Ocean & Coastal Management 126 (2016) 1–8

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Increasing flooding hazard in coastal communities due to rising sea level: Case study of Miami Beach, Florida

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A R T I C L E I N F O

Article history:
Received 11 December 2015
Received in revised form
8 March 2016
Accepted 11 March 2016
Available online 1 April 2016

Keywords:
Sea level rise
Flooding hazard
Tide gauge record
EEMD
Southeast Florida

A B S T R A C T

Sea level rise (SLR) imposes an increasing flooding hazard on low-lying coastal communities due to higher exposure to high-tide conditions and storm surge. Additional coastal flooding hazard arises due to reduced effectiveness of gravity-based drainage systems to drain rainwater during heavy rain events. Over the past decade, several coastal communities along the US Atlantic coast have experienced an increasing rate of flooding events. In this study, we focus on the increasing flooding hazard in Miami Beach, Florida, which has caused severe property damage and significant disruptions to daily life. We evaluate the flooding frequency and its causes by analyzing tide and rain gauge records, media reports, insurance claims, and photo records from Miami Beach acquired during 1998–2013. Our analysis indicates that significant changes in flooding frequency occurred after 2006, in which rain-induced events increased by 33% and tide-induced events increased by more than 400%. We also analyzed tide gauge records from Southeast Florida and detected a decadal-scale accelerating rates of SLR. The average pre-2006 rate is 3 ± 2 mm/yr, similar to the global long-term rate of SLR, whereas after 2006 the average rate of SLR in Southeast Florida rose to 9 ± 4 mm/yr. Our results suggest that engineering solutions to SLR should rely on regional SLR rate projections and not only on the commonly used global SLR projections.

1. Introduction

Flooding hazard due to sea level rise (SLR) is a global problem. It affects about 10% of the Earth's population, roughly 700 million people, who live in low-lying coastal areas (McGranahan et al., 2007). In the US alone, 3.7 million people are living on land within 1 m of high tide and are in high risk of coastal flooding (Strauss et al., 2012). Despite the global SLR problem, coastal flooding hazard is a local problem, due to local elevation and elevation change (subsidence) of coastal communities, regional variations in the rate of SLR (Nicholls and Cazenave, 2010), as well as possible exposure to storm surge induced by extreme weather events (Aerts et al., 2014).

Most assessments of coastal flooding hazard rely on spatial information of coastal communities, including elevation, infrastructure, and population, as well as on expected value of SLR (e.g., Kleinosky et al., 2007; Kirshen et al., 2008, e.g., Strauss et al., 2012). Such assessments provide useful, long-term forecast of the expected hazard due to a 'static' increase of sea level. Some studies also include tide gauge records for estimating flooding hazard due to storm surge (e.g., Nicholls, 2004; Tebaldi et al., 2012) and changes in flooding frequency (e.g., Cooper et al., 2008). However to our knowledge, none of the coastal hazard studies accounts for rain-induced flooding hazard, which arise from reduced effectiveness of gravity-based drainage systems as sea level rises.

The US Atlantic coast is one of the most vulnerable areas to SLR due to its low elevation, large population concentrations, and economic importance. Further vulnerability arises from accelerating rates of SLR, which began in the early 2000's possibly due to the slowing down of the Atlantic Meridional Overturning Circulation (AMOC) (Yin et al., 2009; Sallenger et al., 2012; Ezer et al., 2013). The increasing sea level also resulted in a significant increase of accumulated flooding time along the US Atlantic coast in the past twenty years (Ezer and Atkinson, 2014). Some coastal communities, as Norfolk, Virginia, have already experienced an increase in flooding frequency over the past decade (Kleinosky et al., 2007; Ezer et al., 2013).

The low elevation and highly populated area of southeast Florida is considered highly vulnerable to SLR. Recently, the city of

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http://dx.doi.org/10.1016/j.ocecoaman.2016.03.002
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Miami has been identified as the economically most vulnerable city to SLR in the world (US National climate assessment (Melillo et al., 2014)). Heretofore, the effect of SLR has felt mostly in low-lying coastal communities, such as the City of Miami Beach and some sections of Fort Lauderdale. In this study we assess flooding hazard in Miami Beach, based on documented flooding events that occurred during the time period 1998–2013. Our analysis accounts for three flooding types (rain, tide and storm surge) and reveals a significant increase in tidal flooding frequency since 2006, but also in rain-induced flooding events. Our study also includes a time series analysis of local tide gauge records and a correlation study with high-resolution global climate model. These additional analyses indicate that the post-2006 increased flooding frequency in Miami Beach correlates well with rapid acceleration of SLR in southeast Florida, which may have induced by weakening of the entire Gulf Stream system, as proposed previously (e.g., Ezer et al., 2013).

2. Study area

The city of Miami Beach is built on a barrier island off the coast of southeast Florida (Fig. 1). Throughout its century-long history, the city was subjected to flooding, mainly caused by heavy rain or storm surge. In recent years, rain-induced events have become more frequent and tide-induced (‘sunny sky’) flooding events have increased typically in September-October, around or after the fall equinox. The tide-induced floods have affected mostly low-lying neighborhoods in the western part of the city, which were built on reclaimed mangrove wetlands. Both the rain- and tide-induced events have caused severe property damage and significant disruptions to daily life.

