Chapter 2
Managing Risks in Louisiana's Rapidly Changing Coastal Zone

Donald F. Boesch

2.1 Introduction

While both strategically important to the nation and bountiful in so many ways, Louisiana's coastal zone has always been difficult to access and risky to live in. Much of its landscape consists of wetlands: bottomland forests, swamps, marshes, and mangroves that are continuously, seasonally, tidally, or meteorologically inundated. Most of what passes for dry land is just a few feet above sea level and subject to episodic flooding from the mighty rivers – the Mississippi and the Atchafalaya – that flow through it, locally intense rainfall, and ocean storm surges. Powerful tropical storm winds and associated tornadoes pose additional weather threats to human communities and the built environment.

The complex and dynamic water world that is coastal Louisiana constrains where people live and how they move across the landscape. Early European settlers were confronted by devastating river floods almost immediately after their arrival, and, despite the flood protection systems and elevated infrastructure that were developed over the next 300 years, the threats of rising waters and damaging winds have remained a fact of life for south Louisiana communities and enterprises. Both have moved and adapted in response to extreme weather events in ways that have decreased, but sometimes increased, their vulnerability.

While extreme weather events challenge social resilience, i.e., the ability of communities to cope with and adapt to stresses and disruptions, these transient phenomena are experienced against a background of powerful secular (in the sense of long duration) trends that further test this resilience. Particularly since the mid-twentieth century, the coastal landscapes have been rapidly deteriorating as a net result of geological subsidence, human interference with the processes that build and sustain

D. F. Boesch (✉)
University of Maryland Center for Environmental Science, Annapolis, MD, USA
e-mail: boesch@umces.edu

S. Laska (ed.), *Louisiana's Response to Extreme Weather*,
Extreme Weather and Society, https://doi.org/10.1007/978-3-030-27205-0_2

the coastal landscape, and substantial modification of its hydrology. Moreover, the body of science has made it abundantly clear that human activities are warming Earth's atmosphere and oceans and changing its climate in ways that are enormously consequential for south Louisiana, including accelerated sea-level rise, intensification of precipitation, and more powerful tropical cyclones.

This chapter sets the biophysical stage for the case studies and perspectives on social resilience that follow in this volume. First, I provide an overview of the geomorphic fabric of coastal Louisiana, how it affects human society, and how humans have modified it. I then summarize the kinds of flooding threats, the notable disasters that have occurred, and the flood protection systems that have been created. From there I move to the strategic coastal protection and restoration that is being planned and implemented in Louisiana, before considering global climate change as a threat multiplier that will also have to be addressed. Finally, I conclude with some perspectives on the implications of the rapidly changing coastal landscape for social resilience within these other coastal regions of the United States.

2.2 Geological and Human Development

2.2.1 Creation and Evolution of Coastal Landscapes

The people of south Louisiana live on the youngest land in the United States, except for a few small purchases built on barrier islands or filled shallows. As the massive glaciers rapidly melted at the end of the last ice age about 20,000 years ago, the level of the world's oceans rose by about 120 m (400 feet) over 12,000 years (Stanford et al. 2010). Large areas of coastal land were submerged becoming continental shelves, and shorelines retreated until sea level reached a relatively stable point about 7000 years before the present. The level of the world's oceans was nearly constant or slowly declining during the period of European settlement of North America (Kemp et al. 2011). Today, residents of most US coastal areas today live along those same shorelines. But in Louisiana the escarpments marking those 7000-year-old shorelines are now far inland from the Gulf Coast, north of Lake Pontchartrain, and just below Baton Rouge and Lafayette (Saucier 1994).

When the rapid rise in sea level finally slowed, a large marine embayment stood between Baton Rouge and Lafayette into which the Mississippi and other great rivers flowed. With the inland march of the sea finally stalled, sediments discharged by these rivers began to fill up the embayment and then reclaim the shallow Gulf of Mexico by protruding successive delta lobes (Blum and Roberts 2012; Bentley et al. 2016). As a delta lobe grew through the deposition of river-borne sediments, it created branching distributaries, some of which left remnants as today's bayous. Sediments were deposited at river mouths and via overbank flooding, crevasse formation, and infilling of older distributaries (Roberts 1997). As flow gradients diminished, the river sought a quicker path to the sea, breaking out to begin a new delta

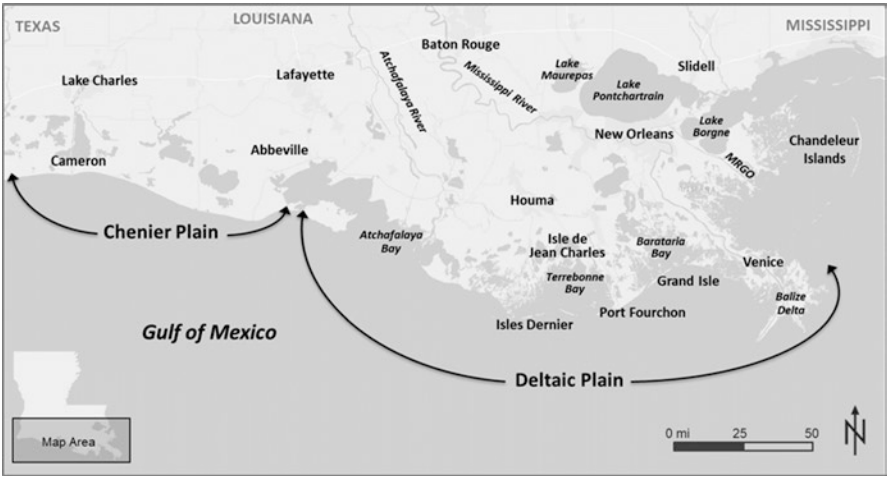

Fig. 2.1 Map of southern Louisiana showing important cities, water bodies, and geologic provinces. (Base map courtesy of Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community)

lobe. The river's flow did not switch all at once, and the flow was often conveyed down both the old and the new delta.

Eventually, five or six major deltas – depending on how they are distinguished – were formed over the past 4600 years (Roberts 1997; Bentley et al. 2016) with their remnants constituting the landscapes of the Mississippi Deltaic Plain (Fig. 2.1) from Abbeville in the west to the border of the state of Mississippi in the east. The easternmost St. Bernard Delta was active between 2800 and 1000 years ago, extending beyond today's Chandeleur Islands and enclosing large coastal embayments, creating today's lakes Maurepas, Pontchartrain, and Borgne (Fig. 2.2). The earlier Teche Delta (3500–2800 years before present) and Lafourche Delta (1000–300 years ago) filled in the landscapes between the present Atchafalaya and Mississippi rivers. The towns lying along today's bayous Teche and Lafourche sit on natural levee deposits of the past main channels of the great river. The presently active Plaquemines Delta below New Orleans is only 750 years old, and its iconic extension to the edge of the continental shelf in the form of a bird's foot (the Balize Delta) has only existed for about 550 years or since shortly before Columbus discovered America.

