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Do the Adaptations of Venice and Miami to Sea Level Rise Offer Lessons for Other Vulnerable Coastal Cities?

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Abstract
Both Venice and Miami are high-density coastal cities that are extremely vulnerable to rising sea levels and climate change. Aside from their sea-level location, they are both characterized by large populations, valuable infrastructure and real estate, and economic dependence on tourism, as well as the availability of advanced scientific data and technological expertize. Yet their responses have been quite different. We examine the biophysical environments of the two cities, as well as their socio-economic features, administrative arrangements vulnerabilities, and responses to sea level rise and flooding. Our study uses a qualitative approach to illustrate how adaptation policies have emerged in these two coastal cities. Based on this information, we critically compare the different adaptive responses of Venice and Miami and suggest what each city may learn from the other, as well as offer lessons for other vulnerable coastal cities. In the two cases presented here it would seem that adaptation to SLR has not yet led to a reformulation of the problem or a structural transformation of the relevant institutions. Decision-makers must address the complex issue of rising seas with a combination of scientific knowledge, socio-economic expertize, and good governance. In this regard, the "hi-tech" approach of Venice has generated problems of its own (as did the flood control projects in South Florida over half a century ago), while the increasing public mobilization in Miami appears more promising. The importance of continued long-term adaptation measures is essential in both cities.

Keywords Climate change · Vulnerability · Coastal cities · Barrier islands · Adaptive management · Resilience

Introduction

Climate change is expected to have severe impacts on coastal areas in particular due to sea level rise (SLR). This can increase flood risk, coastal erosion, and loss of low-lying systems (e.g., deltas, coastal lagoons, barrier islands) due to permanent inundation (Kirwan and Megonigal 2013; Passeri et al. 2015). The most recent mean global SLR projections by the Intergovernmental Panel on Climate Change (IPCC 2014) range from 0.32 to 0.63 m by 2081–2100 for the RCP4.5 and RCP6.0 emissions scenarios. Other IPCC emission scenarios increase the likely envelope to 0.26–0.82 m (IPCC 2014). Independent estimates of future sea level suggest that global SLR could approach or possibly exceed 1 m by 2100 (Pfeffer et al. 2008; Vermeer and Rahmstorf 2009; Nicholls 2011; Kopp et al. 2016; De Conto and Pollard 2016).

The impact of SLR is not felt equally around the globe; some locations experience greater rise than others because of subsidence of local terrain, local hydrological factors, and oceanic currents, among other regional factors such as glacio-isostatic adjustment (Thead 2016). Several studies examined the vulnerabilities of global coastal cities to climate hazards (De Sherbinin et al. 2007). Adaptation measures are difficult to implement because they require long time horizons, whereas politicians typically operate on short-term horizons. Incentives need to be intelligently designed so that politicians, officials, and the private sector find it in their interests to build less risk-prone cities.

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Varrani and Nones (2017) compared Jakarta and Venice and suggested a mixed approach of adaptable planning instruments that consider future uncertainties. Moreover, they suggest that policymakers and system designers should use approaches developed to create adaptive plans, which are flexible and can respond when new information appears or when conditions in the environment change. Fu et al. (2017) compared adaptive planning strategies for SLR of US coastal cities. They found that the analyzed localities always lack the necessary information and incentives to plan for emerging issues, such as SLR. The contemporary plans are limited in their planning toolkit, and the existing plans generally led to weak implementation of the adaptation strategies, as well as tenuous establishment of linkages to local planning endeavors. To examine these issues further, we review and critically compare the regions surrounding Venice, Italy, and Miami, Florida, USA. Both regions are experiencing recent acceleration of the SLR and have transportation infrastructure, storm and wastewater systems, drinking water supplies, energy grids, real estate, as well as human and ecosystem, and populations that are highly vulnerable and at risk. Both have adopted many of the same interventions although the contexts vary. At the same time, we note some significant differences in adaptive strategies due to the physical settings, administrative, political, and social realities. Nevertheless, both cities' adaptation measures may be effective and could have global applicability. We explore the lessons that Venice and Miami can offer each other, as well as to other coastal cities to counter the effects of rising seas.

Study cities

Our work analyzes the physical and socio-economic settings of the two cities, as well as their administrative environments. We examine and compare the management strategies implemented to counteract the effects of the SLR in both cities.

Venice

Founded in the 5th Century, Venice became a major medieval maritime power in the Mediterranean. The Venice Lagoon houses over 100 small islands, the largest of which have been urbanized over the centuries (Fig. 1a). The Venice Lagoon appears to be one of the most vulnerable zones to SLR in Italy, with several square kilometers of land at or below sea level. In particular, most of the wetlands and beaches of the ~300 km of North Adriatic coast present medium-to-high vulnerability to inundation and flooding (Lambeck et al. 2011; Torresan et al. 2012).

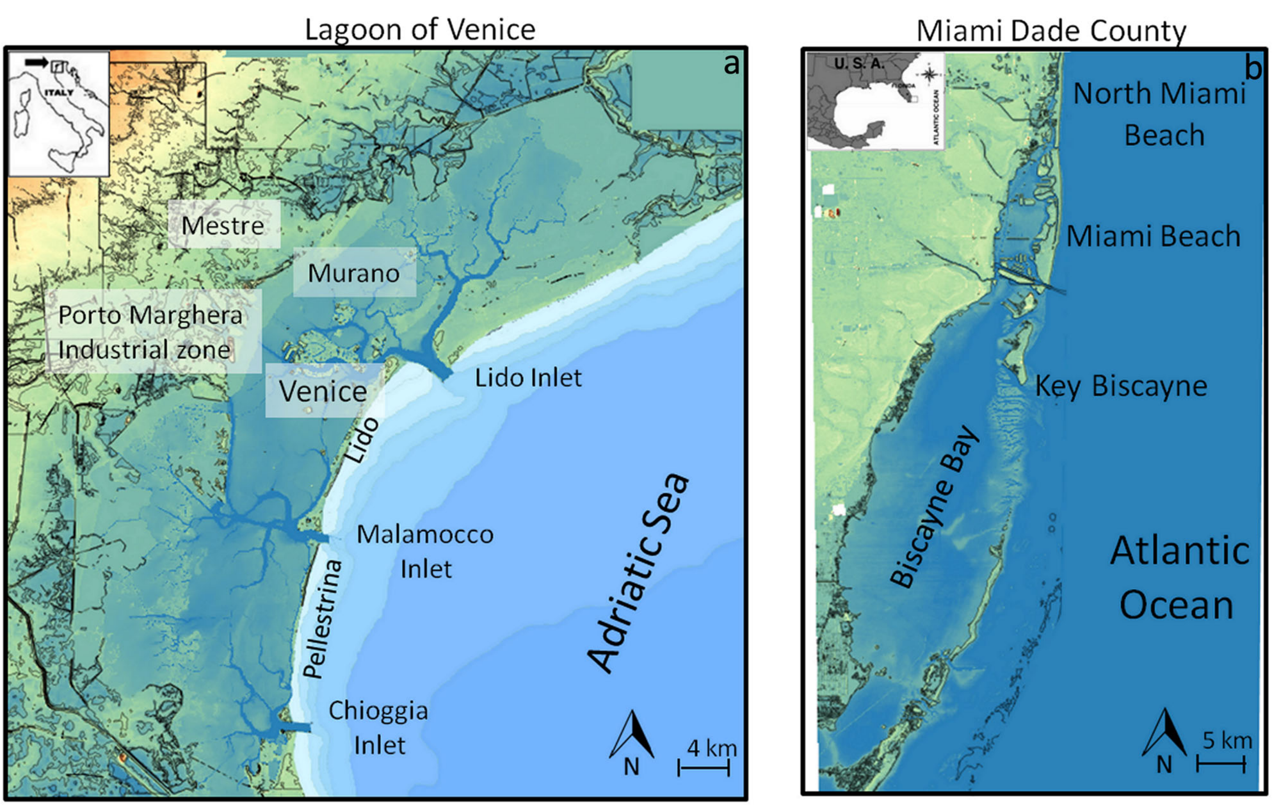

Fig. 1 Coastal areas of Venice Lagoon **a** and Miami-Dade County **b**

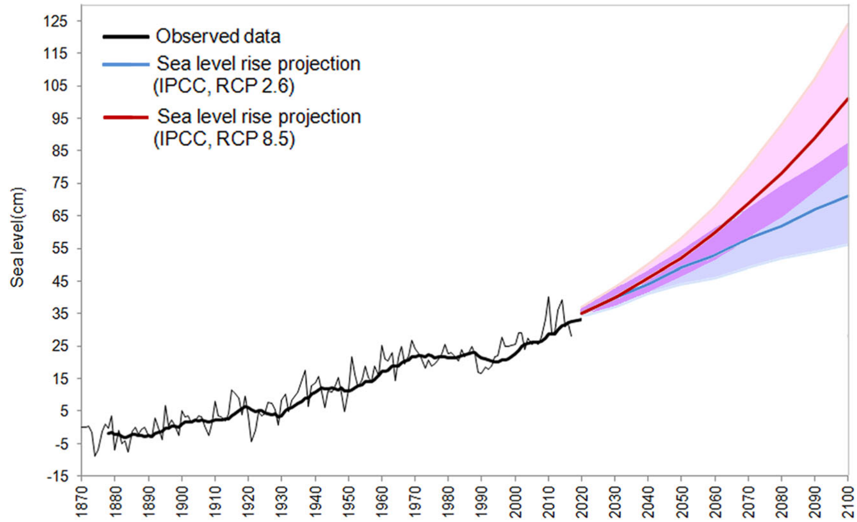

Fig. 2 Graphic of historic and future sea-level trends in the Venice area. The assessed likely range is shown as a shaded band. Observed data from: Comune di Venezia, Centro Previsioni e Segnalazioni Maree. Projections data from: IPCC 2014

The average water level in Venice Lagoon is ~25 cm above the 1897 standard (Carbognin et al. 2009; Zaggia et al. 2017). The variability and specific tide guage data were extensively discussed also by Camuffo et al. (2017); land subsidence (human-induced subsidence, eustasy, and morphological changes in the Lagoon) and SLR are jointly responsible for higher water levels that have caused increasingly frequent flooding (Fig. 2). The most dramatic flooding event was the disastrous event of 4 November 1966 when water levels were 1.94 m higher than the 1897 standard (Trincardi et al. 2016). Since then high water events (*acqua alta*) are even more frequent, and currently around 10% of the city is flooded 15–20 times a year. In October 2018, the combination of strong winds and exceptionally high tides caused the worst flooding in decades (1.56 m above the standard).

For more than a millenium, Venice has co-existed with the sea and created and adopted numerous interventions to adapt to flooding and the aqueous milieu[1]. Venice is one of the first cities to address rising seas and adapt to this reality. Adaptation measures changed significantly during the past 20 years as the region and Italian State opted for a high tech experimental solution of mobile flood gates at the three entrances to the Venice Lagoon from the Adriatic (MoSE).

Miami

Miami was founded merely just over 100 years ago, and today over 2.6 million people reside in the metropolitan area (Miami-Dade County) (Fig. 1b). While Miami lacks the architectural masterpieces of Venice, it also draws millions of tourists and in a sense is a "maritime power" due to its port that labels itself the "Cruise Capital of the World". Also similar to Venice, Miami is extremely vulnerable to flooding and rising seas. Miami is one of four major US coastal municipalities out of 180 that exceed the national average for the percentage land area less than 1 m elevation. About 90% of Miami is below 6 m above sea level (Weiss et al. 2011).

Sea levels in South Florida have increased ~20 cm since the 1930s (Zervas 2009). As global mean sea level continues to climb in the future, extreme events such as storm surges from hurricanes and tropical storms, as well as extreme ("king tides") tides will be superimposed on a higher base level (Sweet et al. 2017) (Fig. 3). Several streets on the west side of the City of Miami Beach flood at least six times per year during "king tides" around the fall equinox. Furthermore, in recent times sea level in Miami area is rising much faster than other places in US (Valle-Levinson et al. 2017) and also faster than the global average rates (Church et al. 2013). The situation is even more complicated, due to uncertain patterns in Atlantic Meridional Overturning Circulation, changes in ocean circulation, and changes in gravitational attraction due to ice melt, as well as variable rates of SLR due to solid Earth's response to the last deglaciation (Stammer 2008; Milne et al. 2009; Hay et al. 2015). Evaluations of cities most vulnerable to losses from flooding rank Miami in sixth place of global cities and first place of U.S. cities (Ghose 2013). Furthermore, Miami has been recently identified as the economically most vulnerable city to SLR in the world (US National Climate Assessment (Melillo et al. 2014)). Using U.S. Army Corps of Engineers estimates for SLR, the Union of Concerned Scientists predicts that Miami Beach

[1] In 2011, Venice was chosen as a role model city for cultural heritage protection by the UN Office for Disaster Risk Reduction (UNISDR 2009). As one media commentator noted following the 2012 Super Storm Sandy that caused damages of about $75 billion, "The perils of Venice are real; this treasury of civilization does need protecting. But Venice has some lessons to teach about how to live with the sea."

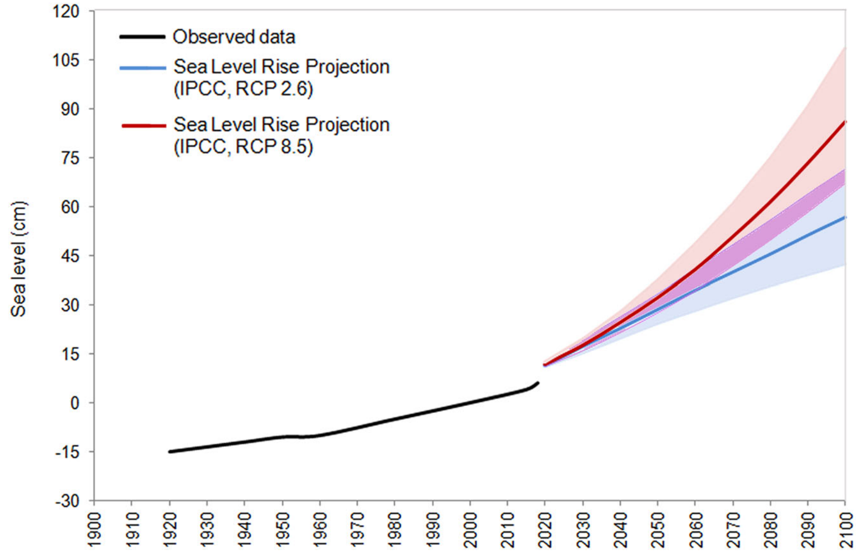

Fig. 3 Graphic of historic and future sea-level trends in Miami Dade County. The assessed likely range is shown as a shaded band. Observed data from: https://tamino.wordpress.com/2018/04/29/sea-level-on-the-u-s-east-coast/. Projections data from: http://sealevel.climatecentral.org/ssrf/florida

streets will flood about 380 times per year by 2045 (UCS 2017). Zhang (2011) used LIDAR data in a case study of South Florida under 0.5 m and 1.5 m SLR scenarios by 2100. They suggest that inundation is nonlinear and gradual before reaching a threshold when it accelerates due to the region's topography. Miami-Dade County (MDC) is the most vulnerable jurisdiction in their study of South Florida. The smaller SLR value would inundate wetland areas of southeast MDC while the higher SLR value would lead to catastrophic inundation of MDC making it impossible to support today's population on higher ground. Miami has only recently become aware of its vulnerabilities but is actively addressing the threats as we will describe below.