3. Multi-disciplinary datasets

In order to characterize the recent flooding history of Miami Beach, we examine temporal information from five independent datasets: tide gauge, rain gauge, media reports, insurance claims, and photo documentation. The tide gauge record is of the National Oceanographic and Atmospheric Administration's (NOAA) operated Virginia Key station, which is located 5 km southwest of Miami Beach (Fig. 1). The rain record is of the NOAA's station USW00092811 located within Miami Beach. A two-year data gap (2001–2002) in the NOAA station record was filled by data from the nearby Miami-2 station, operated by the South Florida Water Management District. Media reports were collected using Google search and other search engines. The insurance claim record is the Miami Beach subset of flooding insurance claims, which are mandatorily reported to Federal Emergency Management Agency (FEMA) by insurance companies. The locations of the reported claims are shown in Fig. 1b. The last dataset, photo documentation of flooding events, was acquired by the city of Miami Beach since 2009.

The Virginia Key tide gauge station started operation in 1994 and has delivered sea level height record with a 6-min sampling rate, which provides a full and detailed description of the twice-daily tide cycle (green line in Fig. S1). However, some of the station's early data is available only as in monthly average format. In this study we analyze a time series consisting of the highest daily tide record, which is reported by NOAA as HH. The data are presented in the North America Vertical Datum 88 (NAVD) datum. More information on the tide record is provided in the Supporting Information (Section S1).

We present the HH tide gauge and rain data in yearly time series, which allows comparison of seasonal variations and flooding occurrences from one year to another (Fig. 2, Section S2). Flooding events are tagged based on three record types: media reports, insurance claims and Miami Beach photo documentation. Each record is independent and spans over a different time period. Media reports were collected using Google search and other search engines for ‘Miami Beach flooding’; their record covers the entire time span of our study 1998–2013. The insurance claim data are a subset of flood insurance claims that insurance companies are required to report the FEMA upon triggering of property (not cars) flood claims. FEMA shares this record with various agencies at county, state, and federal levels. We obtained our record for the years 1998–2012 from the Miami-Dade County's Public Works and Waste Management office, which provided a subset of the dataset containing locations and times of claims. Due to the Privacy Protection Act, other claim details were not provided to us. The third tagging record is photo archive collected by the city of Miami Beach. These three datasets allow us to tag flooding events and relate them to high tide and/or heavy rain conditions.

4. Cross-reference analysis

The annual time series presented in Fig. 2 show the cross-reference analyses of four representative years. In 2003 no flooding event was recorded. The HH tide record did not exceed 40 cm and no major rain event occurred. In 2005, four flooding events were tagged by insurance claims. The first two events (6/5 and 6/20) occurred during rain events. The other two events occurred during the passage of hurricane Katrina (8/25) and Wilma (10/24) and were caused by storm surge. In 2009 four flooding events were tagged by insurance claims (6/5), media reports (6/5 and 9/17), and Miami Beach documentation (6/24 and 11/18). The first event was caused by heavy rain (>200 mm) that resulted in massive flooding and a high number of insurance claims (53). The second flooding event (6/24) occurred during heavy rain and high tide conditions. The last two events (9/17 and 11/18) occurred during high tide conditions (>40 cm) with no rain (‘sunny-sky flooding’). In 2013 we documented six flood events, two caused by heavy rain (4/14 and 7/17), and the other four by high tide conditions. Three of these events occurred in the fall-winter, around or after the fall equinox (9/17, 10/17, and 12/3), when sea level in the Miami area is highest. Interestingly, a fourth tide event was documents in the spring (3/13), just before the spring equinox, which is the second peak of sea level in the study area. The complete cross-reference analysis, including the dates and sources of the tagged flooding events, is presented in the Supporting Information (Section S4).

The cross-reference analysis allows us to evaluate the annual number and the causes of the Miami Beach flooding events (rain, tide, storm, and unexplained). A summary of all annual events according to types is presented in Table 1 and displayed visually in Fig. 3. We first summarized all available records, which show a significant increase in flooding occurrences since 2007 (Fig. 3a). By dividing the flooding record into two 8-year long periods (1998–2005 and 2006–2013), it is easy to notice a significant increase in both rain- and tide-induced events. During the first period, we counted 9 rain and 2 tide events, whereas in the second period we counted 15 rain and 15 tide events, an increase of 66% in the number of rain events and 750% of tide events. The record also shows a decrease in the number of storm events from three events in the first period (1998–2005) to zero in the later period. As storm events occur during anomalously high sea level conditions caused by storm surge, they are not indicative of regular sea level conditions and, hence, were omitted from our analysis.

Because the Miami Beach documentation record covers only the last five years of the study period, events documented by this record might bias the statistics. Thus, we repeated the same analysis using only the media and insurance records (Fig. 3b). When