SLR ranging from 0.18 to 0.59 m by 2100 and Rahmstorf's 2007 projection of 1.4 m.

These studies of SLR impacts typically delineate inundation zones by projecting future sea levels on topographic maps or DEMs, and analyzing the impacts of inundation-related processes such as storm surge flooding, saltwater intrusion, and coastal erosion. However, the reliability of such analyses has been limited by poor vertical resolution (>1.5 m) of DEMs. Moreover, few studies have quantified inundation processes, analyzed their effects on the SLR impact, or provided answers for the following questions: (1) Do inundation processes exhibit acceleration due to topography even if the SLR rate is constant, and are there site-specific tipping points in the inundation process beyond which impacts become calamitous? (2) What is the effect of SLR acceleration on inundation dynamics? (3) What are the policy implications of non-linear inundation? Answers to these questions are essential for the design of sound policies capable of reducing the tremendous risk associated with possible rapid SLR. This paper addresses these questions and estimates the SLR impacts on human population and real property by analyzing inundation dynamics based on highly accurate DEMs derived from airborne light detection and ranging (LiDAR) measurements for the Florida Keys.

2 Study area

The Florida Keys are one of the most susceptible island systems in the United States to SLR-induced inundation because most elevations are less than 2 m above current sea level. The Keys are an arcuate chain of about 1,700 islands, beginning at Soldier Key south of Biscayne Bay, Miami, extending in a south–southwest direction first, then gradually turning to the west toward Key West, and ending in the Dry Tortugas (Fig. 1). The total area of the Florida Keys is about 360 km^2. The study area, beginning at Palo Alto Key and ending at Key West, includes the portion of the Florida Keys within Monroe County, Florida and comprises approximately 95% of the total area of the Florida Keys.

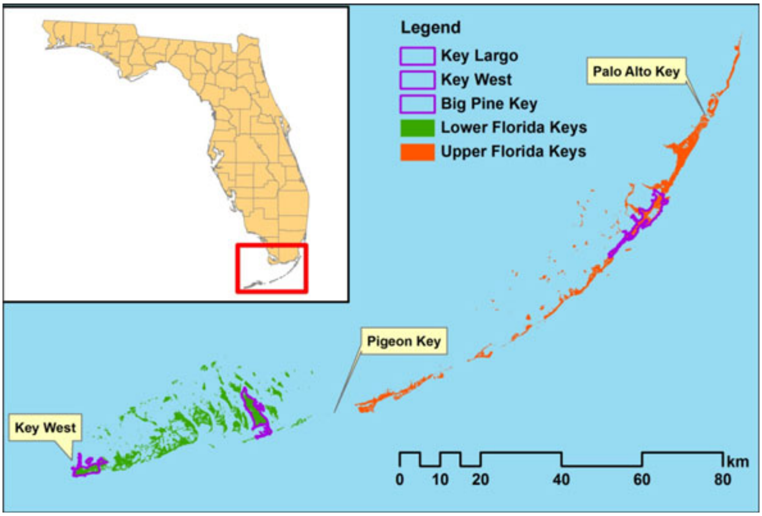

Fig. 1 The location of the study area, which excludes the islands north of Palo Alto Key. The boundaries of Key Largo, Big Pine Key, and Key West (*purple outlines*) are displayed. The boundary of Big Pine Key is separated by water and the boundary of Key West is the city boundary. The boundary of Key Largo is based on the boundary of the census-designated place for Key Largo, which is the population concentration area identified by the United States Census Bureau for population statistics

The Florida Keys were built on a fossil coral reef established during a higher sea level stand in the late Pleistocene, about 125,000 years ago (Halley et al. 1997). They can be divided into the Upper and Lower Florida Keys using Pigeon Key as a separator (Fig. 1). In the Upper Florida Keys, the surface bedrock is composed of coralline limestone, whereas in most of the Lower Florida Keys (i.e., from Big Pine Key west), the surface bedrock is an oolitic limestone deposited above the coralline facies, which dips 8 m or more below the surface. The shapes of islands in the Upper Florida Keys are distinct from those in the Lower Florida Keys; the Upper Florida Keys are narrow and aligned parallel to the island arc, while the Lower Florida Keys are wider and are mostly aligned perpendicular to the archipelago's trend.

The 2000 census data showed that the total population of the study area was 72,529, with an average density of 234 people per square kilometer. Much of the population is concentrated on just a few islands such as Key West, which houses approximately 30% of the Keys' population. The values of real property on land within the study area totaled $39 billion in 2007, with a mean parcel value of $527,000, according to tax data from the Monroe County Appraiser's Office. The Lower Florida Keys are also the home of three national wildlife refuges including the National Key Deer Refuge, established in 1957 to protect both the deer and the diverse elements of its habitat.

3 Data

3.1 Census block

Census data consist of Topologically Integrated Geographic Encoding Referencing (TIGER) line files, which delineate the geographic boundaries of census units, and tables that list the aggregation of population and housing for each census unit. The data can be downloaded from the U.S. Census Bureau (www.census.gov), which undertakes a census of population and housing for the United States every ten years. TIGER/Line data have been converted by a number of vendors into a format compatible with GIS files. The 2000 census block data for Monroe County were used in this study because the block is the smallest census unit typically associated with an aggregated population of 85 people (Peters and MacDonald 2004). A block within a city is typically delineated by four intersecting streets with a grid road structure, while a block in a rural area may cover many square kilometers. Tabular data listing the number of people and other related information for census blocks were joined to a block shapefile in ArcGIS to estimate the population influenced by SLR.