Methodology

This study reviews literature, observations and discussions with government officials, representatives of environmental and civic groups, and natural and social scientists.[2] Moreover, the authors are researchers in both cities who are closely involved in SLR adaptation issues.

The two countries represent distinct cases in relation to the extent of their engagement with planned adaptation. Venice was one of the first European cities to adopt a high-tech adaptation project (Suman et al. 2005) and an associated national and regional implementation plan, complemented by other adaptation actions within various municipalities. To date, Miami has adopted strategies for beach management and flood response (Ariza et al. 2014). Within each country, we examine different administrative units to represent areas where interest and action in adaptation were high.

Physical and Human Environments

Venice

Physical setting

The Venice Lagoon forms part of an important barrier—island system; it is the largest shallow coastal lagoon in the Mediterranean region (Molinaroli et al. 2009a). This complex system is affected by multiple natural and anthropogenic forcing factors, and characterized by high heterogeneity in physical, biogeochemical, and biological conditions of mutually interacting habitats (Table 1). A series of man-made changes to Venice Lagoon between the 15th and 20th Centuries (river diversions, construction of jetties at the inlets, and deeper dredging of navigation channels) have had a significant impact on the lagoonal morphology (Molinaroli et al. 2009b; Sarretta et al. 2010). By 1968 more than 50% of the natural lagoon had been reclaimed for business-related purposes, (e.g., industrial complex of Porto Marghera, fish-farming) (Online Resource 2). All these changes contribute to amplify the flood surge.

Venice has literally sunk almost 25 cm during the last century. For more than 50 years through the 1970s, industries in the area pumped groundwater, a practice that—in conjunction with natural sinking of 10 cm for tectonic reasons—accelerated the city's natural subsidence. Combined with a continuous eustatic rise in sea level, subsidence has further increased relative SLR by ~1.5 mm year $^{-1}$ between 1972 and 2002 and up to 5 mm year^{-1} in the southern lagoon margin in recent years, likely related to the works

[2] The list of people interviewed and documents examined can be found in Online Resource 1.

Table 1 Comparison of basic attributes of the two study areas

	Venice Lagoon and surrounding areas	Biscayne Bay and surrounding areas
Total area (km^2)	550	1111
Mean depth (m)	1.2	2
Tidal range (m)	0.7	1.0
Average elevation (m)	1.5	1.6
Population of lagoonal cities (10^3)	55	143
Population on mainland (10^3)	180	2600
Average housing value (USD/m^2)	5000	2000
Annual number of tourists (10^6)	30	22.5
Annual number of cruise tourists (10^6)	2	5.3

carried out for the littoral reinforcement (Teatini et al. 2012; Bock et al. 2012; Tosi et al. 2014).

Subsidence of the lagoon has increased the frequency of flooding events (*acqua alta*) and favored sediment erosion and the increasing influence of marine processes (Fletcher and Spencer 2005; Fagherazzi et al. 2006; Sarretta et al. 2010). In addition to "normal" high water during the last 20 years, ten "exceptional" events (>140 cm) have occurred, during which ~80% of the city surface and more than half of the public space dedicated to pedestrian use have been inundated.

Antonioli et al. (2017) projected the relative sea level change along the coastline of the North Adriatic by 2100, as well as flooding risk scenarios for the Venice Lagoon. They utilized three scenarios of expected SLR, of 0.53 m, 0.97 m (min and max), and 1.4 m (Rahmstorf 2012, 2015) and calculated the extent of flooded areas. The lower SLR will flood more than 30% of the historic city, while the worst scenario will affect more than 85% (Fig. 4). Moreover, they hypothesized that the combination of SLR and possible decrease of rainfall will produce a negative sedimentary budget and significant shoreline retreat.

Estimates of shoreline retreat on the barrier islands of Lido and Pellestrina range from 40 to 75 m, under SLR scenario of 85 cm for year 2100 (MAV-CVN 2013). Because barrier islands buffer the mainland coastal areas from storm surge and ocean waves, changes in their shape or partial disappearance due to erosion may lead to a reduced protection of the Lagoon and Venice (Ramieri et al. 2011).

Human activity

During the past century the resident population in historic insular Venice decreased from ~170,000 to ~50,000 today.

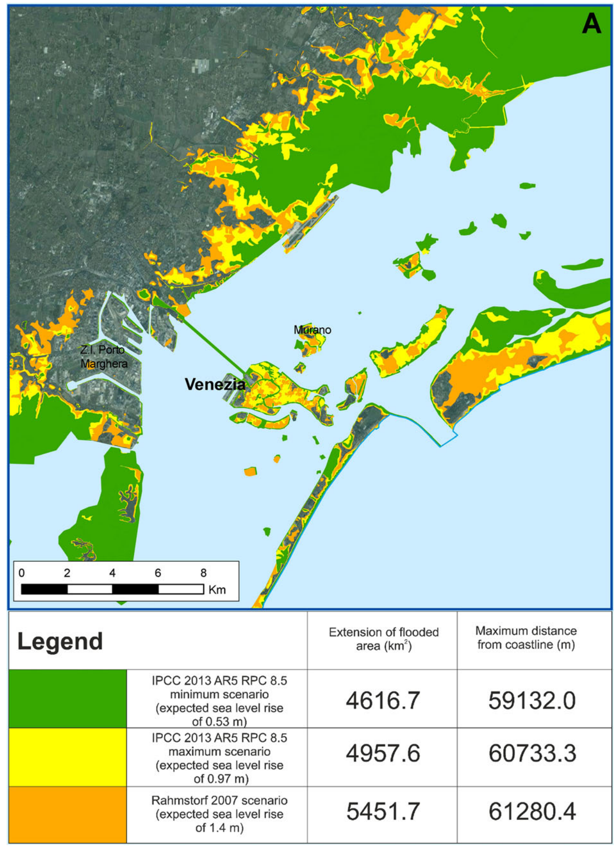

Fig. 4 Flooding scenario of lands adjacent to the Venice Lagoon using three relative SLR models (adapted from Marsico et al. 2017)

Moreover, due to deterioration of the housing stock, the increasing frequency of floods, increasing numbers of inhabitants continue to move from the historic city to mainland urban centers (Favero 2014). As a result, the ancient city has become a residential, tourist, and cultural center. Approximately 70% of the sales of residential property in Venice involves international buyers, and consequently, the housing costs in Venice are the highest of any Italian city—almost \$5000/m^2 (Idealista 2015).

Tourism is Venice's most important economic activity, but also a major source of pollution, as well as a negative influence on the quality of life of Venetian residents. The "tourist presence" has increased from 1.5 million person–days in the 1950s to about 10 million today, with about 4 million visitors staying an average of 2.3 days. In addition, some 15–20 million daily visitors, including some two million cruise tourists, arrive each year, compared with around 200,000 in 1990.

Other economic activities not directly related to the historic city are chemical industries, the modern commercial port, and beach tourism (Lido and nearby barrier islands). At the end of the 1970s Venice became the main port of the Northern Adriatic Sea. Currently, the average number of port calls is around 3500 with 3000 through the Malamocco

Inlet (essentially all commercial vessels) and 500 through the Lido Inlet (mostly cruise ships). Legislation prohibits cruise ships over 90,000 tons from entering the lagoon because of the risks they create when passing through the Grand Canal, and institutions were obligated to find an "alternative route"[3]. The competent institutions have proposed several alternatives that have been rejected for various reasons (environmental impacts, risks, required dredging).

The need for protection of Venice and its lagoon from high-water became evident after an assessment of the damage caused by the dramatic floods of November 4, 1966. That event caused ~US$400 million damage to people, buildings and monuments and also led the Italian Legislature to approve the Special Law setting the stage for broad interventions to minimize the vulnerability from future floods. Vergano and Nunes (2007) calculated damage estimates ranging between $10 and 30 million for each of the 15 exceptional high tide events (over 140 cm) that have occurred since 1966. The impacts of climate change on coastal tourism, focusing on the historical center of Venice, for example, have been estimated at a loss of €35–40 million in 2030. Similar estimates have been made for the clam aquaculture, focusing on the most important areas of the Venice Lagoon in terms of productivity (a loss of €10–17 million in 2030). Flooding from SLR in Venice may result in losses in economic activities of perhaps more €100 million in 2030 (Carraro and Sgobbi 2008).

Three special laws for the protection of Venice

The first Special law for the protection of Venice (Law No. 171, 1973, "Interventions for the Safeguarding of Venice") declared that the Venice Lagoon (VL) area represented important national interests due to its environmental, scenic, historical, archeological, artistic, and socio-economic features. The legislation created an inter-institutional committee (*Comitato*) composed of the Minister of Public Works (chair), Minister of Education, Minister of the Economy, Minister of the Merchant Marine, Minister of Health, Minister of Agriculture and Forestry, President of the Veneto Regional Commission, President of Venice Provincial Administration, the Mayors of Venice and Chioggia, as well as representatives of two additional municipalities.

The Special Law established the exceptionally broad authorities of the State (National Government) in VL: regulation of water levels in the lagoon and defense against high waters ("*Acque Alte*"), lagoon boundaries, port infrastructure, littoral defense, restoration of state-owned historic buildings, canal and bridge systems, restoration of publicly owned art, and management of natural and artificial waterbodies that could be important in saving Venice.

This first special law also instituted a Commission for Safeguarding Venice (CSV) that would have broad representation, including the President of the Veneto Region (presiding chair), representatives of national ministries (Public Works, Merchant Marine, Agriculture and Forestry), president of the Venice Water Authority (*Magistrato alle Acque*: MAV), as well as numerous regional, provincial, and municipal officials.

The membership of the commission was established at 20 persons. The mission of the CSV focused largely on interventions related to buildings and monuments, as well as land use modifications resulting from public or private works.

The second Special law (Law No. 798, 1984, "New Interventions for the Protection of Venice") is specific about national funding. The legislation specified the precise distribution of the national funds among the different governmental levels (State, Region, Municipalities, Port Authority), as well as their destination for specific projects.

Funds were to be dedicated to projects, and infrastructure to return the hydrological equilibrium of the lagoon; address the degradation of the watershed; protect against flooding of urban areas—including construction of moveable gates at the lagoon entrances (MoSE); implement antipollution efforts; build coastal defense structures; maintain lagoon boundaries; protect historical buildings; and develop studies to reroute petroleum shipments in the lagoon and open fish farms to tidal flows.

This more recent legislation modified the membership of the *Comitato*. The presiding chair became the President of the Council of Ministers. Revised membership included the Minister of Cultural and Environmental Patrimony, Minister of Ecology, and Minister of Scientific Research. Law No. 798 authorized the Ministry of Public Works to grant contracts for these works and studies to a *sole concessionaire*. Thereafter, the Ministry of Public Works and the MAV granted this concession to *Consorzio Venezia Nuova* (CVN). In order to finalize the planned interventions MAV and CVN have signed eight covenants, for a total budget €800 million. The same law established that the *Comitato*'s responsibilities included direction, coordination, and control of the execution of interventions programmed and funded by this legislation.

The third Special law (Law No. 139, 1992, "Interventions for the Protection of Venice and its Lagoon") distributed funds and responsibilities among the different levels of government. This most recent special law defined the responsibilities of the Region (pollution prevention,

[3] Ministry of Infrastructure and Transport. Decree of 2 March 2012. General provisions to limit or prohibit the transit of merchant ships for the protection of sensitive areas in the territorial sea. (Official Journal No. 56 of 7-3-2012). Due to a derogation from the law in 2018 the large vessels, with a maximum limit of 90,000 tons, still entered the lagoon.

cleanup in the watershed immediately adjacent to VL, establishment of environmental standards) and the Venice Municipality (cooperation with the Region regarding wastewater treatment in the historical center of Venice, maintenance of seawalls along the canals).

Miami-Dade County (MDC), Biscayne Bay and Barrier Islands

Physical Setting

Toward the east of mainland Miami lies shallow Biscayne Bay and the barrier islands of Miami Beach, Virginia Key, and Key Biscayne, with elevation ranging between 1.5 m and 3.5 m above MLW. Topography was not a reliable diagnostic feature of prior coastal landscapes because the land surface was generally formed by wetlands or sandy plains of low local relief, except for outcrops of the karstified Atlantic Coastal Ridge (ACR) and coastal dune systems. The study area is a nearly level plain with a general elevation of 0–8 m above sea level except along the ACR, which rises to ~12 m.

The coastal configuration of MDC is controlled by the underlying bedrock (e.g., Banks et al. 2007). The bedrock in the region consists of Quaternary Key Largo limestone overlain by oolitic facies of Miami limestone that was exposed to precipitation and air during glaciations leading to partial dissolution (Foster 1983; Finkl and Andrews 2008; Precht and Miller 2007). The bedrock controlled the seafloor morphology and shoreline position (Banks et al. 2007; Finkl and Warner 2005). A great number of coastal sediment bodies were built between 3300 and 3000 YBP and also between 2300 to 2500 YBP (Wanless et al. 1994). Land surface morphology in the area is related to (1) materials of the land, (2) oscillations of sea level, (3) shoreline processes, (4) climate, (5) solution of parent rocks, and (6) erosion (Finkl and Restrepo-Coupe 2007).