A new delta complex began to emerge in Atchafalaya Bay with the 1973 flood (Roberts et al. 2003), more than 20 years after the Atchafalaya River had captured more than 30% of the flow of the Mississippi and Red rivers and its vast swamp basin filled with sediments (Piazza 2014). With the flow since 1963 regulated under law at 30% of water of the lower Mississippi, two delta lobes have been building in the Atchafalaya Bay along central coastal Louisiana.

As the Mississippi river deltas switched back and forth to build southeastern Louisiana, sediments discharged into the Gulf or released from eroding shorelines drifted to the west along the coast under the influence of currents and waves.

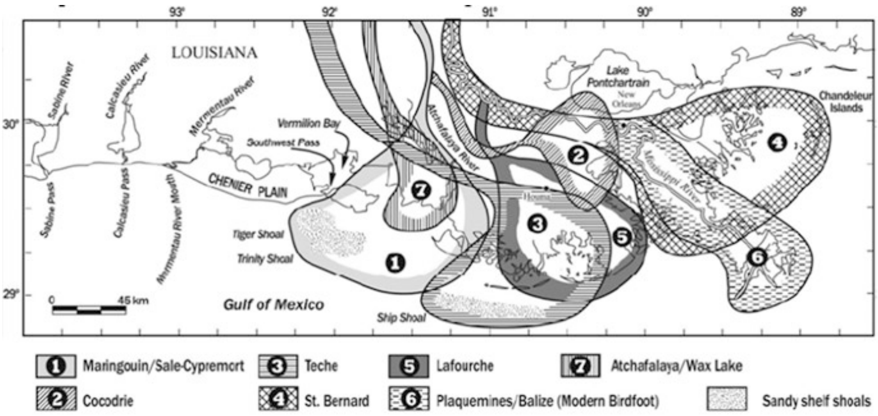

Fig. 2.2 Delta lobes of the Lower Mississippi River Deltaic Plain numbered in chronological order of formation. (Image source: McBride et al. 2007)

This also resulted in the development of new land in the form of a strandplain characterized by old sandy or shelly beach ridges running parallel to the coast and separated by marshes and swamps (Penland and Suter 1989; Bentley et al. 2016). This Chenier Plain (Fig. 2.1), referring to the oak (chêne in French) trees growing on the ridges, extends for 200 miles along the Louisiana coast from Vermillion Bay to Galveston, Texas. Throughout much of southwestern Louisiana, the Chenier Plain extends inland about 30 miles from the coast.

Once deprived of the river sediments that nourish them, the landforms of both the Mississippi Deltaic Plain and Chenier Plain deteriorate under the effects of geological subsidence caused by compaction of the accumulated sediments and the exposure to forces of the waves, tides, and surges of the Gulf of Mexico. The outer edge of the delta erodes, and the sand deposits remaining are reshaped as flanking barrier islands and the inter-distributary wetlands open up as estuarine bays, such as present-day Barataria and Terrebonne bays (Blum and Roberts 2012). Still, tidal wetlands are sustained for centuries by trapping eroding sediments and growing upward as the soil beneath them subsides (Reed 1989). The skeletal framework of distributary ridges and barrier islands protect interior wetlands from marine forces and saltwater intrusion (Salinas et al. 1986). Coastal ecosystems, consisting of tidal wetlands and channels and shallow bays, are enormously productive of fish and wildlife during this phase (Twilley et al. 2016). Eventually, the barrier island arc becomes detached from land by a broad sound, such as is the present condition for the Chandeleur Islands to the east (Fig. 2.1). Finally, all that remains of the barrier islands are submerged sandy shoals located miles offshore on the inner continental shelf of the Gulf of Mexico. Subsiding and eroding, the deterioration of landforms is exorable until a subsequent delta revisits the area.

The Chenier Plain also underwent periods of land building, when the river delta had moved toward the west, and then erosion, when the delta shifted farther away toward the east (Penland and Suter 1989; Bentley et al. 2016). The beach ridges consisting of coarser sediments were formed during these erosional periods. Deprived of delta sediments, wetlands in the Chenier Plain are currently subsiding at a much faster rate that they are able to vertically accrete soils (Jankowski et al. 2017). In contrast, sediment supplies to the Deltaic Plain wetlands allow them to accrete more soil.

Since human habitation, the expansive coastal zone of Louisiana has always been young, low lying, wet, and highly dynamic, thus posing challenges to human survival, health, prosperity, and social fabric.

2.2.2 Human Settlement and Its Risks

Native Americans first occupied the dynamic Mississippi Deltaic Plain about 2000 years ago (McIntire 1958). They left remnants of their occupation in the form of shell middens and earthen mounds located near river channels or distributaries or on barrier ridges. The mounds accommodated their refuge during occasional river and estuarine flooding, providing the community resilience required for living in this bountiful but challenging wet landscape.

Although the establishment of the outpost of Natchitoches preceded it by 4 years, the site of New Orleans was selected for the first French settlement in south Louisiana in 1718 because it controlled the lower Mississippi River and also afforded access via Bayou St. John to Lake Pontchartrain (Colton 2005). In making this decision, Sieur de Bienville was well aware of the frequent risks of river flooding, but, as geographer Peirce Lewis noted, New Orleans was the "inevitable city" in the "impossible" site. The early city was built on the natural levees of the Mississippi River that rose no more than 12 feet above sea level. The colonists did not have to wait long as floods the next spring slowed construction (Campanella 2008). Then, in September 1722, hurricane winds knocked down shoddily built structures, wiping the haphazard slate clean for laying out the street grid that exists in the Vieux Carré today.

Also that year, construction of the first artificial levees to protect from river floods began. Still, frequent floods inundated farms that were spreading along the banks of the river above New Orleans, destroying crops and damaging homes. Moreover, floodwaters reaching the backswamps beyond the natural levees cause backwater flooding of relatively developed areas otherwise protected by river levees. Colonial laws in 1728 and 1743 required landowners to build and maintain levees along their properties fronting the river. By 1763 these stretched 50 miles above the city (Colton 2005). By the time Louisiana became a state in 1812, artificial levees extended from as far north as the Red River to below New Orleans along the west bank and from Baton Rouge to below New Orleans on the east bank. Still, there were occasional urban inundations during the late eighteenth and early nineteenth century due to breaches in the levees fronting the city or its suburbs or resulting from crevasses farther upriver that filled the backswamp and inundated the city from the rear. The most notable example was the 1849 crevasse at Sauvé Plantation that displaced 12,000 of New Orleans' 116,000 residents, the city's worst flood until Hurricane Katrina in 2005 (Campanella 2008).