3.2 Property parcel

The property data consist of parcels, which outline the geographic boundary of properties, and associated tax roll data, which list the name and address of the owner, year built, and just value for a property. This study utilized 2007 parcel and tax roll data for Monroe County, which was the most current data available at the time of the study. The just value of a property was used to estimate anticipated property loss due to various SLR scenarios. Just value is "the amount a purchaser, willing but not obliged to buy, would pay a seller who is willing but not obliged to sell" according to the Florida Constitution, $193.011, and represents a fair market value of a property. The just value of a property changes with fluctuations in the real estate market. The total just value for real properties in Monroe County was $31, $39, $40, and $37 billion in 2005, 2006, 2007, and 2008, respectively based on statistics from the Florida Department of Revenue (http://dor.myflorida.com/dor/property/). The parcel and tax roll data were provided by the Monroe County Property Appraiser's Office.

3.3 LiDAR DEM

The LiDAR data used in this study were collected in 2007 by 3001 Inc., under contract with the Florida Division of Emergency Management. The spacing of LiDAR measurements averaged 1.3 m, producing an average point density of two points per square meter (3001 Inc. 2008a). An accuracy assessment was performed by calculating elevation differences between ground control points (GCP) and filtered LiDAR points, which represent bare-earth elevations (3001 Inc. 2008b). The average vertical root mean square (RMS) error of the LiDAR data is less than 0.09 m, which corresponds to a vertical accuracy of 0.17 m at the 95% confidence level. A DEM with a horizontal resolution of 5 m was generated by interpolating filtered LiDAR data using the ordinary Kriging method with a search radius of 30 m (Davis 2002). Sensitivity analysis indicated that this resolution is sufficient to generate reliable statistics for impacted land areas, population, and property values on most islands of the Florida Keys.

3.4 Shoreline

A digital shoreline was also produced by 3001 Inc. The shoreline depicts boundaries of islands (>2 km^2) embedded within water bodies. Digital shorelines were created using stereo-compilation, digitizing, and manual editing of LiDAR and ortho-photograph data. A quality control procedure was implemented to verify the positions and elevations of the shorelines. Visual examination by overlaying the shorelines with 2006 digital aerial photographs with a horizontal resolution of 0.15 m indicates that the shoreline matches the land and water boundary well.

4 Methodology

We focused on analysis of projected SLR impacts during the 100 year period from 2000 to 2100, which has been commonly used in other studies (Nicholls 2004). Following the methods described by Zhang (2010), sea level is set to reference the NAVD88 vertical datum. Based on water level records from the Key West tide gauge, which has the longest Florida Keys record, the difference between the mean of the higher high water (MHHW) height from 1995 to 2005 and the NAVD88 datum is about 0.01 m. Therefore, using NAVD88 as a vertical reference during creation of inundation maps is appropriate, and any land that falls below 0 m is theoretically inundated at least two times per day, on average, in coastal areas with semidiurnal tides. The tides at the Atlantic Ocean side of the Florida Keys are controlled by semidiurnal tides of the southern Atlantic Ocean, whereas tides in Florida Bay are mainly influenced by the mixed semidiurnal tides of the eastern Gulf of Mexico (Gibson et al. 2008; He and Weisberg 2002).

A fundamental step in quantifying inundation due to SLR is the creation of inundated areas, also known as inundation polygons, for a particular height of sea level. These polygons are then used to identify the affected populations and properties through spatial queries and statistical analyses. Derivation of inundation polygon and associated statistics for population and property for one scenario of SLR is insufficient to quantify impact because of the large uncertainty in the projection of future sea level for the next 100 years (Hansen 2007; Meehl et al. 2007). It is preferable to estimate inundated area, population, and property based on a series of SLR scenarios determined by the range of uncertainty. A series of SLR scenarios from 0.15 to 5.1 m with intervals of 0.15 m was created to analyze the impacts. We chose these parameters because the worst RMS errors for LiDAR measurements were close to 0.15 m (3001 Inc. 2008b), and most elevations of the Florida Keys are less than 5 m. This broad array of scenarios allows a comprehensive overview of the potential SLR effects over the next 100 years, and provides the best and worst cases.

Another issue that arises in defining areas inundated by SLR is that most shorelines are continuously altered by various coastal processes (Zhang et al. 2004). Since it is difficult to predict the shoreline changes caused by these dynamic processes, it is assumed that the topography of the study area remains unchanged in the future. This assumption is reasonable for the Florida Keys because the underlying limestone bedrock is covered by only a thin (<0.2 m) layer of soil in most places (Ross et al. 1992). Therefore, the Florida Keys islands will not migrate as sea level rises, as is the case for barrier islands composed mostly of unconsolidated sand, and the inundation process will likely dominate over erosion, especially when the SLR rate is high.

Since spatial queries were involved in the calculation of inundated land, population, and property values, ArcGIS was selected to perform inundation analysis due to its rich spatial computation functions and its popularity in research communities and government agencies.

4.1 Derivation of inundation polygons

The inundated area for a rise of h in sea level is equivalent to the coastal area below the elevation h if both sea level and elevation are referenced to the same vertical datum (NAVD 88 in this study). Thus, the task of deriving inundation polygons became one of extracting the coastal land area in a DEM below a given elevation. A modified procedure from Zhang (2010) was employed in this study as follows:

1. Given a SLR scenario (elevation), h, and a DEM grid (D), a new grid, G, was produced using the *Raster Calculator* tool in ArcGIS using formula [D] $\leq h$. The value of a cell, g, in G became:

$$g = \left\{ \begin{array}{c|c} \mathbf{0} & if\ d > h \\ \mathbf{1} & if\ d \leq h \\ NoData & d = NoData \end{array} \right\}$$

   where d represents the value of a cell in D.