Finkl and Andrews (2008) showed how depressions in the bedrock provided accommodation space for marine sediments between shore-parallel lithified paleoshorelines, currently buried onshore by recent sediments. The topography of the area was also shaped by the glacio-eustatic fluctuations of sea level during the Quaternary.

Higher than present sea levels deposited a layer of marine sands to produce terracing of the landscape. The inter-reefal sand flats contain calcareous sands, coral fragments, and intercalated clays and slits. The relict rocky ridge coral reef facies surrounding these inter-reefal flats rise up from the underlying bedrock to form the Florida Reef Tract, a coral reef system that extends longshore (Precht and Miller 2007).

The previously mentioned barrier islands are parallel to the offshore coral reefs and to the exposures of bedrock on the seafloor. Although some may have been barrier islands, most appear to have been barrier spits connected to the mainland. Today we observe the result of inlet cutting that occurred many decades ago. Therefore, the barrier islands are not true barrier islands, but the result of coastal engineering (Finkl 2014). Commonly barrier islands are composed of sediments that lay unconformably on a substrate, (e.g., Venice Lagoon area). The MDC barrier islands are rock-cored.

The limestone bedrock is very porous and highly permeable and today holds the surficial Biscayne Aquifer. Biscayne Bay occupies a limestone depression east of the mainland extending some 48 km north to south with widths of up to 13 km. The bay is shallow with natural depth in the center of 2–4 m (Hoffmeister 1982). The central and southern bay has natural shallow openings to the Atlantic unlike the more isolated northern bay. Freshwater delivery to Biscayne Bay occured naturally through some 12 transverse glades, diffuse freshwater flow, and groundwater (Biscayne Aquifer) (Obeysekera et al. 1999; Lodge 2010). Northern Biscayne Bay has been extensively modified during the past century (Online Resource 3). Two inlets have been opened to the Atlantic. Most of the fringing mangroves have been removed, filled, and bulkheaded for residential development.

Serious alteration of freshwater delivery to Biscayne Bay began in 1948 with the approval of the Central and Southern Florida Project for Flood Control that resulted in severe alteration of the Everglades ecosystem located to the west of the Atlantic coastal ridge (Grunwald 2007). The project's canals reduced the freshwater sheet flow south to Everglades National Park and Florida Bay (Sklar et al. 2005; Aumen et al. 2015). This major infrastructure project constructed a series of levees and canals that block sheet flow to Biscayne Bay and reduced risk of flooding opening vast areas of the county to residential development. The diffuse flows and trans-glade wetland flows have been changed to point sources with the construction of 19 drainage canals that are opened and closed in manners to avoid flooding and saltwater intrusion into the Biscayne Aquifer. As a result, Biscayne Bay has lost many of its estuarine functions and has become much more saline (Lodge 2010).

The barrier islands of Miami Beach, Virginia Key, and Key Biscayne were built up with dredged material from Biscayne Bay (second decade of the 20th Century) (Goodell 2017). Preliminary results from Fiaschi and Wdonski (2016) detected localized subsidence, up to 3 mm/year during the period 1993–2005, mainly in reclaimed land located along the western side of Miami Beach. Although the detected subsidence velocities are quite low, their effect

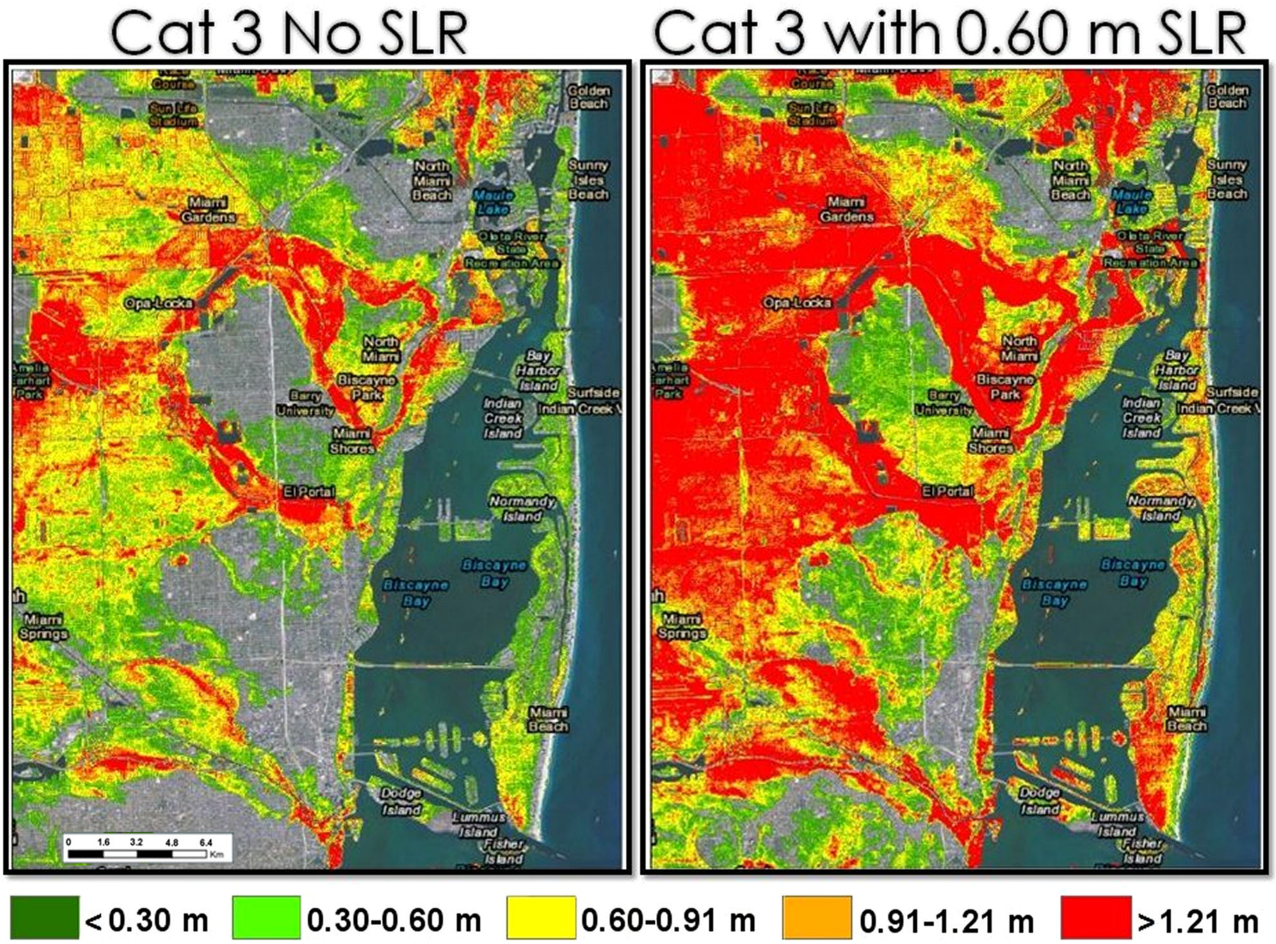

Fig. 5 The map (**a**) indicates depth of flooding in MDC from a storm surge associated with a Category 3 hurricane with no SLR. The map (**b**) indicates depth of flooding in MDC from a storm surge associated with a Category 3 hurricane and SLR of 0.60 m. Maps are based on the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) surge model used by the National Hurricane Center. (modified from: Fig. 2, Miami-Dade County 2014b; maps prepared by Dr. Keren Bolter)

on the flooding hazard is significant, because houses originally built on higher ground have subsided since the city was built, about 80 years ago, by 16–24 cm down to flooding hazard zones. The combined effect of subsidence, SLR, and increasing groundwater levels further expose subsiding areas and low-lying areas to the west of the coastal ridge to high flooding hazard (Bloetscher and Romah 2015).

The South Florida peninsula contains the only subtropical climate in the US mainland (Corcoran and Johnson 2005); the region has high exposure to hurricanes and associated storm surges, as well as, high rainfall events. Of the Category 3 to 5 hurricanes that made landfall on the US Atlantic Coast between 1851 and 2008, 39% struck Florida (NOAA/AOML 2009). Based on over a century of data, the average return period for a hurricane strike (Categories 1 to 5) to Miami Beach is 5 years while for a "strong hurricane" (Categories 3 to 5) the return period is 18 years (Keim et al. 2007). Malmstadt et al. (2019) and NOAA's National Hurricane Center (2019) also estimate similar return periods. Using the National Hurricane Center's prediction of 5–7 years as the frequency at which a hurricane could be expected within 50 nautical miles of Miami gives the annual probability of a strike between 14 and 20%. Pielke et al. (2008) calculated normalized hurricane damages in the USA from the years 1900 to 2005 and noted that of the top 20 normalized damages from hurricanes, 9 impacted Florida. The Great Miami hurricane of 1926 could produce $500 billion in damages were it to occur after 2020. Increased storm intensity (Patricola and Wehner 2018) compounded with Florida's rapid coastal development, population increases, and SLR suggest that potential losses to property from tropical storms will be extremely high. Nicholls et al. (2007) ranked 130 key port cities around the world for the most exposed to coastal flooding assuming SLR of 0.5 m by 2070. Miami ranked in 1st place in exposed future assets in 2070 and 9th in terms of population exposed to coastal flooding. Figure 5 illustrates the projected impact of flooding in MDC taking into account both SLR and the storm surge generated by a Category 3 hurricane.[4]

Human Activity

The Miami modern history only began in 1896 with the arrival of the Florida East Coast Railway that brought tourists from the northern US. From a population of 4955 persons in 1900, MDC's population increased to 488,689 persons by 1950. By 2010, the county's population had surpassed 2.5 million people (Table 1). MDC has more people living less than 1.3 m above sea level than any state except Louisiana (and Florida itself). About 25% of the county's land is less than 1 m above sea level. The City of Miami Beach, located on the barrier island of its name, is located at elevation of 1.3 m above MSL. In 1915, Miami Beach housed about 10% of the county's population until about 1950. The population peaked in 1980 and since that time, has decreased slightly toward the present level of ~88,000 (Suburban Stats 2018). The smaller barrier island of Key Biscayne to the south of Miami Beach, has a current population of ~12,000 persons (Suburban Stats 2018) barely sitting above the sea with average elevation 1 m.

The growth of MDC has been explosive during its 120 year history. This fast growth rate has presented challenges for comprehensive land use planning. Despite the region's vulnerabilities, high rates of growth and property values continue to increase. Florida's lack of state income tax means that MDC has a high dependence on local property taxes for its budget. Since 2006, Miami Beach has experienced a SLR of 9 mm per year (Wdowinski et al. 2016; Treuer et al. 2018). Assuming similar rates in the future and no adaptation measures, a SLR of 0.5 m by 2070 could threaten assets of $3.5 trillion in MDC and displace 300,000 persons (Hanson et al. 2011; Hauer et al. 2016, Treuer et al. 2018). Rao (2016) suggests that a 2 m SLR could result in lost home values of $400 billion in Florida by 2100. An intermediate SLR range predicted by NOAA for 2050 could result in annual flood losses of $25 billion (Sweet et al. 2017; Treuer et al. 2018). Assuming population growth, moderate SLR rates, and implemented adaptation measures, losses from flooding in Miami may still increase to $2.55 billion by 2050 (Hallengatte et al. 2013; Kulp and Strauss 2017).

The principal economic activities in MDC today are tourism, real estate development, financial services, and international trade. MDC accounted for about 30 percent of the $71.8 billion that visitors to Florida spend each year. Miami Beach attracted over 7 million overnight visitors in 2015 who spent almost $12 billion during their stay. During that same year, MDC hosted 15.5 million overnight visitors who spent $24.4 billion.

Political–Administrative Environments

Venice

Several institutions possess administrative and technical competence to deal with problems related to climate change in Venice. Among these are Italian governmental agencies at the State (national), regional, provincial, and municipal levels, as well as UNESCO[5]. Ideally, institutional coordination should support effective management of the Venice Lagoon in light of threats. Constant change presents additional management challenges, a reality examined by both Suman et al. (2005) and Munaretto and Huitema (2012). Suman et al. (2005) studied the Venice Lagoon and its watershed with reference to integrated coastal management. Those authors argued that—at that time—public participation and area-based management were often neglected by administrative bodies involved in the planning of coastal projects and public works. Their analysis highlighted a substantial absence of coordination among the various administrative bodies in charge of planning and management at various governmental levels and various economic sectors. More recently, Munaretto and Huitema (2012) have analyzed water and environmental management in the Venice Lagoon and have concluded that the existence of the Special Law no. 789 of 1984 inhibits participation and real polycentricity, making it difficult to change policy and address problems on a bioregional scale. The complex division of responsibilities and the extensive set of public and semipublic authorities (e.g., the Water Authority, the Veneto Regional Government, the Superintendency for the Architectural and Landscape Heritage of Venice, the Venice Port Authority) involved in the management of the Venice Lagoon suggest that the system indeed exhibits a certain degree of polycentricity in the sense that power is shared among many actors with overlapping responsibilities. The authors suggested "adaptive co-management" as a way to manage challenges of environmental governance, including uncertainty. The recent changes of some of the administrative bodies and the appearance of a new administrative entity—the Metropolitan City—create additional

[4] Using sophisticated modeling to predict SLR impacts, Lentz et al. (2016) illustrate that simple inundation models of SLR may be too simplistic and may not lead to the best prediction of SLR impacts. They suggest that the type of land cover (e.g., beaches or wetlands) may have some capacity to respond dynamically to SLR.

[5] Venice and its lagoon were added to the list of UNESCO World Heritage Sites in 1987.