Nonetheless, the increasing effectiveness of artificial levees along the lower river provided security that allowed expanded development of New Orleans and across the river along the west bank. Paradoxically, it also elevated the threat of river flooding by reducing outlets for floodwaters either over the levees or through natural channels, thus raising the stage of the river for a given flow rate. This realization initiated a nearly century-long debate over whether flood protection should continue to rely on a levee-only strategy or also incorporate floodways to lower the river levels (Barry 1997).

This debate came to a head following the Great Mississippi River Flood of 1927 that inundated 26,000 square miles from Cairo, Illinois, to the Gulf, displacing a half-million people and threatening New Orleans (Barry 1997). The Flood Control Act of 1928 shifted policies from levees- only to include not only massive levees and floodwalls but also control structures and spillways, all under the responsibility of the federal government. Today, high stages in the lower Mississippi are constrained by opening the Bonnet Carré Spillway, sending water to Lake Pontchartrain, or the West Atchafalaya or Morganza floodways, sending water down the Atchafalaya Basin.

As human settlements expanded from along the Mississippi River, across the Atchafalaya Basin to the land of the Attakapas in southwestern Louisiana, and down the bayous of the Mississippi Deltaic Plain, occasional river floods also threatened them. Settlements along Bayou Teche were often flooded, particularly during the 1927 flood (Bernard 2016). Bayou Lafourche carried a portion of the Mississippi flow until it was dammed in 1904. However, there are only modest, if any, artificial levees along these waterways; flooding has been mitigated through various flow control structures.

As development began to extend into the backswamps, canals and levees were constructed to facilitate drainage. Eventually, this required the removal of rainwater by perpetually operated pumps. The dewatering of the highly organic soils of these former swamps resulted in the loss of soil volume due to oxidation and enhanced subsidence (Colten 2005; Dixon et al. 2006; Campanella 2008). Consequently, much of the inhabited area of New Orleans and its suburban parishes lies below sea level, although that land was originally at or slightly above sea level when development began. Similar loss in elevation occurred where there were failed attempts to drain wetlands for conversion to agricultural polders. The resulting urban and agricultural bowls became more susceptible to rainfall-driven flooding and reliant on large-capacity pumps that can keep up with heavy rainfall.

Even before wetland drainage and development, bald cypress and other swamp and bottomland trees were mostly cut down for timber. The loss of tree cover, coupled with drainage and navigation canals (such as the Carondelet and New Basin canals through which commodities were transported into New Orleans), increased the susceptibility of urban areas to winds, tidal incursions, and storm surges. Many of these older canals were filled in or fitted with gates to reduce the risk of flooding resulting from tidal and storm surges; however, massive navigational channels were constructed perpendicular to the coast during the latter half of the twentieth century

(Gulf Intracoastal Waterway, Mississippi River-Gulf Outlet or MRGO, Houma Navigation Canal, and Calcasieu Ship Channel to Lake Charles). They have hastened saltwater intrusion and the resulting loss of cypress swamps and facilitated propagation of tropical storm surges toward population centers distant from the coast (Freudenburg et al. 2009b).

2.2.3 Broader Coastal Deterioration

The area of land, including wetlands, in the coastal zone of Louisiana more or less continuously expanded after sea level stabilized about 7000 years ago. Surely, abandoned delta lobes subsided and eroded, but new lands created in newly active delta lobes countered the resulting losses. The Chenier Plain lost ground when eastern delta lobes were most active but gained ground when the river switched it course to the west. The multi-millennial trend in slow net land gain was dramatically reversed during the twentieth century, with best estimates of land losses during the late 1970s of 32 square miles per year (83 km^2/y), now slowed to 11 square miles per year (28 km^2/y). Altogether, over 2000 square miles of land were lost between 1932 and 2016 (Couvillion et al. 2017).

Changes in the Mississippi-Atchafalaya River Basin are responsible for some of the losses. The present Balize Delta is perched on the edge of the continental shelf and deposits much of its terminal load of alluvial sediments into deep waters of the Gulf of Mexico, bypassing the coastal zone where these sediments could be held in wetlands and on shorelines. Erosion associated with land clearing within the Basin during European expansion increased the river's sediment load during the nineteenth century, but then dams constructed throughout the catchment by the middle of the twentieth century trapped sediments upstream. That, coupled with improved soil conservation practices, has resulted in a reduction by half of the suspended sediment of the lower Mississippi since the 1950s (Meade and Moody 2010; Heimann et al. 2011) to loads probably less than those occurring when major delta lobes were being built (Chamberlain et al. 2018). More of the combined river flow began to travel down through the Atchafalaya Basin after Henry Shreve cleared the Great Raft of logs clogging the Red and Atchafalaya rivers in the 1830s. This extensive basin trapped a large share of the riverine sediments transported such that a new delta did not begin to emerge in Atchafalaya Bay until 1973 (Piazza 2014).

Additionally, constraining the flow of the lower Mississippi with its channel by effective flood protection levees and closure of distributary channels almost all the way to its mouth have prevented the broad contribution of riverine sediments to the subsiding wetlands and shallow waters. Indeed, this was foreseen back as far as 1897, when an article on the Mississippi River Delta published in the *National Geographic* (Corthell 1897) stated: "no doubt the great benefit to the present and two or three following generations accruing from a complete system of absolutely protective levees excluding the flood waters entirely from the great areas of the lower delta country, far outweighs the disadvantages to future generations from the subsidence of the Gulf delta lands below the level of the sea and their gradual abandonment due to this cause." Unfortunately, we have already reached the fourth generation without a Plan B.