2. The cell values (g) of the grid G were then reclassified using the *Reclassify* tool based on the following expression:

$$gi = \left\{ \begin{array}{c|ll} \mathbf{1} & g = 1 \; or \; g = NoData & (i.e., d \leq h \; or \; d = NoData) \\ NoData & g = 0 & (i.e., d > h) \end{array} \right\}$$

   where gi is the cell value of the reclassified grid, GI. Cells in D with values d which satisfy the condition $d > h$ were assigned a value of *NoData* in GI, and cells in D inundated by a rising sea were defined with a value of 1. In order to connect inundated areas of disconnected islands, *NoData* cells in D that represented the ocean water outside the land area were also defined with a value of 1. The connectivity of a cell in D with elevation $d \leq h$ to *NoData* cells (ocean) is determined by recursively examining the four neighbors of the cell. Cells in GI with values of 1 and without a connection with cells of *NoData* values in D represented inland areas with elevations that are lower than the rising sea, but are not inundated.
3. The grid GI was converted into shape files using the *Raster to Polygon* tool with the *Simplify Polygons* option. The *Simplify Polygons* was used to remove small fluctuations or extraneous bends of an inundation polygon from its boundary while preserving its essential shape. Once the *Raster to Polygon* conversion was completed, the largest polygon which included the *NoData* area in D was selected and exported as a new polygon shapefile. This new polygon delineated coastal land area that is inundated by a SLR with a magnitude of h. The remaining polygons represent low-lying inland areas with elevations $\leq h$ that are surrounded by natural or anthropogenic barriers and are separated from the inundated areas.
4. The inundation polygons were then clipped with shoreline polygons. This step removes *NoData* areas in D from inundation polygons and produces a polygon shapefile that contains only the land areas inundated by a particular SLR scenario.
5. All procedures above were repeated for 35 SLR scenarios.

4.2 Calculation of inundated population and property

Total population impacted by a given SLR scenario was calculated as the sum of the populations within census blocks whose centroids, the geometric centers of parcels, fell within inundation polygons. The population sums of those census blocks that were completely within, and those that intersected portions of inundation polygons were also computed to estimate the lower and upper boundaries of impacted populations. The property value loss attributable to salt water inundation can be estimated using a method similar to one used to calculate impacted population by converting property parcels into centroids (Zhang 2010). Inundation of a property is assumed if the inundation polygon contains the centroid point of the parcel. Total property loss was calculated by summing all property values associated with centroid points inside the inundation polygon.

The limitation of this method is that it does not provide information on whether a property parcel is completely or partially inundated for a given SLR scenario. Therefore, to produce a more accurate analysis of the cost associated with inundated properties, the property value loss of a parcel due to inundation was estimated by multiplying its just value by the ratio of the inundated area of the parcel to the total parcel area. Note that this method can also be used to estimate the impacted population, but was not employed here because the sizes of census blocks were too large and the populations were not evenly distributed within a block. The total property loss, which is defined as a proportional property value loss (PPVL), was derived by summing property value losses for all parcels. The lower and upper boundaries of the proportional property value loss were also calculated based on the percentage of inundated area within a parcel. The lower proportional property value loss (*LPPVL*) was defined as a sum of property values of all parcels with inundated areas of which are greater than 90% of the parcel areas. The upper proportional property value loss (*UPPVL*) was defined as a sum of the property values of all parcels with inundated areas of which are greater than 10% of the parcel areas.

4.3 Projection of future sea level rise

In order to create a sound policy to cope with the impact of future SLR in the Florida Keys, it is not only necessary to project the magnitude of SLR by 2100, but also to estimate the speed of SLR, which has an immense influence on the inundation process. The relative SLR for the Florida Keys is a combination of global SLR and the movement of local land masses. The geologic evidence (Halley et al. 1997) and recent measurements from global positioning systems (Sella et al. 2007) indicate that the Florida Keys is tectonically stable. The average global SLR rate for the twentieth century was 1.8 mm/year, which is close to the rate of 2.2 mm/year at Key West tide gauge derived using the annual mean sea level record from 1913 to 1997 (Douglas 2001), thus it is reasonable to assume that the future SLR rate for the Florida Keys will be the same as the global rate. Using the acceleration pattern described by Church and White (2006), Rahmstorf (2007), and Vermeer and Rahmstorf (2009), six quadratic curves for SLR from 2000 to 2100 were constructed for scenarios of 0.3, 0.6, 0.9, 1.2, 1.5, and 1.8 m SLRs by 2100 (Fig. 2). Parameters for quadratic equations were estimated using these six scenarios, in conjunction with global mean sea levels

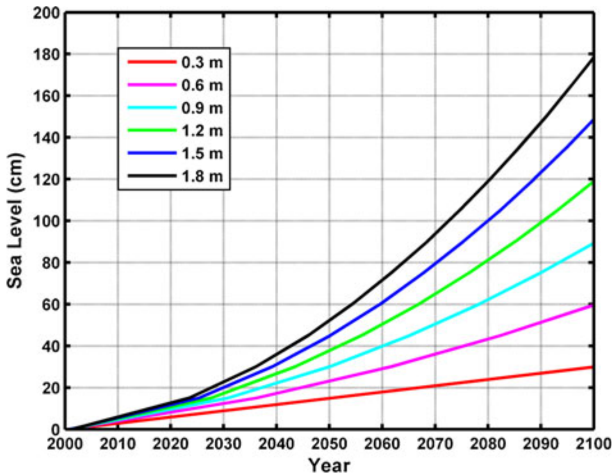

Fig. 2 Six quadratic curves for SLR scenarios of 0.3, 0.6, 0.9, 1.2, 1.5, and 1.8 m by 2100

estimated from satellite altimeter measurements from 1993 to 2007 (Zhang 2010). The baseline sea level (zero) was set to be the 2000 global mean sea level.