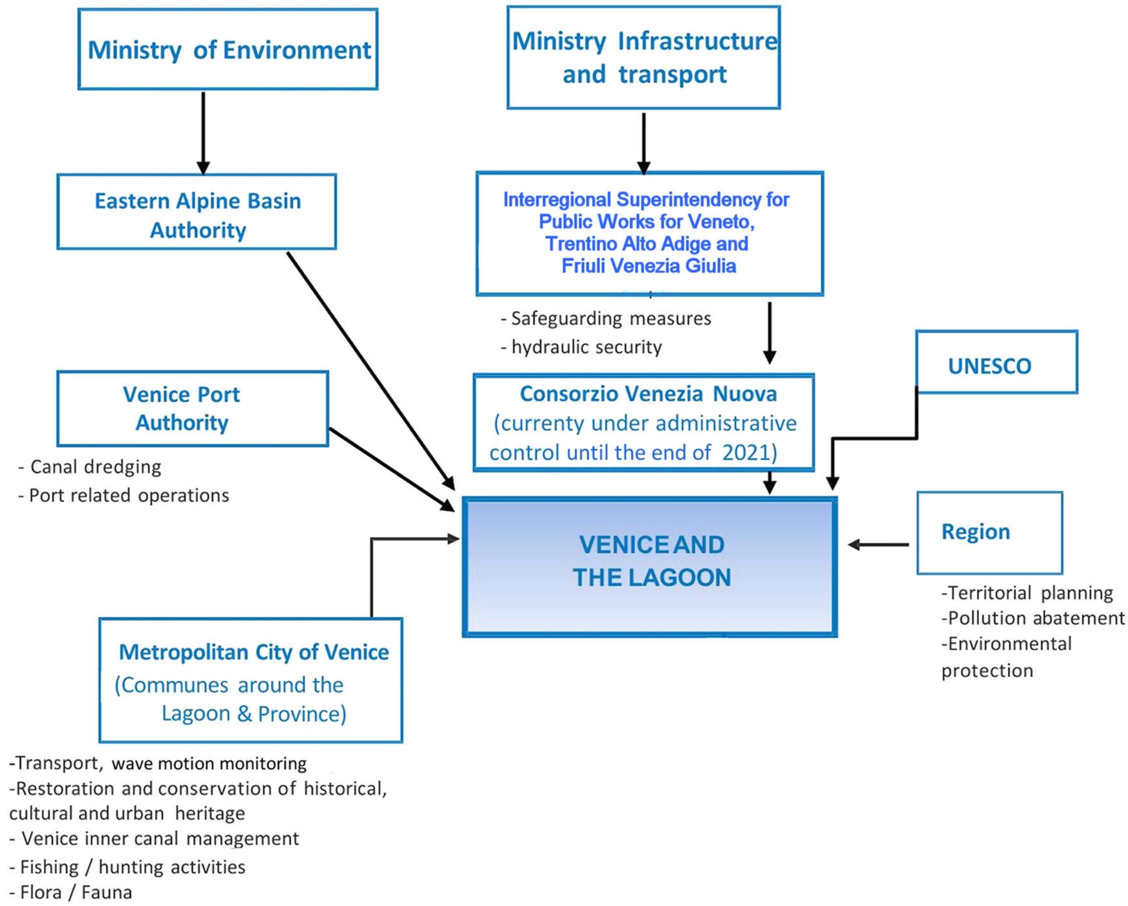

Fig. 6 The new institutional setting in Venice and their relationships

complexity. We note the principal actors below, and their relationships in Fig. 6.[6]

"Interregional Superintendency for Public Works for Veneto, Trentino Alto Adige and Friuli Venezia Giulia", previously Venice Water Authority (VWA), a branch of the national Ministry of Infrastructure and Transport, is responsible for pollution abatement and maintenance in the lagoon, as well as flood defenses. *Eastern Alpine Basin Authority*, is responsible for management plans of all regional water bodies.

The *Veneto Regional Government* is responsible for pollution abatement in the lagoon's drainage basin, tourism and transport on the mainland, landscape, and some aspects of navigation.

The recently created *Metropolitan City of Venice* will take over some of the responsibilities of the communes around the lagoon and the Province.[7] The *Venice Port Authority*, a national entity, is responsible for shipping channels across the lagoon, the Giudecca Canal through Venice, and the ports in Venice and around the lagoon.

Roggero and Fritsch (2010) explored the governance arrangement concerning fishery management and morphological remediation of Venice Lagoon and underlined some negative aspects directly linked to the scale of the agencies involved.

Rusconi (2016) analyzed the problems related to lagoon management after the 2014 elimination of the Venice Water Authority (VWA), arguing that it was inappropriate to define the tasks of the eliminated VWA only related to the Venice Lagoon, neglecting the overall hydraulic and maritime contexts. Ecosystem-based management of the waters of the "Hydrographic Sub-unit of the Watershed, Venice Lagoon and Adjacent Sea" is required, according to the Management Plans implemented by the Veneto Region. The absence of a coordinating body, potential conflicts between a new Special Law now under discussion and European Directives (Water and Floods), and the potential transfer of overall management to the Metropolitan City of Venice are issues that create uncertainty.

[6] A complete list of the institutions involved and their respective roles is available in Online Resource 4.

[7] The Province in 2008 prepared a Flood Plan ("Piano Mareggiate") with a management geodatabase of the Venetian coasts containing all geomorphological data.

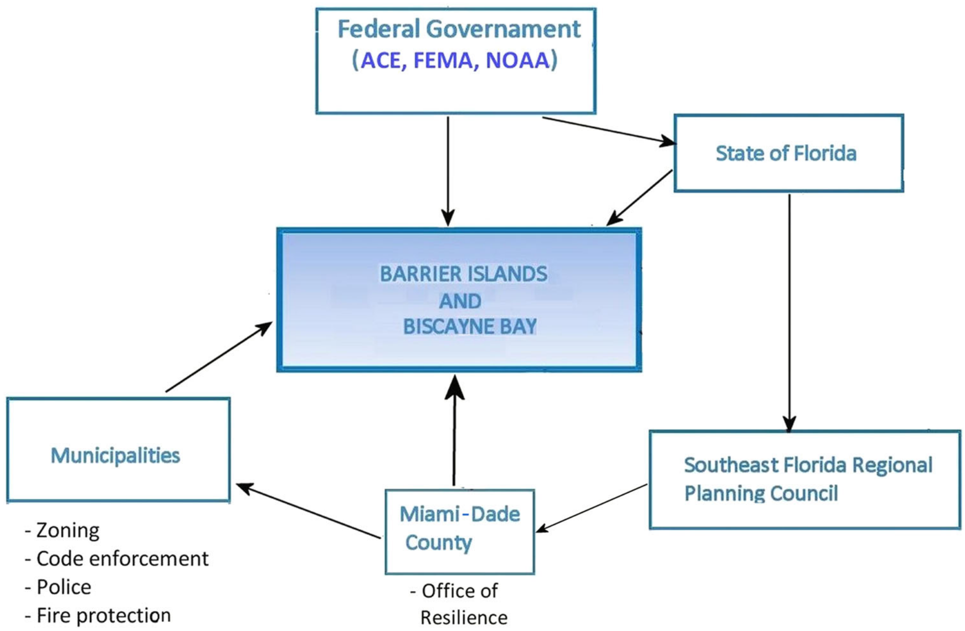

Fig. 7 The institutional setting in Miami-Dade County

A management plan was finally created in 2012 for the Venice UNESCO World Heritage Site. However, this document only gives superficial discussion of SLR. In 2015, UNESCO warned that Venice might be included in the list of UNESCO "World Heritage Sites in Danger" if Italy had not banned large cruise ships from the city's lagoon and created a sustainable tourism strategy (UNESCO 2015).

Miami

Miami's administrative framework is less complex than that of Venice and is divided between the national (federal) government, the State of Florida, MDC and its municipalities. While perhaps less complex, the US situation remains challenging and vertically fragmented. Figure 7 shows the relationship between the institutions.[8]

The federal government appeared to be moving toward action to address climate change during the Obama Administration. In February 2013, Federal agencies released their first Climate Change Adaptation Plans. The 2013 President's Climate Action Plan summarized federal agency policies to address climate change issues. Key among the identified efforts was the development of partnerships between federal agencies and local governments to assess vulnerability to infrastructure and identify solutions that reduce risks. Federal efforts would support community-based efforts to prepare for climate change and enhance resilience via federal grants and technical assistance. However, the Trump administration from January 2017, has retreated from numerous climate change initiatives. Nevertheless, the U.S. Global Change Research Program's Fourth National Climate Assessment clearly states the urgent need for enhanced, coordinated adaptation efforts (Fleming et al. 2018; Maxwell et al. 2018). Despite these policy shifts from the Executive Branch, numerous federal agency programs continue to have direct relevance to SLR and flooding. Of particular significance are the programs of the US Army Corps of Engineers (USACE) and the Federal Emergency Management Agency's National Flood Insurance Program. The USACE is responsable for developing infrastructure that protects against flooding. The USACE, together with the South Florida Water Management District, are the principal actors of the Comprehensive Everglades Restoration Plan (CERP) at a cost of over US$10 billion with a timeline of over three decades (Aumen et al. 2015). We address CERP's linkages to SLR adaptation in eastern MDC below.

Major federal agency efforts examining various aspects of climate change and sea level rise provide important information for local adaptation efforts. The US Geological Service has collaborated with MDC in the generation of 30 year scenarios of SLR and increased groundwater pumping that indicate elevation of the water table contributing to increased vulnerability from flooding (Hughes and White 2016). The National Oceanic and Atmospheric Administration's Coastal Services Center has developed numerous

[8] A complete list of the institutions involved and their respective roles is available in Online Resource 4.

Table 2 Adaptation to flooding (Venice)

Venice			
Realized	Pros	Cons	Transferability
1700: Construction of walls "*murazzi*" (walls made of cemented rocks).	Protection of the lagoon and the city against the sea	The barrier system has been tightened	–
1970s: A network of walkways is installed along the main pedestrian routes.	Pedestrian mobility around the city;	None	YES
1980s: The protection of ground floors, adaptation of electrical systems, and placement of steel barriers at the entrance to buildings	The strong awareness of its citizens to adopt adaptation measures to protect their assets	None	YES
>1984: Interventions from Special Law: (1) restoration of the *murazzi* (sea-walls); (2) nourishment of eroded beaches; (3) prohibition of methane extraction and drilling of new artesian wells; (4) elevation of low-lying parts of the urban center; (5) dredging of internal Venice canals. (6) Wetland creation;	Protection of inhabitants of Pellestrina and Lido and the historic city against the sea	After 1998 there was not enough money to comply with the intervention for (1) (2) and (5) every 10 years, as planned.	(1), (3) Not suitable, but possible in other cities (2) YES, but in Miami worked better (4) YES, (5) YES (6) YES (mangroves and seagrass beds)
1994–1998: Public paved areas are being raised, to defend against tides up to 100–110 cm.	Commercial activities and cultural heritage of the city are protected	None	YES
2003: MoSE (Experimental Electromechanical Module) expected to be completed 2020–2022	Flood protection in case of waters higher than 120 cm (~10 episodes/year)	Not working between 90–110 cm (40–50 episodes/year) (1) The majority of funding has been dedicated to the MoSE project. Measures previously implemented (wetland creation and beach nourishment) were halted. (2) The mobile barriers are producing changes in the structure of the lagoon inlets, with consequences for the dynamics of the lagoon ecosystem. (3) Additional annual costs for the interruption of ship traffic due to the operation of the MoSE	Not suitable for Miami; the geological setting of the city and vulnerability to hurricane storm surges make the adoption of mobile sea barriers similar to MoSE impractical. Possible in other cities.
>2005: Flood information by alarms in real time via web and smartphone	Protection of commercial activities	None	YES
Recommendations and Future			
Elevation of St. Mark's Square	Protection of the Historic Square	Not yet implemented	Very difficult
2016: Veneto Regional Government. Integrated management of the coastal zone (ICZM): Study and monitoring for the definition of the interventions to protect the coasts from erosion in the Veneto Region (guidelines)	Comprehensive Plan: includes climate change adaptation measures	Not yet implemented	YES

Table 3 Adaptation to flooding (Miami)

Miami			
Realized	Pros	Cons	Transferability
1926–1975: Construction of wood and rock groins located every block of Miami Beach	May have temporarily built up the beach	Unattractive. Blocked the natural flow of sand	–
1975–1982: Nourishment of ~17 km of beach. 1986–1988: The second phase of the project. Extension of the nourishment an 4.0 km. A total of 14,076,765 cubic meters of sand were used.	Part of Miami Beach was protected. 80% reduction in storm damage during a 100-year storm event. This project is thought to be one of the most durable replenishment projects in the US	Costly. Harm to offshore coral reef habitats. Burial of intertidal habitats	YES
2000: In response to 1992 Hurricane Andrew the State of Florida Building Commission adopted the Florida Building Code (FBC)	Stricter building standards for construction, modification and repair	Amendments every three years	YES
2014: The City of Miami Beach began to implement the MDC recommendation for SLR with the development of design standards for city infrastructure that would account for SLR during a 30–50 year time horizon. For example, basic standards were altered to increase the storm rainfall events from 15 to 19 cm during a 24 h period, and tailwater elevations were increased from 20.4 to 82.3 cm North American Vertical Datum (NAVD).	Benefits for the future	No requirements for existing infrastructure	YES
2017: Miami Beach has begun to elevate streets in areas that are most vulnerable to flooding.	Elimination of street flooding in low-lying areas	Potential flooding of businesses that are lower than the elevated streets	YES
2017–2018: Overhaul of the stormwater system in Miami Beach with the installation of 70 one-way pumps in areas that are most susceptible to flooding.	The pumps have worked during recent flooding events.	Expensive. Degradation of Biscayne Bay water quality from street runoff	YES
Recommendations and Future			
2012: Regional Climate Action Plan with 110 Action Items. Reduction of greenhouse gas emissions, and emergency management that decision-makers at the county and municipal levels can adopt to mitigate and adapt to climate change.	Although it will take many years to adopt and implement the recommendations, these are important initial planning steps	Not yet implemented	YES
The RCAP recommended that municipalities and counties develop policies and standards to improve resilience to coastal and other impacts from climate change and sea level rise and include these in their planning documents. The RCAP encouraged local governments to incorporate the concept of "Adaptation Action Area" into their planning documents, identify areas vulnerable to coastal flooding and sea level rise. An additional recommendation concerns the development of sea level rise scenario maps and flood maps that reflect the 100-year storm event under future sea level rise scenarios to incorporate into Comprehensive Planning documents.	Building and land use codes should be revised to reduce losses from new construction or redevelopment in areas vulnerable to sea level rise and flooding.	Not yet implemented	YES
2013: MDC formed the Sea-Level Rise Task Force charged with making recommendations to the County's Comprehensive Development Master Plan. The principal recommendation was to "accelerate the adaptation planning process by seeking and formally	Comprehensive Development Master Plan includes climate change adaptation measures	These goals are important first steps, but they remain to be fully implemented.	YES

Table 3 (continued)

Miami			
Realized	Pros	Cons	Transferability
selecting the engineering and other relevant expertize needed" to develop plans for flood protection, salinity barriers, pumps, and road/bridge designs.			
2016: the City of Miami Beach adopted new standards for major renovation and new construction that will provide for increased protection against storm surges and sea level rise.	Protection against sea level rise and storm surges	Not required for existing structures.	YES
2017: Miami-Dade County CDMP for 2020–2030 contains 12 elements, several which directly address climate change and sea level rise. The two most relevant elements are Land Use and Coastal Management. The Land Use Element states lofty goals of identifying hazard-prone areas and areas vulnerable to SLR and tidal flooding; identifying the most vulnerable public infrastructure. Revising the Land Use and Zoning Maps to take flooding and storm surge risk into account; coordinating efforts with other jurisdictions, and not subsidizing programs that encourage growth on barrier islands. This element also states that SLR projections determined by the SEFRCCC should be considered in all future County decisions regarding location, design, and development of public facilities and infrastructure.	Comprehensive Development Master Plan includes climate change adaptation measures	These goals are important first steps, but they remain to be fully implemented	YES
2017: the Office of Emergency Management of MDC released an updated of Florida Comprehensive Emergency Management Plan (CEMP). This extensive document specifies the responsibilities of the federal, state, and local governments, as well as organized stakeholders, in the face of various emergency situations that may occur and attempts to coordinate planning, response, mitigation, and recovery from identifiable hazards	Useful to identify storm surge planning zones based on current sea levels. Fosters inter-governmental cooperation.	–	YES

tools that provide coastal managers with information for their adaptation efforts. Among these are coastal LIDAR data, an online mapping viewer to illustrate potential SLR and flooding in coastal areas, and integrated shoreline data from NOAA and other federal agencies available on a single website (https://shoreline.noaa.gov/about.html).