In addition to changes in the supply and distribution of sediment subsidies required to sustain the coastal plain landscapes, other human activities have resulted in land, and particularly wetland, losses. These include the kind of wetland "reclamation" and dredge and fill activities that caused wetland losses elsewhere, but particularly notable in Louisiana have been the extensive dredging of canals through the coastal wetlands. This includes not only the larger canals constructed for commercial or industrial navigation mentioned earlier but also myriad smaller canals mainly dredged for access to drilling sites and laying pipelines associated with oil and gas production. Dredged canals were seldom backfilled and generally do not fill in naturally by themselves. The spoil banks left interfere with the tidal water-level fluctuations needed for healthy, accreting wetland soils. The wetland losses associated with these indirect hydrological effects may be several times greater than the direct dredge and fill effects, potentially accounting for most of the observed wetland loss (Turner 1997), although this has been questioned (Day et al. 2000). Independent estimates suggest that the net effect of oil and gas canals has been responsible for at least 30% and possibly 50% of the wetland losses during the second half of the twentieth century (Penland et al. 1996). Needless to say, these estimates were strongly contested by the oil and gas industry, and the industry's responsibility has been caught up in political debates and judicial cases concerning liability for the costs of addressing the coastal wetland crisis.

Scientific evidence is also compelling that withdrawals of oil, gas, and associated briny water have increased subsidence rates and thus wetland loss rates in the vicinity of shallow oil and gas fields, such as those in Terrebonne Parish (Morton et al. 2006). The slowdown in fluid withdrawals from these old fields may be the principal cause of the reduction in the rate of subsidence as evidenced in the Grand Isle tide gauge record (Kolker et al. 2011). Similarly, the substantial reduction in new oil and gas canal dredging may have contributed to the lower rates of coastal wetland loss in recent decades (Couvillion et al. 2017).

In aggregate, the multiple consequences of human activities have resulted in deltaic deterioration over less than a century that would take a millennium due to natural processes, such as subsidence, delta lobe abandonment, and erosion due to winds and hurricanes. After the scale and rapidity of coastal wetland loss became apparent in the early 1980s, a succession of plans and programs were developed to slow, if not reverse, the losses. The primary motivation was the restoration of the unique coastal environments and the important natural resources they produce. Protection of coastal communities from flood risks proceeded on a separate, and sometimes competitive, or even antagonistic, track. The disastrous effects of Hurricane Katrina and Rita in 2005 made it clear that deterioration of coastal environments had increased storm surge risks and threatened the very existence of many coastal communities. This realization has required a more integrated and simultaneous approach to planning and implementation of the protection of society and restoration of the environment (Day et al. 2007). Projections of future land losses (Fig. 2.3) and increased flood risks as coastal landscapes continue to degrade (Fig. 2.4) have prompted the integrated planning discussed in Sect. 2.6.

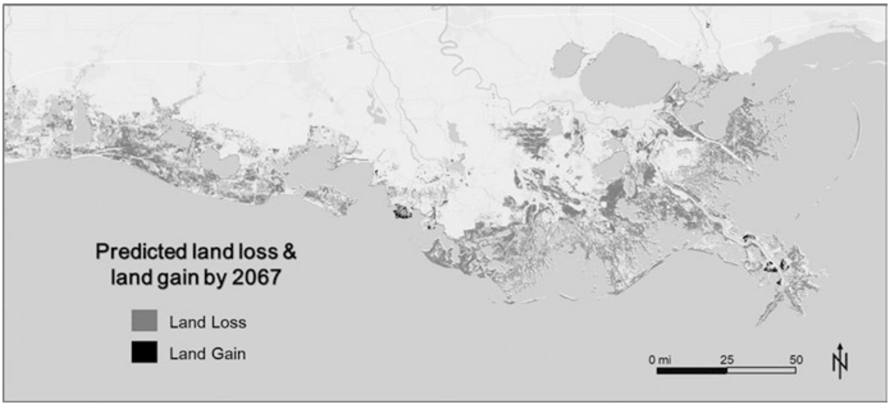

Fig. 2.3 Predicted land change by 2067 along the Louisiana coast. (Land change data retrieved from the Coastal Restoration & Protection Authority [CPRA]; base map courtesy of Esri, HERE, Garmin, © OpenStreetMap contributors, and the GIS user community)

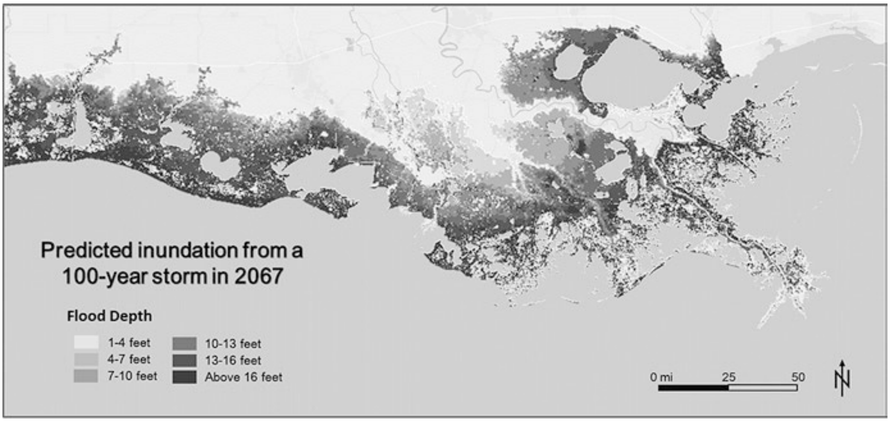

Fig. 2.4 Predicted inundation depths along the Louisiana coast resulting from a 100-year storm in 2067. (Flood depth data retrieved from CPRA Master Plan Data Viewer)

2.3 Extreme Weather Risks

2.3.1 South Louisiana's Climate

Beyond the risks of flooding from the Mississippi and Atchafalaya rivers, there are extreme weather risks associated with coastal Louisiana's climate. South Louisiana has a humid subtropical climate in large part due to the influence of the warm Gulf of Mexico. It has long, hot, humid summers and short, mild winters. Average annual rainfall increases from west to east, from 57 inches (145 cm) in Lake Charles to 64 inches (163 cm) in New Orleans. Rainfall is prevalent during all months, with somewhat higher precipitation in the summer and winter. In summer the prevailing southerly winds provide moist, subtropical weather often favorable for afternoon thunderstorms, sometimes resulting in flooding risks caused by extreme rainfall.

Typically, the most extreme rainfall (as much as 20 inches in a day) has been associated with tropical storms. Even greater rainfall amounts (40–60 inches) occurred in the Houston area when Hurricane Harvey stalled offshore in late summer of 2017 (van Oldenborgh et al. 2017). A similarly stalled depression dumped up to 31 inches of rain in the Amite and Comite river basins near Baton Rouge just a year earlier (van der Wiel et al. 2017). The devastation of these two flood events acted as a wake-up call that, in addition to river floods and tropical storm surges, Gulf Coast communities might be increasingly vulnerable to more extreme rainfall events caused by global warming. The connection with climate change is discussed later but has called into question the adequacy of existing floodplain management and drainage infrastructure for present and future conditions of extreme precipitation. Areas under forced drainage are particularly vulnerable. In August 2017 almost 10 inches of rain resulted in extensive flooding, damage, and inconvenience in New Orleans, which worsened because some of the city's drainage pumps were offline and the drains and catch basins had not be adequately maintained.