5 Results

5.1 Upper Florida Keys

Of the 170 km^2 of land in the Upper Keys, an area of 150 km^2 was analyzed. The total population of this area is about 34,000 and total property value is approximately \$20 billion. About 41 km^2 land with \$350 million real property and 1,200 people is already below NAVD 88, and thus influenced by salt water at least twice a day on average during semidiurnal high tides (Table 1). A comparison of the inundation polygon for current sea level (0 m SLR) with the vegetation map of the Florida Keys created based on aerial photographs by Monroe County in 1991 indicates that most of these inundated areas are coastal mangrove forests. For a SLR scenario of 0.3 m, there is a 40 km^2 increase in the amount of inundated area, 1,400 people are added to the impacted population, and an additional \$430 million in property values are lost. The inundation primarily impacts low-lying areas that surround the narrow ridge of the Upper Florida Keys (Fig. 3a). Once sea level rises to 0.6 m, which corresponds to the high end of the IPCC projection, many low-lying areas adjacent to the narrow ridge of the Upper Florida Keys will be inundated, leading to impacts on 95 km^2 of land with 6,400 people and \$2.24 billion of real property. With 1.5 m of SLR, 127 km^2 of land with 19,800 people and \$13.44 billion of real property, representing 84% of the land area, 58% of the population, and 66% of the property of the Upper Florida Keys, will be inundated, and only the narrow ridge will remain above the water (Fig. 3a).

Table 1 Inundated land area, population, and property in the Upper Florida Keys for a series of SLR scenarios from 0 to 1.8 m in increments of 0.15 m

SLR (m)	Land area (m^2)	Population	Proportional property value (\$)	90% Proportional property value (\$)	10% Proportional property value (\$)
0	40,527,060	1,235	346,933,704	11,745,599	745,546,144
0.15	67,817,437	2,162	511,960,227	47,792,781	1,250,799,131
0.3	81,810,195	2,663	775,197,841	55,553,677	2,028,167,862
0.45	89,086,614	4,369	1,291,924,034	136,153,571	3,429,508,014
0.6	94,676,469	6,403	2,240,932,440	366,963,881	5,491,634,413
0.75	100,806,406	8,708	3,799,231,729	930,896,233	8,312,559,198
0.9	107,306,014	11,026	5,935,594,438	2,088,040,051	11,528,031,811
1.05	113,563,271	13,623	8,195,918,382	3,885,881,635	13,955,323,317
1.2	118,981,347	15,933	10,317,077,612	5,960,565,709	15,701,401,829
1.35	123,507,099	18,157	12,087,852,990	7,835,377,426	17,029,066,176
1.5	127,311,781	19,802	13,444,892,368	9,403,560,637	17,823,147,139
1.65	130,415,393	20,838	14,507,431,380	10,758,965,912	18,351,374,296
1.8	132,924,224	21,768	15,369,009,734	11,863,545,742	18,616,956,059
Baseline	150,990,328	34,043	20,482,442,188	20,482,442,188	20,482,4421,88

The baseline numbers are total land area, population, and property value for the entire Upper Florida Keys