Despite Florida's high vulnerability to climate change impacts, in recent years at the State level, planning for response and adaptation to climate change not been directly addressed because of the political leadership remained in the hands of climate change skeptics (Korten 2015). In a 2012 evaluation of states' preparation planning for climate change, the Natural Resources Defense Council ranked Florida in Category three out of four categories; the 29 states in Categories three and four are "largely unprepared and lagging behind" (NRDC 2012). Nevertheless, Florida's Land Use Planning legislation obligates counties to develop proactive comprehensive land use plans (F.S. Chapter 163) and provides counties with the opportunity to create "Adaptive Action Areas" (AAA) that experience coastal flooding due to extreme tides, storm surges, or vulnerability to SLR. AAA designation is a key to priority funding for adaptation planning (Bloetscher et al. 2016).

At the regional government level, the Southeast Florida Regional Planning Council (SEFRPC) is a four county (Palm Beach, Broward, Miami-Dade, Monroe) planning agency that recommends regional plans and advises counties on specific development projects. As we describe below, the SEFRPC is playing a leading role in coordinated SLR adaptation. The South Florida Water Management District, one of five in Florida, has begun to consider climate change and SLR in water resources planning in the Everglades ecosystem and Southeast Florida (SFWMD 2018).

The local government is led by strong MDC Mayor and Board of County Commissioners with authority over schools, water and sewage, and land use planning. Governance is shared between the MDC government and some 34 muncipalities, as well as incorporated areas. Municipalities are responsible for zoning, code enforcement, police, and fire protection. MDC's Office of Resilience assesses vulnerabilities and forges collaborations with county agencies, other levels of government, and stakeholders to promote environmental sustainability. The Office of Resilience has coordinated the development in 2014 of the County's first Climate Action Plan that addresses mitigation measures to reduce greenhouse gas emissions and measures to adapt to climate change impacts (Miami-Dade County 2014a). As we will mention below, some of the County's municipalities have also developed climate action plans.

Adaptation Efforts

Adaptation to climate change is essential to manage present risks and potential for more serious future changes, and has entered the planning agenda of many cities around the world (Araos et al. 2016; Juhola and Westerhoff 2011). With improvements in high-resolution modeling, it is possible to map the expected SLR in specific locations (LIDAR), both worst-case and expected-case scenarios. In many locations this very detailed awareness of vulnerability leads to proactive planning actions (De Sherbinin et al. 2007). Venice and Miami are both struggling to maintain their environments and economic activities faced with high vulnerability to flooding caused by climate change (Hauer et al. 2016; Antonioli et al. 2017). This section describes some adaptation measures that Venice and Miami have implemented to mitigate risks (Tables 2 and 3).

Venice

Venice has a long history of adaptation to flooding. Early Venetians developed technologies to build on the water, construct firm foundations, and raise building heights (Mancuso 2014). Archeologists have found signs that ancient Venetians gradually raised the ground level as high as ~2 m. In St. Mark's Square, the lowest point of Venice, there are five levels of older pavement beneath today's plaza (Keahey 2002). The inhabitants of Venice diverted the lower course of the rivers to shape the city to their needs (Caniato 2005). In 16th and 17th Centuries city planners actively altered the lagoon and surrounding environments, building canals to help facilitate shipping and further river diversions, as well as constructing sea barriers. During the 18th Century, work continued to improve navigability, and at the barrier island of Pellestrina, the "*murazzi*" (walls made of cemented rocks) were constructed to form barriers against the sea.

More recently, several adaptation measures were adopted in Venice to counteract the flooding events, especially after the "big flood" of 1966. They can be subdivided in widespread interventions and the mega-technical barrier system, first proposed in 1981 and funded through the 1984 Special Law. The following interventions stem from this legislation: (1) restoration of the seriously damaged *murazzi* (seawalls) beginning in 1990, (2) nourishment of eroded beaches, (3) prohibition of methane extraction and drilling of new artesian wells, (4) elevation of low-lying parts of the urban center, (5) construction of lagoonal wetlands, and (6) dredging of internal Venice canals.

The city is constantly confronted with the problem of *acqua alta*. To allow pedestrian mobility around the city at high tide, a network of walkways is installed along the main pedestrian routes, generally at ~110 cm above the standard sea level. Today flood information is provided by alarms and in real time via web and smartphone, and some public transport lines are diverted to alternative routes. Among the nonstructural measures for prevention, preparedness and response, Venice also counts on the strong awareness of its citizens and their ability to adopt adaptation measures to protect their assets. Examples of these types of measures are the protection and improvement of ground floors, adaptation of electrical systems, and placement of steel barriers at the entrance to buildings to keep water out (Indirli et al. 2014).

Recently, some authors (Gambolati et al. 2009) have proposed a program of anthropogenic uplift of the city of Venice that would involve the injection of seawater into a 600–800 m deep brackish aquifer underlying the Venice Lagoon (Comerlati et al. 2003, 2004). According to Comerlati et al. (2003, 2004), Venice might be very uniformly raised by 25 cm over a 10-year period based on injection boreholes and at controlled injection rates.

MoSE

The centerpiece of the Special Law was MoSE (an acronym for *Modulo Sperimentale Elettromeccanico* or Experimental Electromechanical Module), begun in 2003 and expected to be completed no sooner than 2020–2022. The mobile tidal barrier project will prevent flooding through the installation of 78 mobile gates, laid at the bottom of the seabed at the three inlets—Lido, Malamocco, and Chioggia—separating the Venice Lagoon from the Adriatic Sea.[9] Since 2003 the majority of funding has been dedicated to completion of the MoSE project.[10] As a result, measures that previously had been implemented, such as wetland creation and beach nourishment, ceased for lack of funding.

Strong debate has surrounded MoSE since its conception regarding: (1) its effectiveness and high cost (Ammerman and McClennen 2000; Kaluarachchi et al. 2014); (2) changes in the structure of the lagoon inlets, with consequences for the dynamics of the lagoon ecosystem as a whole; (3) the direct costs of the interruption of ship traffic due to the operation of the MoSE, resulting from longer waiting times for ships crossing the Venice Lagoon (Vergano et al. 2010). Further critiques concerned interference with the ship traffic with a sea-level rise of 50 cm (Umgiesser and Matticchio 2006), as well as environmental degradation, particularly water quality. Finally it was suggested that a potential seismogenic source located inland near Venice might generate a tsunami wave possibly affecting the MoSE gates if they were closed during the event (Panza et al. 2014).

[9] For the constructive details of the MoSE, the debate, the costs and the critical points refer to the Online Resource 5.

[10] In the period 1992–2004 the average annual funding of the Special Law dedicated to Venice was €143 million, reduced to ~€20 million in the period 2005–2014.

Miami

In Miami initiatives to respond and adapt to climate change and SLR originate primarily at the local level and are relatively recent. The County Commissions of the four southeastern counties (Broward, Miami-Dade, Monroe, and Palm Beach) approved the Southeast Florida Regional Climate Change Compact (SEFRCCC) in 2010 to create a united front to face regional climate change. Since then, the SEFRCCC Steering Group has adopted consistent methodologies and assessed the vulnerabilities from sea level rise in the four county region based on one, two, and three foot (0.3, 0.61, and 0.91 meter) increases in sea level. In October 2012, the SEFRCCC produced a Regional Climate Action Plan with 110 Action Items related to reduction of greenhouse gas emissions, water supply systems, sustainable communities, transportation infrastructure, and emergency management that decision-makers at the county and municipal levels can adopt to mitigate and adapt to climate change (Southeast Florida Regional Climate Change Compact Counties 2012). Although it will take many years to adopt and implement the recommendations, these are important initial planning steps.

In 2013, MDC formed the Sea Level Rise Task Force charged with providing recommendations to the County's Comprehensive Development Master Plan (CDMP). The principal Task Force recommendation in 2014 was to "accelerate the adaptation planning process by seeking and formally selecting the engineering and other relevant expertize needed" to develop plans for flood protection, salinity barriers, pumps, and road/bridge designs (Miami-Dade County 2014b). Many of these adaptive strategies are those suggested by Nicholls (2011).

Miami-Dade County CDMP for 2020–2030, issued in 2017, contains 12 elements, several of which directly address climate change and sea level rise (Miami-Dade County 2017). The two most relevant elements are Land Use and Coastal Management.

The details of the recent Comprehesive plans (like RCAP and CDMP) are described in Table 3, "Recommendations and Future". All these goals are important first steps, but they remain to be fully implemented.

While MDC has only recently begun to expressly consider the risks of SLR, the region has extensive experience in measures associated with coastal erosion and shoreline protection (Table 3, "Realized"). The 1926 Category 3 hurricane that struck Miami caused major damage to infrastructure and significant beach erosion on Miami Beach. The first efforts to address coastal erosion began shortly afterward with construction of wood and rock groins. By the 1950s, no dry sand beach existed on 56% of the shoreline at high tide. In 1966 Congress authorized the MDC Beach Erosion Control and Hurricane Surge Protection Program via the Flood Control Act with the primary goal of addressing beach erosion. Development and implementation of this major beach nourishment program was a cooperative arrangement between the US Army Corps of Engineers (USACE) and MDC. The original project, carried out between 1975 and 1982, excavated ~10 million m^3 of sand, and by 2006 ~14 million m^3 of sand had been excavated for beach nourishment. The Miami Beach project is thought to be one of the most successful replenishment projects on the US Atlantic and Gulf of Mexico coasts (Pilkey and Dixon 1996).

Additionally, in response to 1992 Hurricane Andrew that caused major damage in MDC, in 2000 the State of Florida Building Commission adopted the Florida Building Code (FBC) and considers amendments every three years. The FBC incorporated stricter building standards for construction, modification, and repair of buildings. Barrier island Miami Beach is the MDC municipality that has been most aggressive in addressing flooding from SLR. In 2014 the municipality began to implement the MDC recommendation to address SLR with the development of design standards for city infrastructure that would account for SLR during a 30–50 year time horizon. Based on these standards, design standards for road elevations, stormwater outlets, seawall elevations, and building finished floor elevations were modified. In April 2016 the City of Miami Beach adopted new standards for major renovation and new construction that will provide for increased protection against storm surges and sea level rise. The minimum base flood elevation (BFE) was increased from 7.0 ft NGVD to 8.0 ft (2.1–2.4 meter) NGVD. Similarly, the Freeboard was increased from 0 ft above BFE to +1–+3 ft (+0.31 to +0.91 meter) above BFE. Required elevations for seawalls were also increased from 4.76 ft (1.5 meter) NGVD to 7.26 ft (2.2 meter) NGVD for seawalls. The ordinance also established a minimum yard elevation of 6.56 ft (2.0 meter) NGVD where none existed previously.

Miami Beach has begun to elevate streets in areas that are most vulnerable to flooding. The City initiated the overhaul of its stormwater system with the installation of 70 one-way pumps in areas most susceptible to flooding. These pumps replace the reverse gravity pumps that recently caused street flooding during king tide events. During recent flooding events, the pumps have worked, although they have been responsible for water pollution (fecal matter) of Biscayne Bay.

One of the largest hydrological restoration programs in the USA (CERP) is attempting to return the sheet flow of freshwater southward to a more "natural" state before engineering projects shunted much of the freshwater away from southeast and southwest coastal areas that became prime sites for urban development. The original CERP plans did not consider climate change or SLR, but this has begun to change in recent years with new modeling and calls for integrating potential climate change uncertainties (precipitation, upstream flows, SLR, population growth) into long-term ecosystem restoration planning (Koch et al. 2015; Nungesser et al. 2015; Obeysekera et al. 2015). The linkages between CERP and SLR adaptation of coastal MDC have yet to be fully envisioned.

Discussion

Having presented the two case studies, we now address the main questions. Tables 2 and 3 summarize the adaptation measures with the pros and cons in each city to allow clear statements on what they could learn from each other.

Initially, we note the commonalities between the two scenarios. Both Venice and Miami are high-density coastal cities that are highly vulnerable to SLR and flooding. Both sites include barrier islands and shallow lagoons that have experienced great anthropogenic modification—increasing their vulnerabilities. Large numbers of tourists visit both cities often by cruise ship, and in fact, tourism is their principal economic generator.