Extreme temperatures also pose both social and environmental risks. Historically, New Orleans experiences an average of 75 days per year with temperatures 90 °F or above. Prolonged heat waves or very warm and humid conditions that coincide with power outages caused by tropical storms, such as happened in New Orleans after Hurricane Katrina, pose very serious human health risks. Periods of very hot and dry conditions have been associated with sudden dieback of salt marsh, the so-called Brown Marsh phenomenon that affected over 100,000 ha of salt marsh in the Mississippi Deltaic Plain in the year 2000 (Visser et al. 2002). On the other hand, hard freezes during the winter can kill or stress black mangrove shrubs that characterize some tidal wetlands very near the Gulf of Mexico. Conversely, expansion of mangroves into salt marsh vegetation has been observed following a succession of years without killing freezes (Perry and Mendelssohn 2009).

2.3.2 Tropical Cyclones

Of course, coastal Louisiana is notoriously at risk from the storm surges and damaging winds of tropical cyclones, including depressions, tropical storms, and hurricanes. As was mentioned earlier, the first residents of New Orleans were introduced to the ferocity of a hurricane just 4 years after the city's founding. Over the period of record, an average of about one tropical storm or hurricane per year met landfall along the Louisiana coast (Roth 2010), but there have been periods where there are none (recently 2014, 2015 and 2016) and other years where have been two or more in a year. The occurrence of two powerful storms each in 2005 (Katrina and Rita) and in 2008 (Gustav and Ike) is etched in the memory of many south Louisiana residents.

A strong hurricane hit New Orleans in 1837. While it flooded marshes adjacent to Lake Pontchartrain, the city itself was buffered from the storm surge because of the largely intact marshes and swamps separating it from the lake, except around the two navigation canal basins (Campanella 2008). Another notable hurricane struck the Isles Derniers in Terrebonne Parish in 1856, killing more than 218 vacationers enjoying the relief of beach breezes without any warning of the approaching storm (Dixon 2009). Another hurricane in 1893 killed more than 2000 residents of Cheniere Caminada, between Grand Isle and Port Fourchon. Survivors abandoned that settlement, moving north to other communities farther up Bayou Lafourche (Brasseaux and Davis 2017).

In 1947 a late summer hurricane struck New Orleans with over 100-mile-per-hour winds, pushing modest storm surges inundating outlying areas to the east and in Jefferson Parish (Roth 2010). In response to this storm and one the following year, there was additional levee construction along the Lake Pontchartrain shore and adjacent marshes. In June 1957, Hurricane Audrey came ashore near the Sabine Pass, creating a 12-foot storm surge that destroyed the town of Cameron, causing damage 25 miles inland and killing 526 people in Louisiana alone.

In 1965, Hurricane Betsy had its landfall at Grand Isle with 160-mile-per-hour winds. Facilitated by the Gulf Intracoastal Waterway and the recently completed Mississippi River Gulf Outlet, its large storm surge reached Lake Pontchartrain and breached floodwalls to inundate much of the Gentilly, the Ninth Ward of New Orleans, and the neighboring suburbs in St. Bernard Parish. In response, Congress enacted the Flood Control Act of 1965 that put the federal government in the business of storm protection by raising and constructing levees and strengthening floodwalls to provide Category 3-level storm protection (Campanella 2008). Now protected, areas of New Orleans East subsequently experienced an explosive growth in residences and businesses, in a "levee effect" that paradoxically increases future damages by luring homebuyers into floodplains (Freudenburg et al. 2009a). Despite the protection by levees, the newly developed areas were not protected adequately from interior flooding due to poorly designed drainage (Baxter 2014).

Hurricane Katrina in 2005 had effects that in many ways mirrored those of Betsy, with a massive storm surge on the east side of the river assisted by the navigation canals and meeting little resistance from the by now nearly nonexistent cypresses swamps and deteriorated marshes. Post-Betsy levees in St. Bernard Parish and New Orleans East were overtopped, and floodwalls failed along the Inner Harbor Navigation Canal and the ungated drainage outfall canals penetrating into the city. This inundated not only the Ninth Ward, including post-Betsy developments in New Orleans East, and St. Bernard Parish but also the 80% of the city beyond the high ground along the Mississippi River (McQuaid and Schleifstein 2006). Because of the extent, persistence and devastation of the saltwater flooding and loss of power and other services, most New Orleans residents had to relocate away from the city. Many never returned. Altogether, 1836 people died directly as a result of Hurricane Katrina (Bevan et al. 2008), 1577 of them in Louisiana, and Katrina's total property losses have been estimated at $125 billion (Vigdor 2008).

There is a very voluminous literature on the events, effects, causes, responses, and lingering impacts of the Hurricane Katrina disaster. To the audience of this volume, I recommend books by the veteran reporters McQuaid and Schleifstein (2006) and the deeply experienced social scientists Freudenburg, Grambling, Laska, and Erikson (2009a). Both books emphasize that the disaster was as much human-caused as natural.

Less than a month after Katrina in 2005, a second highly powerful storm struck coastal Louisiana when Hurricane Rita came ashore near the Texas border. It caused major damage to communities in Cameron Parish and elsewhere along the southwest Louisiana coast, damaged freshwater wetlands in the Chenier Plain by inundating them with saltwater, and resulted in storm surge felt along the entire Louisiana coast. Some areas affected by Katrina were flooded again.

During September 2008 Hurricane Gustav came ashore in Terrebonne Parish, and Hurricane Ike had its landfall near the mouth of Galveston Bay just 2 weeks later, flooding and re-flooding many coastal Louisiana communities from Cameron to Plaquemines parishes. Two million people evacuated from south Louisiana in advance of Gustav's arrival, with its storm surge even splashing over newly installed floodwalls in eastern New Orleans.

During the decade of 2000s, Louisiana experienced the effects of a record number of tropical cyclones, including six hurricanes and six tropical storms. These disasters, particularly the Hurricane Katrina disaster, prompted national and regional responses to strengthen storm surge protection and to integrate protection with the rehabilitation of the degrading landscape. These responses are reviewed in the next two sections, starting first with the congenital Louisiana challenge of flood protection.