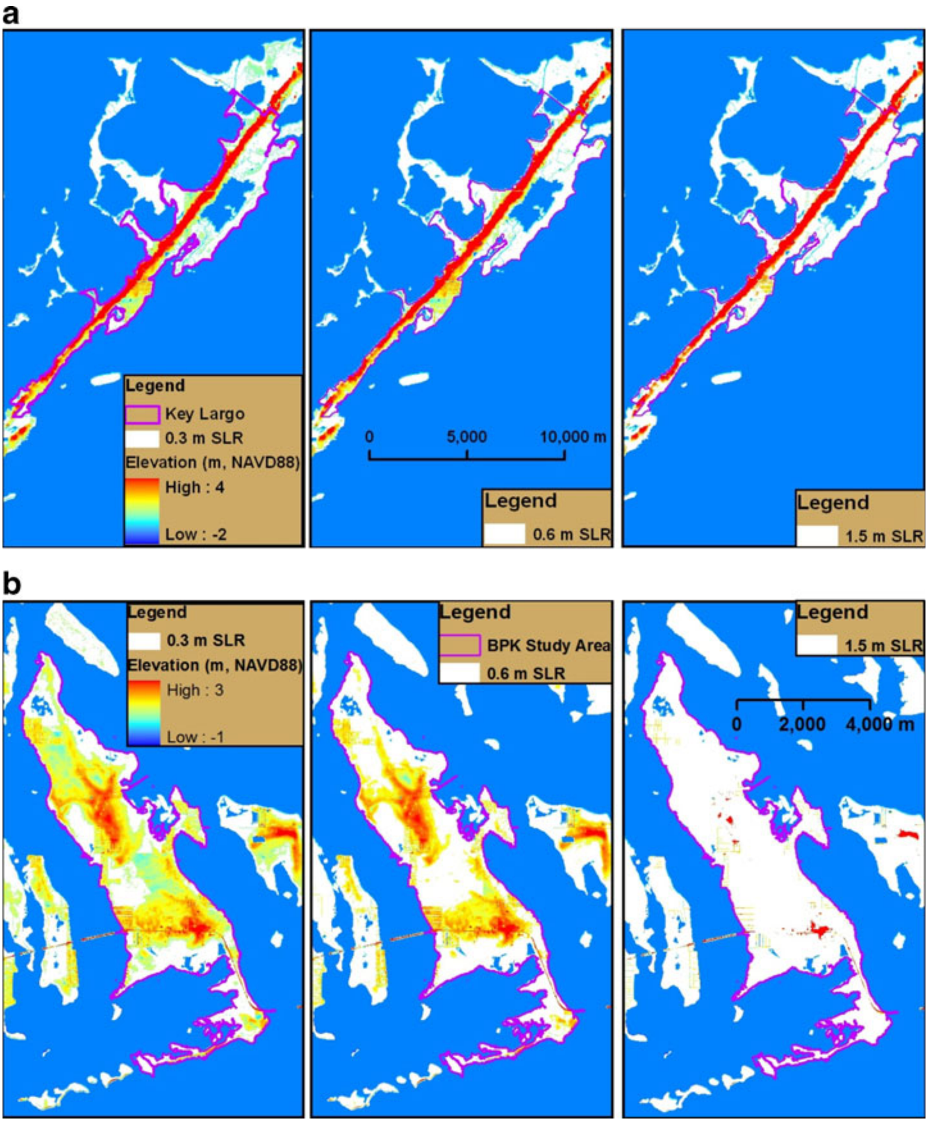

Fig. 3 **a** The inundation maps of Key Largo for 0.3, 0.6, and 1.5 m SLRs, with the inundated area depicted in *white*, and **b** the inundation maps of Big Pine for 0.3, 0.6, and 1.5 m SLRs. The linear features in (**b**) are highways (without bridges) connecting the Florida Keys

The current distribution of land area in the Upper Florida Keys presents a large peak at 0–0.3 m and a small peak at 0.75–0.9 m with a long tail at higher elevation (Fig. 4a). The hypsometric curve, which delineates the cumulative distribution of land area, shows that the inundation of land area will be fastest at the early SLR stage, although most of the lands inundated during this stage are not currently inhabited. With a constant SLR rate, the pace of land inundation will slow down during later SLR states. Compared to the land area distribution, the distribution

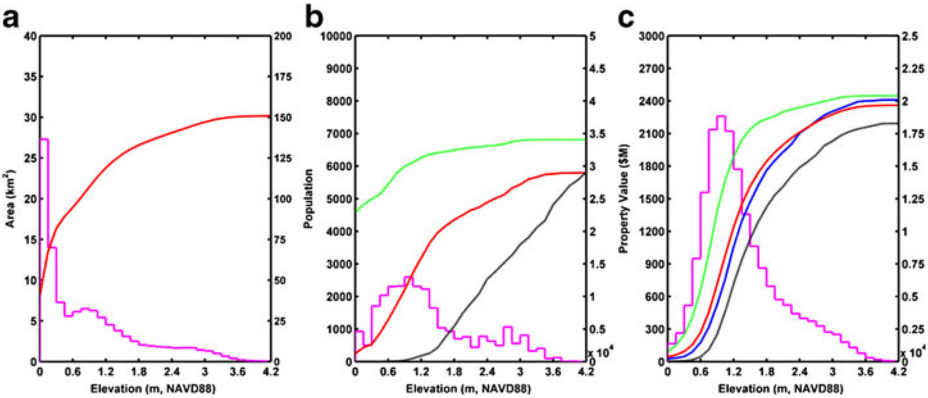

Fig. 4 **a** The histogram (*purple solid line*) of land areas over elevations and hypsometric curve (*red solid line*) for land areas for the Upper Florida Keys. The left *Y* axis is for land area, while the right *Y* axis is for cumulative land areas. **b** The histogram of population (*purple solid line*) over elevations and hypsometric curve (*red solid line*) for population for the Upper Florida Keys. The lower (*black dash line*) and upper (*green dash line*) boundaries of population values were estimated by counting populations of census blocks that are completely within and intersected with inundation polygons. The left *Y* axis is for population and the right *Y* axis is for cumulative population. **c** The histogram (*purple solid line*) of property values over elevations and hypsometric curve (*red solid line*) for property values for the Upper Florida Keys. The left *Y* axis is for property values and the right *Y* axis is for cumulative property values. The cumulative property value (i.e., PPVL) of the hypsometric curve was estimated based on the ratio of the inundated area of a parcel to the total parcel area. The *LPPVL* value (*black dash line*) was estimated using parcels with inundated areas that are greater than 90% of the parcel areas. The *UPPVL* value (*green dash line*) was estimated using parcels with inundated areas that are greater than 10% of the parcel areas. The cumulative property value loss estimated using a centroid based method (*blue solid line*) is also displayed for comparison

of population over elevations is broader and more irregular (Fig. 4b). The peak of the population distribution is at intermediate elevations, with the majority of the population in the Upper Florida Keys living on land with elevations of 0.3–1.5 m, the remainder distributed at elevations of 0–0.3 and 1.5–3.6 m. Therefore, the impact of inundation on population at the very early and late stages of SLR is slow, while the impact during the middle stage is fast. The tipping point, beyond which the impact of inundation on population occurs much faster, lies near an elevation of 0.3 m. The distribution of property values skews toward the higher elevation, but takes on a more regular, bell shape compared to land and population distributions (Fig. 4c). Most property is focused at elevations from 0.45–1.8 m with a long, gradual tail toward higher elevations. The cumulative property value curve thus exhibits an S shape, indicating a tipping point at about 0.45 m, beyond which inundation of property will accelerate, later decelerating as SLR passes 1.8 m.

The cumulative property value loss (i.e., PPLV) was calculated based on the ratio of the inundated area of a parcel to the total parcel area. However, the PPLV is only a simple index to measure the property value loss due to inundation. For example, a more than 10% decrease in property value could occur even if only 10% of a property parcel is inundated. It is difficult to estimate the exact loss due to many factors that can affect property values. Thus, the lower and upper property loss boundaries (LPPVL and UPPVL) were derived for given ratios of inundated area in percentage, e.g., 90% and 10%, to provide the range of property values impacted by the inundation (Fig. 4c). Note that the UPPVL value is much larger than the PPVL value at the early and middle stages of inundation. For example, the UPPVL values at elevations of 0.3 and 0.9 m are at least twice as large as the PPVL values.