Because both cities are highly vulnerable to flooding, we examine the experiences they have with flooding and how management activities have evolved. Flooding and SLR are priority issues in Venice and Miami—although the directions the cities have chosen for adaptation differ somewhat. In the historic Venice *Acqua Alta* flooding has become much more serious and frequent in recent decades—due to regional subsidence, as well as SLR. A certain variability characterizes the natural subsidence (~1 mm/year), mainly because of the heterogeneous nature and age of the lagoon subsoil, consistently with the "geological" subsidence of the "Venice area" of 1.3 mm/year and 0.6 mm/year (Antonioli et al. 2017). Venice is still experiencing land subsidence due to human activities, mainly restoration works. However this component affects the city at a very local scale for short time intervals with rates up to 10 mm/year (Tosi et al. 2013).

The adaptation responses have emanated from all levels of government (Table 2). The municipality developed warning plans and designated elevated walkways for residents and tourists. Interventions have also included pumps, abandonment of the ground floors of some buildings, wetland creation and restoration, beach nourishment, seawalls, and, most recently, the adoption of a hightech experimental solution of mobile sea barriers (MoSE) at the three inlets. Most of these interventions can be adapted to the situation in Miami (Table 3). In terms of lessons learned, however, the MoSE project, designed almost four decades ago over which measurable SLR has occurred, has failed to integrate new information about SLR into its evaluation of impacts. As a result, projections suggest that the gates may be closed more often than not. Essentially, with future SLR, the MoSE will become an extremely costly and unacceptable intervention.

In Miami awareness and concern about SLR is recent but growing rapidly. Initial efforts to address the threats have begun at the county and city levels with little direct political and financial support from the national and state levels (with the exception of beach renourishment projects). However, actual implementation of adaptive measures is minimal to date. South Florida opted for a high-tech engineering solution to flooding over half a century ago with the Central and Southern Florida Project for Flood Control and is now attempting to remedy the resultant environmental damage with the Greater Everglades Ecosystem Restoration Plan (CERP). This flood control infrastructure project reduced the potential of the ecosystem to respond to climate change. Moreover, the comprehensive package of restoration projects initially failed to consider climate change and SLR. This situation has now begun to change, but the linkages between adaptive management of Everglades restoration and resilience of coastal MDC to SLR have yet to be fully developed.

Adaptation strategies have involved numerous governmental levels in both cases. Initial activity in Miami largely involves planning goals with little actual implementation—although the relatively wealthy and progressive City of Miami Beach has begun to elevate some streets, install pumps, and approve new construction regulations. Recent experiences with devastating hurricanes (Andrew 1992 and Irma 2017), as well as king tide flooding events that have drawn much media attention, appear to have begun to create sensitivity in the region to scenarios of impacts from SLR in the coming decades (Wachinger et al. 2013; Treuer et al. 2018). Numerous town hall meetings, citizen workshops, and media events have elevated the discussion of the issue. This increasing awareness may help to overcome short-term vision and "wait-and-see" attitudes. Nevertheless, Miami's adaptation responses to date illustrate the "low-regrets incremental approach" described by Butler et al. (2016). Local governments are hesitant to overadapt given the uncertainties of SLR magnitude, timeframe, location of impact, and potential success of adaptation measures.[11] However, as communities, such as Miami Beach, begin to experience impacts of SLR, they become more concerned about not adapting and begin to adopt legally enforceable policies. This could offer an important lesson for Venice, which lacks a public outreach process to facilitate the growth of awareness.

Apparently, the "techno" approach of Venice suggests some negativities, while *the increasing public mobilization in Miami is noteworthy*. Our analysis of the two cities points out that there are other interventions that are worth evaluating. Therefore, more questions arise: *What has worked well at each location and do the current long-term management strategies incorporate adaptation*?

For the historical Venetian city the interventions achieved both in Venice (e.g., elevation of the urban center, alarms in real time, etc.) and along the barrier islands, such as nourishment and restoration of seawalls have worked well. Concerning adaptation to flooding and SLR, all the debates today are related to MoSE and the discussion is absent about the future of the barrier islands (Lido and Pellestrina) and the economic and environmental vulnerabilities that Venice may face by 2050 or 2100 in light of a 50–100 cm rise in sea level. *In short, Venice has overrelied on the large experimental infrastructure alternative and has failed to incorporate adaptive management. To effectively implement adaptive management it must overcome its institutional fragmentation constraints*. In this light, Venice's experience today is somewhat similar to Miami's seven decades ago with the construction of the Central and Southern Florida Project for Flood Control and the initial Everglades Restoration Project from two decades ago.

The Miami Beach nourishment project, initiated in 1975 has certainly been a successful measure, demonstrating the importance of continuing long-term intervention, which has not occurred in Venice. However, the geological setting of Miami and vulnerability to hurricane storm surges makes the adoption of mobile sea barriers similar to those in Venice impractical (Table 2).

Both cities illustrate that adaptative management strategies to SLR present scientific/engineering issues, as well as significant ecological and socio-political challenges. Adaptive approaches must integrate the best available technologies along with current information about the environmental health of the ecosystem, residents and communities, and political realities.

Venice demonstrates that, while new defense technologies have the potential to reduce vulnerability and diversify management tools, technical solutions in themselves are not necessarily the sole panacea. Rather, it is necessary to integrate the best technical measures into a strategic context that also considers the environmental, social and economic issues specific to any coastal area (Zanuttigh 2011). The lagoon is a continuously evolving system that responds

[11] Some debate whether South Florida is rising, falling, or essentially stable, or additionally, whether SLR rates in South Florida differ from current or predicted rates of global SLR. Communities in Florida can more or less use the global/eustatic SLR estimates for their local planning purposes. Florida may be sinking at a rate of about -0.5 ± 1.6 mm/year. This very preliminary value of -0.5 mm/year with its very large uncertainty of ± 1.6 mm/year, should be viewed very cautiously, but a sinking Florida is in general agreement with geophysical models of Earth's changing shape due to post-glacial rebound from the last ice age (Maul 2008).

rapidly to human activities. As such, the long-term health and viability of this important system is contingent upon *sound and effective coastal area management* that should be an outcome of an integrated vision and participatory and adaptive approach (Suman et al. 2005). Given the complex nature of how ecosystems function, great care is required in planning any intervention. While the MoSE infrastructure should protect the city infrastructure, serious questions arise whether it will benefit the lagoon ecosystem, the morphological evolution of coast, and the broad suite of Venice Lagoon uses and resources. We question whether Venice and its lagoon will be more resilient to exceptional high tides after the MoSE barriers are completed in 2020–2022. The analogy to Miami is whether the region´s flood control projects have been beneficial to Biscayne Bay resources and whether they have created a Biscayne Bay and southeast Florida that are more resilient to SLR.

Miami's situation today creates an excellent opportunity for innovation—not only regarding adaptation strategies and also the possibility of linking Everglades restoration projects to SLR adaptation—but also in communication and outreach strategies by government officials, academia, NGOs, and the media. Conversation is focusing on new technologies that might be implemented allowing Miami to continue to exist despite SLR. These concepts include parks as water storage areas, floating homes, and increasing dependence on water transport. Some attention is beginning to identify critical infrastructure and historical structures that must be protected, as well as less "important" and more vulnerable areas that may have to be abandoned. Perhaps Miami may be able to turn the challenges it faces into opportunities and be able to develop expertize in adaptation techniques that could be used elsewhere. The decision-making process appears to be transparent and open to all interested and affected parties. This multiple approach is a good example that could be transferred to Venice, as well as to other coastal cities. Miami needs to learn from Venice´s diverse efforts (high-tech, shoreline protection, ecosystem restoration, urban adaptations)—while Venice needs to recognize that lack of coordination can produce numerous problems, such as excessively complicating the decision-making process instead of simplifying it.

A crucial question is funding for the adaptive measures. Adaptation in both cities has been costly and will be even more expensive in the future. Although some question the usefulness of the MoSE, for which €4.5 billion have already been invested, most people believe that the project should not be abandoned. In addition, the estimates for the maintenance and management of the system are around €100–150 million/year. In Miami recent models estimate the costs of adaptation (shoreline armoring, beach renourishment, abandoned properties, elevation of land and structures) through 2100 to SLR and additionally SLR combined with storm surge, but similar estimates for Venice and barrier islands Lido and Pellestrina are absent. Adaptation costs in Miami rank the highest of any US city—$51 billion to adapt to SLR and $130 billion to adapt to SLR and storm surge (Neumann et al. 2015). Recent research by Treuer et al. (2018) indicates that Miami residents may be willing to pay higher taxes to fund adaptation measures. For example, in November 2017 City of Miami voters approved a general obligation bond of $400 million, half of which will pay for SLR mitigation and flood prevention projects, such as pumping stations and stormwater system upgrades (Magill 2017; Smiley 2017). However, in Miami the absence of direct support for adaptive measures at the national and state levels is noteworthy and a serious limitation.

Meanwhile, in Venice the funding issue has been addressed at the highest government level with a series of Special Laws that provided significant funding for major infrastructure projects intended to safeguard the historic region. For the future it is likely that this procedure will continue. The national government continued to provide high levels of funding for the most recent measures being implemented in Venice.

Ideally, financial support should emanate from all levels of government in a coordinated fashion. Treuer et al. (2018) raise a potential funding challenge; if wealthy coastal residents abandon their homes and coastal real estate values plummet, shrinking local revenues may not be capable of funding adaptive measures. Banks may cease approving mortgages for homes or insurers may refuse to issue policies (Flavelle 2017). Nevertheless, coastal housing values in Miami and Venice are high and appear to be increasing.[12]

Conclusions

Although we recognize that adaptation techniques and planning processes are very site-specific (Thead 2016), we conclude that both cities offer valuable lessons that maybe useful in other locations. We have examined and compared the management strategies implemented in both cities to counteract the effects of the SLR and noted adaptive responses utilized in Venice and Miami that might have applicability elsewhere, as well as their limitations and challenges (Tables 2 and 3, "Transferability").

[12] Both Venice and Miami potentially may lead to "environmental justice" or "climate justice" scenarios. In Miami, wealthier residents residing in vulnerable coastal properties may displace poorer residents living today on higher ground. Venice has already begun to experience a dramatic exodus of local residents to the less vulnerable mainland as living costs and real estate values soar in the historic city. These are topics that are ripe for future social science research.

For more than a millenium, Venice has co-existed with the sea and created and adopted numerous interventions to confront flooding and the aqueous milieu, as a result of an alliance between humans and the sea. Those interventions, such as seawall construction, beach nourishment, canal dredging and wetland creation, have been already implemented in both sites. After the 1966 flood Venice began to diversify its adaptive responses, mainly by adopting adaptation measures to protect its assets, i.e., elevation of low lying parts, raising sea walls, upgrading water drainage system, and dune construction and elevation. Most of these interventions are completely transferable to Miami and other cities. Currently the over-reliance of Venice on the high-tech experimental mobile barriers (MoSE) above other approaches raises many questions. Imposition of a single solution may consume the majority of financial resources. This intervention is not suitable for Miami due to its different geological setting. Although from an engineering perspective the mobile gates may ultimately be successful in Venice, with rising sea levels the adverse impacts on the lagoonal ecosystem and many stakeholders may be profound.

South Florida adopted a high-tech solution to its "threat" of flooding over seven decades ago with its flood control projects. Although successful at flood control, the resulting environmental damage has been profound. Since the turn of the century Everglades restoration projects have begun to address the ecosystem damage but without consideration of climate change. In a sense, the Miami high-tech case is "reverse Venice". Recent discussion of adaptation of some restoration projects (construction of forward pumps on existing coastal salinity control structure to better regulate groundwater levels and control saltwater intrusion; increased freshwater flows to coastal wetlands) may assist urbanized MDC adapt to SLR. In Miami today concern about the risk that SLR presents, in combination with hurricanes and resulting storm surges, has greatly increased. Yet, to date, the region has relied primarily on dune/beach restoration as a protective measure. The severe degradation of central and northern Biscayne Bay ecosystems, as well as the porous limestone geological substrate, both constrain adaptive measures that Miami may adopt. The MDC area can learn from Venice and develop information systems to inform the general public regularly on extreme weather events and the threat of flooding. In Venice, several redundant systems operate, such as mobile-phone messages alerts, newspaper advertisements, sirens, and maps with safe exit routes.

It appears that in the two cases presented here adaptation to SLR has yet to lead to structural transformation of the governance institutions that would allow the systems to progress towards more effective outcomes. In particular, planned adaptation in both cities remains limited by the lack of ecosystem-based approaches, the lack of horizontal (sectoral) and vertical (inter-governmental) integration, and severe funding constraints. Technical, financial, legal, and political support for adaptation must emanate from all levels of government in a coordinated fashion for change to occur. Miami perhaps has greater institutional coordination and high levels of public outreach and discussion, but Venice has displayed greater long-term efforts at all governmental levels. The adaptation measures must be well-coordinated at all institutional levels and based on principles of good governance (transparency, public participation, efficiency, equity, lack of corruption).

Policy Recommendations

From our examination of the cases of SLR adaptation in Venice and Miami, we offer the following policy recommendations:

1. **Plan for redundancy**. Coastal cities should not rely soley on one intervention, but must adopt numerous measures that may appear redundant. Nature-based adaptation measures, such as coastal wetland creation and enhancement, as well as optimal hydrological management, must be important components of the package (Tobey et al. 2010; Fernandino et al. 2018).
2. **Adopt long-term planning horizons**. Venice and Miami should take climate change and long-term planning into greater account and use it to create a greater sense of shared responsibility about the future. Distant futures of 30 or 50 years are beyond the normal planning period for governments, developers, the insurance industry, or homeowners, but good coastal management in light of climate change requires this longer planning horizon (Tobey et al. 2010). Moreover, uncertainty exists with respect to the extent of the vulnerability and possible impacts (Spence et al. 2012, Weber 2016; Treuer et al. 2018). Despite uncertainties about the rate of SLR, vulnerable coastal cities need to address rising seas "yesterday". Delay will only close options, lead to greater losses, and result in greater future costs.
3. **Utilize principles and methodologies of Integrated Coastal Management (ICM)**. Long-term decisions must integrate systems—economic, environmental, social, and institutional. In a sense this calls for the principles and strategies of Integrated Coastal Management. This is necessary so governments and the private sector can examine their investment decisions spatially. ICM facilitates coordination among economic sectors and the authorities that regulate them ("sectoral integration"), as well as cooperation between different governmental levels ("vertical

integration"). ICM also demands broad stakeholder participation in the decision-making process.