2.4 Flood Protection and Its Limits

2.4.1 Mississippi and Atchafalaya Rivers

The lower Mississippi River flood protection system developed after the Great Mississippi River Flood of 1927 has remained secure and effective despite some challenges. The biggest test came during the 1973 flood when Old River Control Structure was very close to failing when a scour hole developed under the Low Sill structure, causing part of the structure to collapse.

That year the Corps of Engineers opened the nearby Morganza Floodway for the first time since its construction in 1954, and up to 300,000 cubic feet per second (8500 m^3/s) of flow was diverted down the Atchafalaya Basin to reduce the flood risks for Baton Rouge and New Orleans. The Morganza Floodway was not opened again until 2011, when up to 173,000 cubic feet per second (4900 m^3/s) of flow was diverted. Opening the Morganza Floodway was also seriously considered in 2017. The Corps has had to open the Bonnet Carré Spillway more frequently after Hurricane Katrina than was typical since it was built in 1934: in 2008, 2011, 2016, 2018, and 2019 (twice).

Whether more extreme Mississippi River flows will be experienced with the changing climate remains to be seen, but multiple lines of evidence indicate that artificial channelization upstream has been the predominant cause of the amplification of flood magnitudes over the past century (Munoz et al. 2018). As the Plaquemines-Balize Delta rapidly subsides at rates exceeding 1 cm per year and the level of the Gulf rises, the elevation gradient of the river decreases, slowing flows and inducing sedimentation that further constrains the channel cross-section (Blum and Roberts 2009; Little and Biedenharn 2014). Conversely, because of the diminished elevation gradient, higher storm surges from the Gulf can propagate farther upstream.

During Hurricane Katrina, storm surges overtopped not only the levees intended to protect lower riverside communities in Plaquemines Parish all the way to Venice from hurricane storm surges but also the taller levees protecting from river flooding. With continued subsidence and accelerating sea-level rise, the ability to protect these lower river communities will diminish. The iconic bird-foot distributary system that has characterized the mouth of the Mississippi River over the last 500 years will at some point cease to exist, thus requiring the engineering of a new navigational access to America's great inland waterway. Already, an increasing proportion of the river's flow is being lost above the head of the passes that constitute the toes of the bird's foot, complicating the challenge of maintaining the main navigational entrance by high-velocity flows.

While planning for the eventuality of a new navigational entrance to the river has been put off by the Corps of Engineers and State pending completion of scientific and engineering investigations of lowermost river, a design competition called Changing Course (2016) produced some intriguing concepts, all of which would be expensive and require substantial changes in where and how people live downriver from New Orleans.

2.4.2 Greater New Orleans

Informed by extensive forensic analyses of Hurricane Katrina, the Corps of Engineers launched an ambitious effort to repair and enhance the flood protection system for greater New Orleans with a network of storm surge levees, strengthened floodwalls, surge barriers, and pumps. Constructed at a cost of $14.5 billion, the system is designed to provide near-complete protection from 100-year storm surge events and to significantly reduce flooding from a 500-year event. The levees were designed to be resilient in that they would not wash away as they did during Katrina, thus overtopping would only last a few hours rather than days. The new system includes a massive barrier east of the city to block storm surges coming from Lake Borgne and the Gulf Intracoastal Waterway and Mississippi River-Gulf Outlet (MRGO). MRGO was also closed to traffic and an armored, earthen dam placed across it.

2.4.3 Exurban Coastal Regions

The exurban areas around greater New Orleans and smaller cities throughout coastal Louisiana have not been afforded that same level of protection. Storm surge from Hurricane Isaac in 2012 raised water levels in Lake Pontchartrain, causing flooding in parts of LaPlace, upriver from New Orleans, and Slidell, across Lake Pontchartrain. Many former residents of New Orleans and St. Bernard Parish had moved to these communities after Hurricane Katrina and were flooded a second time. Extensions of levees, floodwalls, and gates to enhance the protection of communities along the east bank of the Mississippi from Lake Pontchartrain storm surge and communities on the west bank from Barataria Basin storm surge are proposed, but only one has been funded after decades of seeking funding, a $760-million project to protect the east bank of St. John the Baptist Parish and parts of neighboring St. Charles and St. James parishes (Bacon-Blood 2018). Even more expensive are the Morganza-to-the-Gulf system and the Lake Pontchartrain Barrier discussed in the next section on protection and restoration planning.

2.5 Coastal Protection and Restoration Planning

2.5.1 Evolution of Comprehensive Planning

Although there had been some earlier legislative or policy efforts to address the degradation of Louisiana's coastal environments, public and political attention to the problem began to be galvanized with the 1980 assessment that the state may be losing as much as 50 square miles per year of its coastal lands (Gagliano et al. 1981). In 1990, Louisiana members of Congress succeeded in enacting the Coastal Wetland Planning, Protection, and Restoration Act (CWPPRA) that produces a relatively modest, but steady, source of dedicated funding for wetland restoration. An implementation plan was developed, but it was clear that a more comprehensive framework was required that takes into account the dynamic geologic realities of the Louisiana coast (Boesch et al. 1994). In 1998 a state task force produced a strategic plan entitled *Coast 2050: Toward a Sustainable Coastal Louisiana* (Louisiana Coastal Wetlands Conservation and Restoration Task Force 1998).

The year prior to Hurricane Katrina, the Corps of Engineers and the State released the Louisiana Coastal Area (LCA) Ecosystem Restoration Study (USACE 2004), and in 2007 the Congress authorized an overarching program that is, much like the Everglades Restoration Program, comprised of an array of separately authorized projects and the first of the intended specific projects. However, the effects of Hurricane Katrina made it clear that coastal restoration and storm surge protection had henceforth to be evaluated, planned, and executed in consort (Day et al. 2007). In response, the Corps of Engineers undertook the Louisiana Coastal Protection and Restoration Study (USACE 2009), and the State formed the Coastal Protection and

Restoration Authority (CPRA). CPRA produced its first Coastal Master Plan in 2007 and refined the plan in 2012 and again in 2017.

2.5.2 Louisiana's Comprehensive Master Plan for a Sustainable Coast

The latest Louisiana Comprehensive Master Plan for a Sustainable Coast (CPRA 2017; also referred to as the Coastal Master Plan) was approved by the state legislature in June of 2017. The Coastal Master Plan is the product of an extraordinary array of technical and economic analyses that considered varying assumptions about future conditions, resource constraints, and a multitude of project proposals. There was also extensive public consultation throughout its development and after its release prior to its ratification.