5.2 Lower Florida Keys

The total area of the Lower Florida Keys is 190 km^2, total population is 45,000, and total property value is about \$19 billion. At current sea level (0 m), about 57 km^2 or 30% of the total area, \$220 million in property values, and 1,100 residents are impacted at least twice a day during semidiurnal high tides (Table 2). With 0.3 m of SLR, an additional 58 km^2 are inundated, including residences for 2,300 people and property value of \$430 million. The major portion of the inundated land area is mangrove and salt marsh, and the impacted population and property are within the low-lying developed areas adjacent to these wetlands (Fig. 3b). With 0.6 m of SLR, about 143 km^2 or 76% of Lower Florida Keys land will be inundated, with population of 6,900 and property value of \$2.37 billion. For example, on Big Pine Key where the National Key Deer Refuge is headquartered, much developed residential property adjacent to the relatively elevated pine forests of the Refuge will be submerged, while developed areas in the business district on the south side of the island will remain above water (Fig. 3b). The impacts of 1.5 m SLR would be catastrophic to the Lower Florida Keys. In Big Pine Key, most land areas will be under water except for several individual parcels. The inundated land area, population, and property values in the Lower Florida Keys reach 183 km^2 (or 97% of the total area), 36,400, and \$13.40 billion, respectively.

The distribution of land area across elevations in the Lower Florida Keys shows a large peak at 0–0.3 m and a decreasing trend thereafter (Fig. 5a). Compared to the Upper Florida Keys, the slope of hypsometric curve for land area remains relatively constant from 0.15 to 1.2 m and levels off thereafter. This indicates that the inundation of land area will be rapid in the early stages of SLR, but then will

Table 2 Inundated land area, population, and property in the Lower Florida Keys for a series of SLR scenarios

SLR (m)	Land area (m^2)	Population	Proportional property value (\$)	90% Proportional property value (\$)	10% Proportional property value (\$)
0	56,736,371	1,074	221,353,853	3,730,391	464,532,228
0.15	90,636,532	3,183	382,717,069	15,342,057	840,316,909
0.3	114,411,442	3,361	655,434,778	52,679,709	2,029,289,460
0.45	129,920,913	4,539	1,224,705,420	181,684,136	3,303,920,297
0.6	143,135,050	6,949	2,369,571,901	547,028,478	5,493,989,859
0.75	155,093,338	15,345	4,678,123,783	1,771,182,912	8,702,576,513
0.9	165,249,232	23,525	7,011,771,566	3,754,296,737	11,226,315,265
1.05	171,679,574	28,907	9,145,663,444	5,806,885,768	12,559,664,376
1.2	176,199,769	32,154	10,975,331,755	7,804,283,830	13,746,319,466
1.35	180,557,181	34,445	12,246,410,965	9,407,941,252	14,294,849,888
1.5	182,755,421	36,385	13,403,215,863	10,878,090,991	15,492,933,897
1.65	184,157,350	37,676	14,509,092,367	11,673,174,456	16,067,429,057
1.8	185,155,776	38,794	15,284,388,996	13,328,187,223	16,584,403,888
Baseline	188,722,803	45,486	18,789,220,197	18,789,220,197	18,789,220,197

slow even if the SLR rate remains constant. Compared to the land area distribution, the population distribution peaks at 0.6–1.2 m elevation, with a long tail spanning from 1.2 to 2.7 m (Fig. 5b). Therefore, the impact of inundation on population at the early stage is small, and there is a tipping point at 0.45 m, beyond which the impacted population increases rapidly. The increase of impacted population slows down once SLR exceeds 1.2 m. The distribution of property exhibits a broader bell shape, but is also skewed toward higher elevations in comparison to population distribution (Fig. 5c). Most property values are located at elevations from 0.45 to 2 m with a long, gradual tail toward higher elevations. Cumulative property values exhibit an S shape, indicating that there is a tipping point at 0.45 m beyond which the inundation of property will speed up. The inundation of the property will slow down as SLR reaches beyond 2 m.

5.3 Comparison of the Upper and Lower Florida Keys

The major difference in inundation dynamics in the Lower and Upper Florida Keys is that the land areas and population of the Upper Florida Keys are spread over a wider range of elevations, whereas the land areas and population of the Lower Florida Keys are concentrated at lower elevations close to current sea level. The inundation patterns of property for the Upper and Lower Florida Keys show a similar pattern except that the peak of the Lower Florida Keys occurs at a lower elevation.

Comparisons of property losses derived using the centroid point and proportional methods for Upper and Lower Florida Keys (Figs. 4 and 5) indicate that the shapes of the two hypsometric curves are similar. The property loss value from the proportional method is higher than that from the centroid based method at early and middle inundation stages, while the relationship reverses at the late inundation stage. The average difference in property loss values for given SLR scenarios from the proportional and centroid based methods in the Upper Florida Keys is about 11%, while the difference in Lower Florida Key is about 8%.

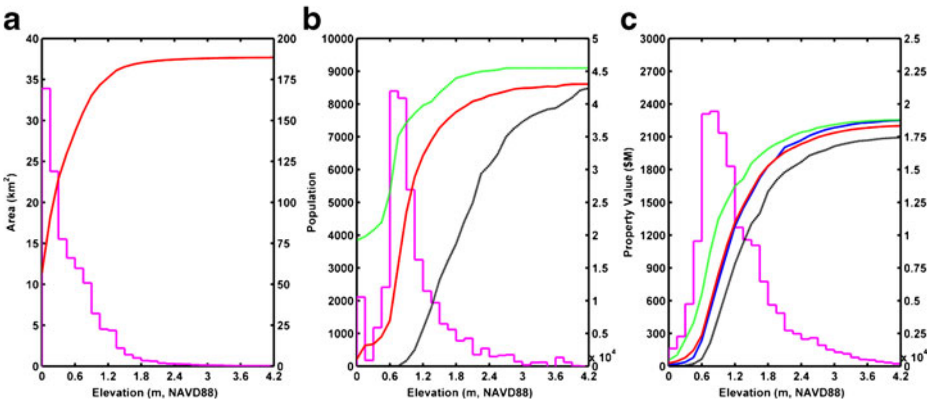

Fig. 5 The histograms and hypsometric curves for land area (**a**), population (**b**), and property values (**c**) in the Lower Florida Keys