4. **Monitor social impacts**. We must carefully track to societal impacts of SLR. In Miami, SLR may increase competition for lower-valued properties at higher elevations, thus making it more difficult for socially vulnerable groups to respond to SLR and potentially displacing them. The gentrification of the historic center of Venice is partly due to the expenses involved in adapting to flooding. This raises the issue of "climate justice".
5. **Utilize adaptive management**. As the many uncertainties lessen (SLR rate, location, timing, success of adaptation measures, ecosystem repsonses, population growth, hurricane and storm surge incidents, etc.), adaptation planning and projects must be flexible and altered as necessary to take into account new information and changed circumstances.
6. **Integrate ecosystem-based natural adaptive approaches**. In South Florida, Everglades restoration plans must integrate climate change impacts with an adaptive management strategy to provide benefits for coastal ecosystems to counteract SLR impacts. Potentially some options will couple with SLR adaptive response in MDC, such as increasing freshwater flow to support coastal mangrove forests as important buffers against SLR and protect peat soils and to control groundwater levels and saltwater intrusion. Similarly, the Venice experience once emphasized wetland creation as a means to address SLR. In short, societies must utilize ecosystem-based approaches when adapting to SLR – considering the wider regional ecosystem impacts to implemented measures and the contributions that the ecosystems themselves can offer.
7. **Create scientific information in vehicles that the public can clearly understand**. Credible scientific information to reduce the range of uncertainty (SLR rates, locations, timeframe) will increase political motivation to act and decrease opposition to over-adaptation.
8. **Evaluate the success of adaptation measures**. After investing funds and efforts to implement adaptation plans and actions, we must evaluate whether they have been successful. This will indicate whether plans and actions need to be altered to increase likelihood of success.
9. **Critically evaluate the ecosystem impacts of large-scale "high tech" solutions**. Often large-scale expensive technologically-based solutions (MoSE and the Central and South Florida Project for Flood Control) cause the loss of ecological resilience and cause an ecological crisis. These "solutions" must integrate the latest climate change information, and decisionmakers must understand their environmental costs.

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Compliance with ethical standards

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References

Ammerman AJ, McClennen CE (2000) Saving Venice. Science 289:1301–1302

Antonioli FM, Anzidei A, Amorosi V, Lo Presti G, Mastronuzzi G, Deiana G, De Falco G, Fontana A, Fontolan G, Lisco S, Marsico A, Moretti M, Orrù PE, Sannino GM, Serpelloni E, Vecchio A (2017) Sea-level rise and potential drowning of the Italian coastal plains: flooding risk scenarios for 2100. Quat Sci Rev 158:29–43. https://doi.org/10.1016/j.quascirev.2016.12.021

Araos M, Berrang-Ford L, Ford JD, Austin SE, Lesnikowski A (2016) Climate change adaptation planning in large cities: a systematic global assessment. Environ Sci Policy 66:375–382. https://doi.org/10.1016/j.envsci.2016.06.009

Ariza E, Lindeman KC, Mozumder P, Suman DO (2014) Beach management in Florida: assessing stakeholder perceptions on governance. Ocean Coast Manag 96:82–93. https://doi.org/10.1016/j.ocecoaman.2014.04.033

Aumen NG, Havens KE, Best GR, Berry L (2015) Predicting ecological responses of the Florida Everglades to possible future climate scenarios: Introduction. Environ Manag 55:741–748

Banks KW, Riegl BM, Shinn EA, Piller WE, Dodge RE (2007) Geomorphology of the southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA). Coral Reefs 26:617–633

Bloetscher F, Romah T (2015) Tools for assessing sea level rise vulnerability. J Water Clim Change 6:181–190

Bloetscher F, Polsky C, Bolter K, Mitsova D, Palbicke Garces K, King R, Carballo IC, Hamilton K (2016) Assessing potential impacts of sea level rise on public health and vulnerable populations in Southeast Florida and providing a framework to improve outcomes. Sustainability 8:315. https://doi.org/10.3390/su8040315

Bock Y, Wdowinski S, Ferretti A, Novali F, Fumagalli A (2012) Recent subsidence of the Venice Lagoon from continuous GPS and interferometric synthetic aperture radar. Res Lett. https://doi.org/10.1029/2011GC003976

Butler WH, Deyle RE, Mutnansky C (2016) Low-regrets incrementalism: land use planning adaptation to accelerating sea level rise in Florida's coastal communities. J Plan Educ Res 36(3):319–332

Camuffo D, Bertolin C, Schenal P (2017) A novel proxy and the sea level rise in Venice, Italy, from 1350 to 2014. Clim Change 143:73–86. https://doi.org/10.1007/s10584-017-1991-3

Caniato G (2005) Between salt and fresh water. In: Fletcher CA, Spencer T (eds.) Flooding and environmental challenges for Venice and its lagoon: state of knowledge. Cambridge University Press, London UK, p 7–14

Carbognin L, Teatini P, Tomasin A, Tosi L (2009) Global change and relative sea level rise at Venice: what impact in term of flooding. Clim Dyn. https://doi.org/10.1007/s00382-009-0617-5

Carraro C, Sgobbi A (2008) Climate change impacts and adaptation strategies In Italy. An economic assessment FEEM Nota di Lavoro, 6:28

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield M, Milne G, Nerem R, Nunn P et al. (2013) Sea level change. PM Cambridge University Pres, Cambridge, UK

Comerlati A, Ferronato M, Gambolati G, Putti M, Teatini P (2003) Can CO_2 help save Venice from the sea? EoS Trans Am Geophys Union 84:546–553

Comerlati A, Ferronato M, Gambolati G, Putti M, Teatini P (2004) Saving Venice by sea water. J Geophys Res 109:F03006. https://doi.org/10.1029/2004JF000119

Corcoran WT, Johnson E (2005) Climate of North America. In: Oliver JE (ed) Encyclopedia of world climatology. Springer, Dordrecht, The Netherlands, p 525–534

De Sherbinin A, Schiller A, Pulsipher A (2007) The vulnerability of global cities to climate hazards. Environ Urban 19(1):39–64. https://doi.org/10.1177/0956247807076725

De Conto RM, Pollard D (2016) Contribution of Antarctica to past and future sea-level rise. Nature 531:591–597. https://doi.org/10.1038/nature17145

Fagherazzi S, Carniello L, D'Alpaos L, Defina A(2006) Critical bifurcation of shallow microtidal landforms in tidal flats and salt marshes Proc Natl Acad Sci USA 103:8337–8341. https://doi.org/10.1073/pnas.0508379103

Favero G (2014) Venezia dopo Venezia: economia e demografia urbana nel novecento (in italian). Lab Ital 15:79–89

Fernandino G, Elliff CI, Silva IR (2018) Ecosystem-based management of coastal zones in face of climate change impacts: challenges and inequalities. J Environ Manag 215:32–39. https://doi.org/10.1016/j.jenvman.2018.03.034

Flavelle C (2017) The nightmare scenario for Florida´s coastal homeowners. Bloomberg News. https://www.bloomberg.com/news/features/2017-04-19/the-nightmare-scenario-for-florida-s-coastal-homeowners

Fiaschi S, Wdowinski S (2016) The contribution of land subsidence to the increasing coastal flooding hazard in Miami Baeach. In: 2nd international workshop on coastal subsidence, Venice (Italy) 30 May–1 June 2016

Finkl CW, Warner MT (2005) Morphologic features and morphodynamic zones along the inner continental shelf of Southeastern Florida: an example of form and process controlled by lithology. J Coast Res, Spec Issue 42:79–96

Finkl CW, Restrepo-Coupe N (2007) Potential natural environments based on pedological properties in the coastal conurbation of subtropical southeast Florida. J Coast Res 23(2):317–349

Finkl CW, Andrews JL (2008) Shelf geomorphology along the southeast Florida Atlantic continental platform: barrier coral reefs, nearshore bedrock, and morphosedimentary features. J Coast Res 24(4):823–849

Finkl CW (2014) East Florida's Barrier Islands: natural vs. man-made. http://coastalcare.org

Fletcher CA, Spencer T (2005) Flooding and environmental challenges for Venice and its lagoon: state of knowledge. Cambridge University Press

Fleming E, Payne J, Sweet W, Craghan M, Haines J, Hart JF, Stiller H, Sutton-Grier A (2018) Coastal effects. In: Reidmiller DR, Avery CW, Easterling RD, Kunkel KE, Lewis KLM, Maycock TK, Stewart BC (eds) Impacts, risks, and adaptation in the United States: Fourth National Climate Assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA, p 322–352. 10.7930/NCA4.2018.CH8

Foster AB (1983) Biscayne National Park. In: Harris A, Tuttle E (eds) Geology of national parks. Kendall/Hunt Publishing Company, Dubuque, Iowa, p 443–452

Fu X, Gomaa M, Deng Y, Zhong-Ren P (2017) Adaptation planning for sea level rise: a study of US coastal cities. J Environ Plan Manag 60(2):249–265. https://doi.org/10.1080/09640568.2016.1151771

Gambolati G, Teatini P, Ferronato M, Strozzi T, Tosi L, Putti M (2009) On the uniformity of anthropogenic Venice uplift. Terra Nova 21:467–473. https://doi.org/10.1111/j.1365-3121.2009.00903.x

Ghose T (2013) The 20 Cities Most Vulnerable to Flooding. Live Science

Goodell J (2017) The water will come: rising seas, sinking cities, and the remaking of the civilized world. Little, Brown, and Company, New York, NY

Grunwald M (2007) The swamp: the Everglades, Florida, and the politics of paradise. Simon and Schuster, New York, NY

Hallengatte S, Green C, Nicholls RJ, Corfee-Morlot J (2013) Future flood losses in major coastal cities. Nat Clim Change 3:802–806. https://doi.org/10.1038/nclimate1979

Hanson S, Nichols R, Ranger N, Hallegarte S, Corfee-Morlot J, Herweijer C, Chateau C (2011) A global ranking of port cities with high exposure to climate extremes. Clim Change 104:89–111

Hauer ME, Evans JM, Mishra DR (2016) Millions projected to be at risk from sea-level rise in the continental United States. Nat Clim Change 6:691–695

Hay CC, Morrow E, Kopp RE, Mitrovica JX (2015) Probabilistic reanalysis of twentieth-century sea-level rise. Nat Clim Change 517:481–484

Hoffmeister JE (1982) Land from the sea: the geologic story of South Florida. University of Miami Press, Coral Gables, Florida

Hughes JD, White JT (2016) Hydrologic conditions in urban Miami-Dade County, Florida, and the effect of groundwater pumpage and increased sea level rise on canal leakage and regional groundwater flow (Version1.2, July 2016). U.S. Geological Survey Scientific Investigations Report 2014-5162. 175 pp. https://doi.org/10.3133/sir20145162

Idealista (2015) Indice annuale 2015 dei prezzi delle abitazioni di seconda mano (2015 annual price index for second-hand housing). https://st3.idealista.it/news/archivie/2015-12/indice_annuale_prezzi_2015.pdf.

Indirli M, Knezic S, Borg RP, Kaluarachchi Y, Ranguelov B, Romagnoli F, Rochas C (2014) The ANDROID case study; Venice and its territory: a general overview. Procedia Econ Financ 18:837–848. https://doi.org/10.1016/S2212-5671(14)01009-0

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team Pachauri RK, Meyer LA (eds)]. IPCC, Geneva, Switzerland, p 151

Juhola S, Westerhoff L (2011) Challenges of adaptation to climate change across multiple scales: a case study of network governance in two European countries. Environ Sci Policy 14:239–247

Kaluarachchi Y, Indirli M, Ranguelov B, Romagnoli F (2014) The ANDROID case study; Venice and its territory: existing mitigation options and challenges for the future. Procedia Econ Financ 18:815–824. https://doi.org/10.1016/S2212-5671(14)01007-7

Keahey J (2002) Venice against the sea: A City Besieged. St. Martin's Press

Keim BD, Muller RA, Stone GW (2007) Spatiotemporal patterns and return periods of tropical storm and hurricane strikes from Texas to Maine. J Clim 20:3498–3509

Kirwan ML, Megonigal JP (2013) Tidal wetland stability in the face of human impacts and sea-level rise. Nature 504:53–60. https://doi.org/10.1038/nature12856

Koch MS, Coronado C, Miller MW, Rudnick DT, Stabenau E, Halley RB, Sklar FH (2015) Climate change projected effects on coastal foundation communities of the Greater Everglades using a 2060 scenario: need for a new management paradigm. Environ Manag 55:857–875. https://doi.org/10.1007/s00267-014-0375-y

Kopp RE, Kemp AC, Bittermann K, Horton BP, Donnelly JP, Gehrels WR, Hay CC, Mitrovica JX, Morrow ED, Rahmstorf S (2016) Temperature-driven global sea-level variability in the Common Era Proc Natl Acad Sci USA 113:E1434–E1441. http://www.pnas.org/content/113/11/E1434

Korten T (2015) Gov. Rick Scott's ban on climate change term extended to other state agencies. Miami Herald, 11 March 2015

Kulp S, Strauss BH (2017) Rapid escalation of coastal flood exposure in US municipalities from sea level rise. Clim Change 142:477–489

Lambeck K, Antonioli F, Anzidei M, Ferranti L, Leoni G, Scicchitano G, Silenzi S (2011) Sea level change along the Italian coast during the Holocene and projections for the future. Quat Int 232:250–257

Lentz EE, Thieler ER, Plant NG, Stippa SR, Horton RM, Gesch DB (2016) Evaluation of dynamic coastal response to sea-level rise modifies inundation likelihood. Nat Clim Change 6:696–701. https://doi.org/10.1038/NCLIMATE2957

Lodge TE (2010) The Everglades handbook: understanding the ecosystem. CRC Press, Boca Raton, Florida

Magill B (2017) Miami taxpayters asked to foot the bill to protect the city from climate change. Climate Liability. https://www.climateliabilitynews.org/2017/08/16/miami-florida-climate-change-sea-level-rise-adaptation/

Malmstadt JC, Elsner JB, Jagger TH (2019) Risk of strong hurricane winds to Florida cities. J Appl Meteorol Climatol 49:2121–2132

Mancuso F (2014) Building on water: the surprising expedients that made possible the birth and growth of Venice. Corte del Fontego Editore, Venice