The Coastal Master Plan is intended to serve as a blueprint for the State's efforts both in flood protection and ecosystem restoration over the next 50 years. The Plan recognizes the reality of a smaller footprint of coastal lands in the future; thus "restoration" in this context is more of the rehabilitation of functions that sustain the ecosystem and maintain as much land as possible than the return to some previous condition. Implementation of the component projects would require $50 billion both from state resources and through federal appropriations and partnerships. The plan includes some 124 projects that could build or maintain more than 800 square miles of land and reduce expected damages from storm surges and other flooding by a purported $83 billion annually by the year 2067 and by more than $150 billion over the full 50 years. These projects include restoration of barrier islands and headlands, sediment diversions from the two major rivers, hydrological restoration, marsh creation using dredged sediment, ridge restoration, cultivating oyster barrier reefs, shoreline protection, structural protection from floods, and nonstructural risk reduction.

The Coastal Master Plan recognizes that not all needs are addressed by its current array of projects. More will be learned through further investigation and adaptive management of projects that are implemented. In particular, the Plan does not address the challenging questions related to lowermost Mississippi River management and how to maintain navigational access while using more of the river's water and sediment resources for restoration. Nor does it address changes in the allocation of river flow between the Atchafalaya and Mississippi river. These are issues of truly national importance that will have to be resolved.

The 2017 Coastal Master Plan places greater emphasis on coastal communities, incorporating understanding of "the cost of continued land loss and the potential effects of restoration projects on local communities, local businesses, and regional and national economies." In particular, there is a greater focus on flood risk reduction and resilience, including different types of nonstructural options and policies to help communities become more resilient.

2.5.3 Nonstructural Adaptation and Relocation

Nonstructural projects included in the Coastal Master Plan have the objective of reducing risks by floodproofing nonresidential structures, raising the elevation of residential structures, and acquisition of residential property. Although it is anticipated that some funding would be provided, all nonstructural projects are considered voluntary. Nonresidential structures in areas with projected 100-year flood depths of 3 feet or less could be renovated so they can be resistant to flood damage. Residential structures located in areas with a projected 100-year flood depth of between 3 and 14 feet could be elevated so that their lowest floors are higher than projected flood depths. Residential acquisition would be offered in areas where projected 100-year flood depths make elevation or floodproofing infeasible. The Coastal Master Plan does not contain specific relocation projects.

Residential acquisition and relocation are obviously very sensitive issues. In coastal Louisiana many residents have multigenerational ties to the places they live and extensive contemporary family and social networks. Still, the reality is that retreat of coastal inhabitants inland has been occurring for a long time, going back at least as far as the relocation of Cheniere Camanada families farther up Bayou Lafourche after the 1893 hurricane. New Orleanians relocated north of Lake Pontchartrain, to upriver communities, or to other parts of the country after Hurricanes Betsy and Katrina. Even less devastating tropical storms prompted movement away from the coast as a result of property damage, insurance settlements, and the cost of complying with new flood insurance requirements. Can this retreat be managed in a more considered manner that maintains the social fabric of communities remaining in the coastal zone or as communities move en masse? In particular, can this be accomplished for marginalized communities that are particularly vulnerable but lack financial resources and political voice?

A current test case is the planned resettlement of a community of Biloxi-Chitimacha-Choctaw people at Isle de Jean Charles, located on a shrinking ridge south of Houma, to a new location 35 miles inland near Shriever. Subsidence attributable to oil and gas withdrawals had hastened the loss of land around Isle de Jean Charles (Morton et al. 2006). The Louisiana Office of Community Development is managing the resettlement with the assistance of a $48 million grant from the US Department of Housing and Urban Development (HUD), with construction beginning in 2019. While the resettlement allows the prospect of keeping the community intact, the residents, while retaining access, will be far removed from the fishing, oyster cultivation, and trapping that have been traditionally the basis of their sustenance.

On a broader front, the State has created, from the same HUD resilience competition as the Isle de Jean resettlement, the Louisiana Strategic Adaptations for Future Environments (LA SAFE) program to assist communities to take proactive steps for adaptation to the rapidly changing coastal environments and risks (Louisiana Office of Community Development Disaster Recovery Unit 2017). The project expressly accepts that some of the most vulnerable communities will need to contemplate resettlement over the next 50 years and that migration is already occurring. Funding thus far is for community engagement and co-design, and sources have not been identified for the significant resources required for residential acquisitions and resettlement nor for the $6.1 billion specified in the Coastal Master Plan for non-structural risk reduction.

2.5.4 Implementation and Controversies

Of course, the Coastal Master Plan will require the funding, public acceptance, legal sufficiency, and engineering feasibility of its component projects. After Hurricane Katrina the federal government provided over $14.5 billion to repair and improve structural defenses against storm surge, and the State and local government have invested heavily in improving drainage. At the same time, despite the federal authorization of the LCA Ecosystem Restoration Program, only modest funding has been made available for environmental restoration. However, as a result of payments, penalties, and damage compensation stemming from the BP Deepwater Horizon oil spill that occurred in 2010, the situation has now been reversed. Approximately $8 billion is likely to be provided from these sources for use in restoration in coastal Louisiana over the next decade or so. As a consequence, the State is now advancing planning and implementation of restoration projects without federal appropriations. Meanwhile, even many Congressionally authorized structural protection projects are slowed because of the lack of federal appropriations and limited state and local funding.

Paramount among these authorized but underfunded structural protection projects is the Morganza-to-the-Gulf array of levees, floodwalls, gates, locks and pump stations stretching 98 miles across Terrebonne Parish from to Gibson to Lockport. Intended to protect population center around Houma, the project is proceeding incrementally using State and local funding. At $8.3 billion, the Morganza-to-the-Gulf protection system is the single most expensive project in the $50 billion Coastal Master Plan. However, it confronts significant challenges with regard to the level of risk reduction that would be provided and the sustainability of wetlands enclosed by the levees (Twilley et al. 2008), as well as the engineering feasibility and cost of constructing significant earthen levees across the soft and subsiding substrates of the Terrebonne Basin.

The Lake Pontchartrain Barrier at a cost of $2.4 billion faces its own challenges, including the environmental effects of constraining tidal flows into Lake Pontchartrain and increased storm surge likely to be felt along the Mississippi coast as storm surges are prevented from entering the lake. If structural protection projects are not completed, significant population centers around Houma and Slidell would face increasing risks.