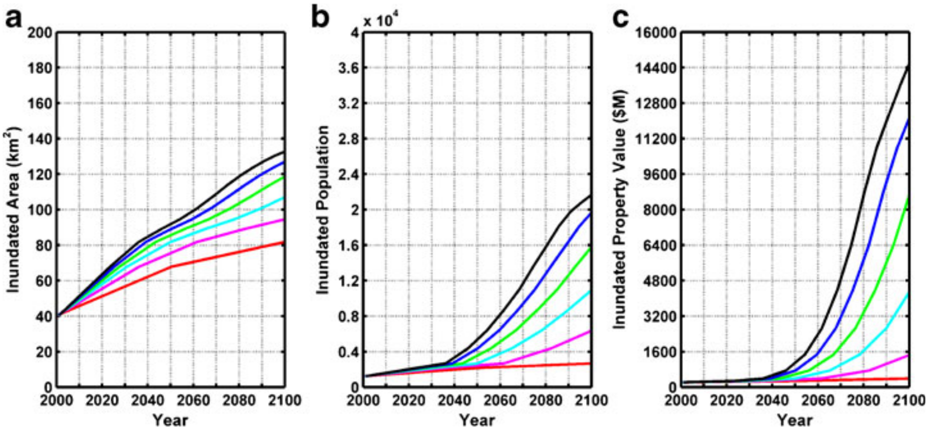

Fig. 6 Land area (**a**), population (**b**), and property value (**c**) hypsometric curves over time for scenarios of 0.3 m (*red*), 0.6 m (*purple*), 0.9 m (*light blue*), 1.2 m (*green*), 1.5 m (*blue*), and 1.8 m (*black*) SLRs by 2100 in the Upper Florida Keys

5.4 Effects of accelerated SLR on inundation dynamics

In order to investigate the effects of accelerated SLR on inundation dynamics, the inundated land, population, and property values in the Upper and Lower Florida Keys were derived for six scenarios of SLR from 0.3 to 1.8 m, at intervals of 0.3 m (Figs. 6 and 7), all assuming that SLR will follow a quadratic form. For the Upper Florida Keys, the inundated areas increase considerably as the magnitude of SLR by 2100 increases. The differences in inundation curves for 0.3, 0.6, and 0.9 m SLRs by 2100 are larger than differences in more extreme scenarios, indicating that the inundation process of the Upper Florida Keys is sensitive to small changes of SLR magnitude at the lower end.

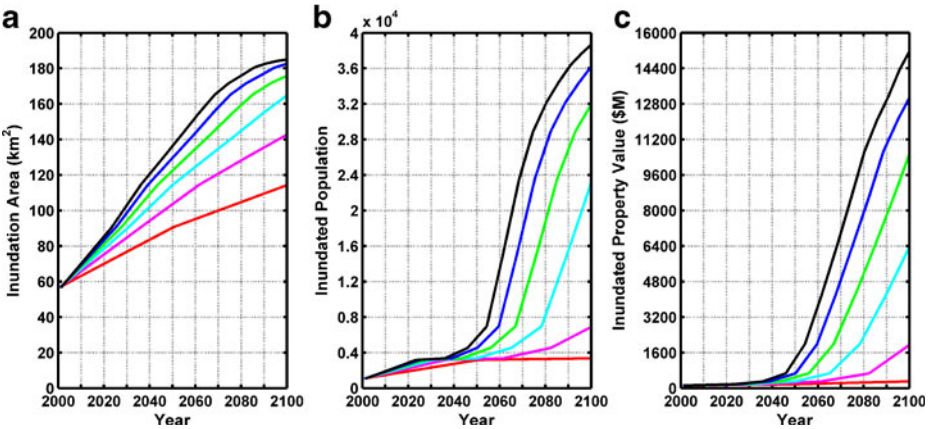

Fig. 7 Land area (**a**), population (**b**), and property value (**c**) hypsometric curves over time for scenarios of 0.3 m (*red*), 0.6 m (*purple*), 0.9 m (*light blue*), 1.2 m (*green*), 1.5 m (*blue*), and 1.8 m (*black*) SLRs by 2100 in the Lower Florida Keys

Before 2035, the increases in impacted population in the Upper Florida Keys are small for all six SLR scenarios (Fig. 6b). The tipping points of inundation dynamics occur between 2035 and 2060 for scenarios of SLR from 1.8 to 0.6 m, respectively. For these scenarios, inundation proceeds with gathering pace after the tipping point is reached as impacted population increases from 5% to 30% of the total population within 20–30 years. The increase of impacted population is much slower for the scenario of 0.3 m SLR without acceleration in comparison with other scenarios. Inundated property values display patterns similar to the population curves, with tipping points occurring between 2045 and 2080, and more gradual changes prior to and more drastic changes after the tipping points.

For all six SLR scenarios, more land area will be inundated in the Lower Florida Keys compared to the Upper Florida Keys. The tipping points for impacted population curves will be reached between 2045 and 2080 for 0.6–1.8 m SLR scenarios (Fig. 7). Before the tipping points are reached, the inundation impact on population is minimal. The inundation dynamics for property values for six scenarios of SLRs is similar to those for population with tipping points also occurring between 2045 and 2080. As in the case of the Upper Florida Keys, the differences in inundation curves for 0.3, 0.6, and 0.9 m SLRs by 2100 are larger than differences in other scenarios.