Marsico A, Lisco S, Lo Presti V, Antonioli F, Amorosi A, Anzidei M, Deiana G, De Falco G, Fontana A, Fontolan G, Moretti M, Orrù PE, Serpelloni E, Sannino G, Vecchio A, Mastronuzzi G (2017) Flooding scenario for four Italian coastal plains using three relative sea level rise models. J Maps 13(2):961–967. https://doi.org/10.1080/17445647.2017.1415989

Maul GA, (2008) Florida's changing sea level in Shoreline.The Florida Beach and Shore Preservation Society. http://www.fsbpa.com/documents/0508Shoreline.pdf

MAV-CVN (2013) Gestione sostenibile dell'identità lagunare veneziana (Sustainable management of the Venetian lagoon identity), C.1. 14, Doc. 70786-REL-T003. 0., 230 pp

Maxwell K, Julius S, Grambsch A, Kosmal A, Larson L, Sonti N (2018) Built environment, urban systems, and cities. In: Reidmiller DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, Stewart BC (eds) Impacts, risks, and adaptation in the United States: fourth national climate assessment, Volume II. U.S. Global Change Research Program, Washington, DC, USA, 10.7930/NCA4.2018.CH11 438–478

Melillo JM, Richmond TTC, Yohe GW eds (2014) Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. https://doi.org/10.7930/J0Z31WJ2

Miami-Dade County (2014a) Climate change action plan. https://www.miamidade.gov/greenprint/pdf/climate_action_plan.pdf

Miami-Dade County (2014b) Sea level rise task force report and recommendations. http://www.miamidade.gov/planning/library/reports/sea-level-rise-report-recommendations.pdf

Miami-Dade County. Department of Regulatory and Economic Resources (2017). Adopted Components: Comprehensive Development Master Plan for Miami-Dade County, Florida. https://www.miamidade.gov/planning/cdmp-adopted.asp

Milne GA, Gehrels WR, Hughes CW, Tamisiea ME (2009) Identifying the causes of sea-level change. Nat Geosci 2:471–478

Molinaroli E, Guerzoni S, De Falco G, Sarretta A, Cucco A, Como S, Simeone S, Perilli A, Magni P (2009a) Relationships between hydrodynamic parameters and grain size in two contrasting transitional environments: the Lagoons of Venice and Cabras, Italy. Sediment Geol 219:196–207

Molinaroli E, Guerzoni S, Sarretta A, Masiol M, Pistolato M (2009b) Thirty-year changes (1970–2000) in bathymetry and sediment texture recorded in the lagoon of Venice sub-basins, Italy. Mar Geol 258:115–125

Munaretto S, Huitema D (2012) Adaptive comanagement in the Venice lagoon? An analysis of current water and environmental management practices and prospects for change. Ecol Soc 17 (2):19. https://doi.org/10.5751/ES-04772-170219

National Hurricane Center (2019) Estimated return period in years for hurricanes passing within 50 nautical miles of various locations on the U.S. coast. https://www.nhc.noaa.gov/climo/#cp100

NRDC (National Academy of Sciences) (2012) Disaster resilience: a national imperative. The National Academies Press, Washington, D.C., 10.17226/13457

Neumann JE, Emanuel K, Ravela S, Ludwig L, Kirshen P, Bosma K, Martinich J (2015) Joint effects of storm surge and sea-level rise on US Coasts: New economic estimates of impacts, adaptation, and benefits of mitigation policy. Clim Change 129:337–349

Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Chateau J, Muir-Wood R (2007) Ranking of the world's cities most exposed to coastal flooding today and in the future. OECD Environment Working Paper No. 1 (ENV/WKP(2007)1)

Nicholls RJ (2011) Planning for the impacts of sea level rise. Oceanography 24(2):144–157. https://doi.org/10.5670/oceanog.2011.34

NOAA/AOML (Atlantic Oceanographic and Meteorological Laboratory) (2009) All U.S. Hurricanes (1851–2008). Miami:, http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512008.txt, Accessed Aug 2016

Nungesser M, Saunders C, Coronado-Molina C, Obeysekera J, Johnson J, McVoy C, Benscoter B (2015) Potential effects of climate change on Florida's Everglades. Environ Manag 55:824–835

Obeysekera J, Browder J, Hornung L, Harwell MA (1999) The natural South Florida system I: climate, geology and hydrology. Urban Ecosyst 3:223–244

Obeysekera J, Barnes J, Nungesser M (2015) Climate sensitivity runs and regional hydrologic modeling for predicting the response of the Greater Florida Everglades Ecosystem to climate change. Environ Manag 55:749–762. https://doi.org/10.1007/s00267-014-0315-x

Panza GF, Bisignano D, Romanelli F (2014) Does MoSE cope with inland tsunamis hazard? arXiv:1406.2821 [physics.geo-ph] https://arxiv.org/ftp/arxiv/papers/1406/1406.2821.pdf

Passeri DL, Hagen SC, Medeiros SC, Bilskie MV, Alizad K, Wang D (2015) The dynamic effects of sea level rise on low-gradient coastal landscapes: a review. Earth's Future 3:159–181. https://doi.org/10.1002/2015EF000298

Patricola CM, Wehner MF (2018) Anthropogenic influences on major tropical cyclone events. Nature 563:339–346. https://doi.org/10.1038/s41586-018-0673-2

Pfeffer WT, Harper JT, Neel SO (2008) Kinematic constraints on glacier contribution to 21st-century sea-level rise. Science 321 (5894):1340–1343. https://doi.org/10.1126/science.1159099

Pilkey OH, Dixon KL (1996) The corps and the shore. Island Press, Washington, D.C.

Pielke RA, Gratz J, Landsea CW, Collins D, Saunders MA, Musulin R (2008) Normalized hurricane damages in the United States: 1900–2005. Nat Hazards Rev 29(1):29–42

Precht WF, Miller SL (2007) Ecological shifts along the Florida Reef Tract: the past as a key to the future. In: Aronson RB ed. Geological approaches to coral reef ecology. Springer, Berlin, p 237–312

Rahmstorf S, Foster G, Cazenave A (2012) Comparing climate projections to observations upto 2011. Environ Res Lett 7:044035. https://doi.org/10.1088/1748-9326/7/4/044035

Rahmstorf S, Box JE, Feulner G, Mann ME, Robinson A, Rutherford S, Schaffernicht E (2015) Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nat Clim Change 5:475–480. https://doi.org/10.1038/NCLIMATE2554

Ramieri E, Hartley A, Barbanti A, Duarte Santos F, Gomes A, Hilden M, Laihonen P, Marinova N, Santini M (2011) Methods for assessing coastal vulnerability to climate change, European Topic Centre on Climate Change Impacts, Vulnerability and Adaptation (ETC CCA) Technical Paper, Bologna (IT), p 93

Rao K (2016) Climate change and housing: Will a rising tide sink all homes? Zillow document. Zillow Research. https://www.zillow.com/research/climate-change-underwater-homes-12890/

Roggero M, Fritsch O (2010) Mind the costs: rescaling and multi-level environmental governance in Venice lagoon. Environ Manag 46:17–28. https://doi.org/10.1007/s00267-010-9449-7

Rusconi A (2016) La gestione della laguna con la soppressione del Magistrato alle Acque. In: Salvaguardia domani, oltre il MOSE. Sala S.Leonardo 4/11/2016 (in italian)

Sarretta A, Pillon S, Molinaroli E, Guerzoni S, Fontolan G (2010) Sediment budget in the Lagoon of Venice, Italy. Cont Shelf Res 30:934–949. https://doi.org/10.1016/j.csr.2009.07.002

SFWMD (2018) 2018 Lower east coast water supply plan update. https://www.sfwmd.gov/sites/default/files/documents/2018_lec_plan_planning_doc.pdf

Sklar FH, Chimney MJ, Newman S, McCormick P, Gawlik D, Miao SL, McVoy C, Said W, Newman J, Coronado C, Crozier G, Korvela M, Rutchey K (2005) The ecological-societal underpinnings of Everglades restoration. Front Ecol Environ 3 (3):161–169

Smiley D (2017) Miami gets $200 million to spend on sea rise as voters pass Miami Forever bond. Miami Herald. http://www.miamiherald.com/news/politics-government/election/article183336291.html

Southeast Florida Regional Climate Change Compact Counties (2012) A region responds to a changing climate: Regional Climate Action Plan.

Spence A, Poortinga W, Pidgeon N (2012) The psychological distance of climate change. Risk Anal 32:957–972

Stammer D (2008) Response of the global ocean to Greenland and Antarctic ice melting. J Geophys Res 113:C06022. https://doi.org/10.1029/2006JC004079

Suburban Stats (2018) https://suburbanstats.org/population/florida/list-of-counties-and-cities-in-florida#CK

Suman D, Guerzoni S, Molinaroli E (2005) Integrated coastal management in the Venice lagoon and its watershed. Hydrobiologia 550:251–269

Sweet W, Kopp R, Weaver C, Obeysekera J, Horton R, Thieler ER, Zervas C (2017) Global and regional sea level rise scenarios for the United States. Silver Spring, Maryland

Teatini P, Tosi L, Strozzi T, Carbognin L, Cecconi G, Rosselli R, Libardo S (2012) Resolving land subsidence within the Venice Lagoon by persistent scatterer SAR interferometry. Phys Chem Earth 40-41:72–79

Thead EA (2016) Sea level rise: risk and resilience in coastal cities. The Climate Institute http://climate.org/wp-content/uploads/2016/10/Erin-Sea-levels.pdf

Tobey J, Rubinoff P, Robadue D, Ricci G, Volk R, Furlow J, Anderson G (2010) Practicing coastal adaptation to climate change: lessons from integrated coastal management. Coast Manag 38:317–335

Torresan S, Critto A, Rizzi J, Marcomini A (2012) Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. Nat Hazards Earth Syst Sci 12(7):2347–2368

Tosi L, Teatini P, Strozzi T (2013) Natural versus anthropogenic subsidence of Venice Sci Rep 3:2710. https://doi.org/10.1038/srep02710

Tosi L, Teatini P, Strozzi T, Da Lio C (2014) Relative land subsidence of the Venice coastland, Italy. Eng Geol Soc Territ 4:171–173

Treuer G, Broad K, Meter R (2018) Using simulations to forecast homeowner response to sea level rise in South Florida: will they stay or will they go? Glob Clim Change 48:108–118

Trincardi F, Barbanti A, Bastianini M, Benetazzo A, Cavaleri L, Chiggiato J, Papa A, Pomaro A, Sclavo M, Tosi L, Umgiesser G (2016) The 1966 flooding of Venice: what time taught us for the future. Oceanography 29(4):178–186. https://doi.org/10.5670/oceanog.2016.87

Umgiesser G, Matticchio B (2006) Simulating the mobile barrier (MOSE) operation in the Venice Lagoon, Italy: global sea level rise and its implication for navigation. Ocean Dyn 56:320–332. https://doi.org/10.1007/s10236-006-0071-4

UCS (Union of Concerned Scientists) (2017) Encroaching tides in Miami-Dade County, Florida, UCS Fact Sheet, pp 1–10. https://www.ucsusa.org/sites/default/files/attach/2016/04/miami-dade-sea-level-rise-tidal-flooding-fact-sheet.pdf

UNESCO (2015) Report of the joint World Heritage Centre/ICOMOS/Ramsar Reactive Monitoring mission to the property of Venice and its Lagoon (Italy), 13–18 October 2015

UNISDR (2009) Terminology on disaster risk reduction. United Nations International Strategy for Disaster Reduction, Geneva, https://www.unisdr.org/files/7817_UNISDRTerminologyEnglish.pdf

Valle-Levinson A, Dutton A, Martin JB (2017) Spatial and temporal variability of sea level rise hot spots over the eastern United States. Geophys Res Lett 44:7876–7882. https://doi.org/10.1002/2017GL073926

Varrani A, Nones M (2017) Vulnerability, impacts and assessment of climate change on Jakarta and Venice. Int J River Basin Manag https://doi.org/10.1080/15715124.2017.1387125

Vergano L, Nunes P (2007) Analysis and evaluation of ecosystem resilience: an economic perspective with an application to the Venice lagoon. Biodivers Conserv 16:3385–3408. https://doi.org/10.1007/s10531-006-9085

Vergano L, Umgiesser G, Nunes P (2010) An economic assessment of the impact of the MOSE barriers on Venice port activity. FEEM Sustainable Development Series, Report 17/2010 35 pp

Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. Proc Natl Acad Sci USA 106:51

Wachinger G, Renn O, Begg C, Kuhlicke C (2013) The risk perception paradox—implications for governance and communication of natural hazards. Risk Anal 33:1049–1065

Wanless HR, Parkinson RW, Tedesco LP (1994) Sea level control on stability of wetlands. In: Davis SM, Ogden JC (eds) Everglades: the ecosystem and its restoration. St. Lucie Press, Delray Beach, Florida, p 199–223

Wdowinski S, Bray R, Kirtman BP, Wu Z (2016) Increasing flooding hazard in coastal communities due to rising sea level: case study of Miami Beach, Florida. Ocean Coast Manag 126:1–8

Weber EU (2016) What shapes perceptions of climate change? New research since 2010. Wiley Interdiscip Rev Clim Change 7:125–134. https://doi.org/10.1002/wcc.377

Weiss JL, Overpeck JT, Strauss B (2011) Implications of recent sea level rise science for low-elevation areas of coastal cities of the conterminous U.S.A. Clim Change 105:635–645

Zaggia L, Lorenzetti G, Manfè G, Scarpa GM, Molinaroli E, Parnell KE, Rapaglia JP, Gionta M, Soomere T (2017) Fast shoreline erosion induced by ship wakes in a coastal lagoon: field evidence and remote sensing analysis. PLoS ONE 12:1–23. https://doi.org/10.1371/journal.pone.0187210

Zanuttigh B (2011) Coastal flood protection: what perspective in a changing climate? The THESEUS approach. Environ Sci Policy 14:845–863. https://doi.org/10.1016/j.envsci.2011.03.015

Zervas C (2009) Sea Level Variations of the United States 1854-2006. NOAA Technical Report NOS CO-OPS 053, 75p, Appendices A–E. https://tidesandcurrents.noaa.gov/publications/Tech_rpt_53.pdf

Zhang K (2011) Analysis of non-linear inundation from sea-level rise using LIDAR data: a case study for South Florida. Clim Change 106:537–565. https://doi.org/10.1007/s10584-010-9987-2