6 Discussion

The large uncertainty in projection of SLR by 2100, ranging from 0.18 to 3 m (Bamber et al. 2009; IPCC 2007; Pfeffer et al. 2008; Rahmstorf 2007), creates difficulties for the implementation of acceptable policy to cope with SLR impacts. A 0.18 m SLR by 2100 which is defined by the IPCC as the best case scenario, would cause limited impacts on the Florida Keys in terms of land inundation, population displacement, and property value losses. An adaptive response policy modified from the current policy for development would be sufficient to handle this scenario. In contrast, a 0.6 m SLR by 2100, which is close to the worst case scenario defined by the IPCC, would have great impacts on the Florida Keys, and a large modification to the current policy would be needed. Civil engineering projects, such as dikes or levees to protect areas from saltwater inundation will have limited effectiveness in this case because of the highly porous nature of the limestone substrate, in addition to their high cost. The effects of a 1.5 m sea level rise on the Florida Keys would be calamitous, and the cost of defending against such impacts will be prohibitive, with 91% of the area, 71% of the population, and 68% of the property inundated. This magnitude is comparable to the Rahmstorf (2007) and Vermeer and Rahmstorf's (2009) worst case scenario, a 1.4–1.9 m SLR by 2100 above the 1990 level. Handling such a severe inundation will need the Federal, State, Monroe County, and municipal governments and residents to work together to create a plan for relocating the majority of the population to higher elevation areas. In summary, it is difficult to form a single option for coping with future SLR impacts on the Florida Keys, given the large uncertainty about the magnitude and rate of SLR within a time frame of 100 years.

Another difficulty in formation of policy for SLR impacts is lack of direct and dramatic evidence prior to tipping points, which vary island-by-island because of the differences in topography and settlement patterns. For example, analysis of inundation dynamics of Key West shows that the hypsometric curve for land area is different from that in Fig. 5a, for the Lower Florida Keys as a whole. There is a tipping point at the elevation of 0.3 m which will be reached in 2050 for a 0.6 m SLR by 2100. The time to reach tipping points for inundated population and property values is after 2060. When the SLR magnitude is less than the tipping point value, the impacts on Key West are small. Obviously, response times to impacts will be dramatically reduced if society waits for the occurrence of direct evidence after the tipping point is reached. In the case of Big Pine Key, the period of slow change at the base of the hypsometric curve for land area is missing, as it is for the Lower Florida Keys as a whole (Fig. 5a), thus, inundation of land area as sea level rises will move forward directly at a fast pace. The interaction of accelerated SLR with inundation dynamics further complicates the lead time before reaching tipping points. The coincidence of relatively small SLR rates with the fast rates of land area change at early stages on Big Pine Key will cause inundation to be slow, delaying the arrival of the tipping point. On the other hand, the coincidence of large SLR rates with fast rates of land area change at the middle stage makes the inundation process even faster after the tipping points.

One way to handle the large uncertainty in SLR impacts is to develop a series of response measures and policies associated with various SLR scenarios based on tipping points and non-linear inundation dynamics. The threshold values for local adaptive responses to a small magnitude of SLR and relocating population, economic foci, and endangered species (Maschinski et al. this volume) in response to a large magnitude of SLR need to be carefully studied in advance. Comprehensive planning and policies for both natural and built environments based on a series of threshold values of SLR specific to the Florida Keys need to be established.

At the same time, SLR and its impacts on the Florida Keys should be monitored closely to activate the corresponding policy when a threshold value is reached. Before populated areas are inundated permanently, SLR will exacerbate existing challenges associated with storm surge flooding, salt water intrusion into freshwater aquifers, and wastewater management. A comprehensive observation network should be established to monitor these processes, which greatly affect peoples' day-to-day lives. The locations most sensitive to SLR are the low-lying areas close to the shoreline, which are often occupied by native vegetation. In contrast to the population and real property that will be impacted little at the early SLR stage, these vegetation communities will respond to SLR quickly, thus change in vegetation communities is a good index for measuring and monitoring SLR impacts. Additionally, the vulnerability of each island to SLR is different because of variation in elevation. For example, Big Pine Key is more vulnerable to impacts at the early SLR stage than Key West in terms of inundation processes of land areas, thus Big Pine Key is the better location for monitoring immediate SLR impacts.

7 Conclusions

To accommodate the large uncertainty in SLR projections, it is necessary to estimate inundation losses for the Florida Keys from a large array of scenarios ranging from 0.15 to 5.1 m SLR. Results from this study showed that a 0.6 m sea level rise at the end of this century would inundate a large area, about 70% of the total area of the Florida Keys. However, this level of sea level rise would not impact an equivalent amount of population (17%) or real property (12%) in the Florida Keys. A 1.5 m sea level rise would cause catastrophic inundation to the Florida Keys, leading to direct inundation of 91% of the total island area, displacement of 71% of the total population, and a loss of 68% of the property value.If sea level rises 1.8 m, there would be very little habitable area remaining in the Florida Keys. Overall, the Lower Florida Keys are more vulnerable to SLR impacts than the Upper Florida Keys due to lower elevation.

The analysis of inundation processes based on LiDAR DEMs indicates that the process is non-linear. It is important for policy-makers to consider these non-linear inundation dynamics when formulating policy. There is a tipping point around 0.4 m elevation in many cases, beyond which the inundation impact on population and property accelerates rapidly. The potential acceleration of sea level rise will amplify the non-linear inundation processes, causing tipping points to be reached sooner. Comprehensive planning and policies coping with SLR impacts on both natural and built environments based on a series of threshold values of SLR for the Florida Keys need to be established in advance. SLR and its impacts on the Florida Keys should be monitored closely to activate the corresponding policy when a threshold value is reached.

Acknowledgements We would like to thank three anonymous reviewers for providing valuable comments and suggestions. Dr. Keqi Zhang was partially supported by the grants from the National Oceanic and Atmospheric Administration and the Florida Division of Emergency Management.

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