While the concept of coastal restoration enjoys substantial public support, individual projects face opposition from some members of the public or confront issues raised in environmental reviews for permits. Prominent among these projects are diversions of sediment from the rivers to slow the loss and even build new wetlands by recreating the processes that built the Mississippi Deltaic Plain in the first place. Sediment diversions are thought by most coastal scientists to be foundational elements of any credible restoration strategy (Boesch et al. 1994; Day et al. 2007). However, some shrimpers, oyster growers, and sport fishermen have raised opposition because the river flows would freshen brackish estuaries and change the distribution of targeted animals (Muth 2014). Local landowners and residents have raised concerns about increased backwater flooding risks, and shipping interests have objected to potential shoaling of shipping channels as river flows are reduced below diversions.

Federal resource agencies have also raised concerns about the effects of estuarine freshening on essential fish habitat and populations of protected bottlenose dolphins, despite the fact that the present estuarine bays are relatively fleeting features resulting from coastal degradation and may be eventually converted to open Gulf waters without intervention for restoration. Nonetheless, planning and engineering for the Mid-Barataria Sediment Diversion at Myrtle Grove are proceeding, armed with funding from oil spill revenues, state political support, and federal commitments for fast-tracking of environmental permits.

Not only might sediment diversions from the river impact the interests of some stakeholders, but they also will likely take decades to build wetlands. Consequently, there are strong proponents of marsh creation using dredged sediments. The costs of marsh creation projects in the Coastal Master Plan total an estimated $17.9 billion of the $50 billion total costs. Not only will funding be a limiting factor but also will the supply of suitable sediment, at least for marsh creation projects located far from the resources of the Mississippi and Atchafalaya rivers. These will require long-distance pipelines, accessing sand resources from shoals on the continental shelf, or dredging nearby bays, raising questions of the high energy as well as financial costs (Day et al. 2005). Furthermore, marshes created by dredged material require periodic renourishment with dredged sediment to counteract subsidence and relative sea-level rise. Marsh creation may be accomplished more quickly than land building by sediment diversions, but is less sustainable.

2.6 Climate Change as a Threat Multiplier

2.6.1 Change Is Happening: Human-Caused and Dangerous

According to an overwhelming scientific consensus, global warming is occurring and is virtually all the result of human activities (USGCRP 2017). The six warmest years on record, in terms of global mean annual temperature, have come in the decade of the 2010s. Natural forces, such as solar activity, have played an inconsequential role in the observed warming since the mid-twentieth century. At current rates of growth in emissions of carbon dioxide and other greenhouse gases, dangerous climate changes would result before the end of this century, threatening the world's biodiversity, acidifying the oceans, amplifying extreme weather events, causing economic hardship, and accelerating sea-level rise to the extent that it would render many low-lying islands and densely populated coastal regions uninhabitable.

These are mainstream scientific assertions (IPCC 2014; USGCRP 2017) that, while widely accepted around the world, are not as widely accepted within Louisiana's political leadership and the south Louisiana citizenry. There are various reasons why this is the case, including perceived economic dependence on the fossil fuel industry, mistrust in government solutions, resentment of the intellectual class, and the fear of cultural eclipse and economic decline about which sociologist Arlie Russell Hochschild (2016) wrote in her book *Strangers in Their Own Lands*. Enigmatically, she argues, those most at risk reject the needed solutions for these reasons. Furthermore, even well-informed Louisianans perceive the current crises as far more the result of natural processes and other human activities than of global climate change in a distant future. In any case, the unwillingness to address the reality and causes of global climate change presents a significant challenge in how its consequences can be brought into planning and action for coastal resilience in coastal Louisiana, both for the environment and for society.

While coastal Louisiana has long had to confront high rates of relative sea-level rise as a result of subsidence, the oceans themselves began to rise beginning only in the late nineteenth century (Kemp et al. 2011). The rise in global mean sea level accelerated through the twentieth century (Dangendorf et al. 2017) and has averaged about 3 mm/year since 1993, when satellite-born altimeters have allowed us to measure the level of entire oceans (Nerem et al. 2018). In addition to the expansion of warming ocean waters and melting of glaciers, the melting of ice sheets perched on Greenland and Antarctica is now contributing to global sea-level rise. Simply projecting the acceleration of rate of rise observed in the satellite record would result in a rise in global sea level of about 65 cm (2.1 feet) by 2100 compared with 2005. On top of subsidence, such a rise would be very challenging for the Louisiana coast but, as will be discussed in the next section, should probably be regarded as the minimum that will likely be experienced.

The scientific consensus at this time is that climate change is unlikely to increase the frequency of tropical cyclones but is very likely to increase the intensity of those that do occur (Knutson et al. 2010). This may particularly be the case on the Gulf Coast as the waters of the Gulf of Mexico continue to warm. A greater percentage of hurricanes are likely to reach Category 4 or Category 5 level on the Safir-Simpson scale. There are many other factors that will influence the trajectories of Atlantic hurricanes, making it impossible to forecast whether the Louisiana coast will experience more or fewer in the coming decades, but those that do impact this coast will probably become stronger.

Climate change also presents risk of increased flooding from extreme rainfall events. Over the last century, precipitation has increased along the northern Gulf Coast, both annually and in the summer (Kunkel et al. 2013). The frequency of rainfall events of 1 inch or more is projected to increase by mid-century and, at the same time, dry spells are likely to become more frequent.

As mentioned earlier, climate change has been implicated in two record-breaking rainfall events and resulting floods, in the Louisiana deluge in the Baton Rouge area in August of 2016 and with Hurricane Harvey around Houston in 2017. Both events occurred when low-pressure systems that developed in the Gulf of Mexico stalled near the coast – consistent with slowdown in tropical storm speeds that has been linked to global warming (Kossin 2018) – allowing them to continue to draw energy and moisture from the anomalously warm waters of the Gulf. Based on observational data and models, researchers found that an event like the Louisiana 2016 deluge is now likely to occur at least 40% more often than prior to the year 1900 and that their precipitation intensity has increased by roughly 10% as a result of human-caused climate change (van der Wiel et al. 2017). For the Houston flood, one study estimated that the chances of observed precipitation accumulations had increased by a factor of 3 and precipitation intensity increased by 15% (van Oldenborgh et al. 2017), while another placed these as a factor of 3.5 and 37%, respectively (Risser and Wehner 2017).

While air temperatures in coastal Louisiana have not increased as much as many other parts of the United States, warmer temperatures later this century are very likely and will pose additional challenges to inhabitants of coastal Louisiana. While there will be fewer killing freezes, an increase in the number of days with temperatures exceeding 95 degrees Fahrenheit (35 degrees Celsius) is projected (Kunkel et al. 2013). Cooling degree days (a measure of how much and for how long outside air temperature is above 65 degrees Fahrenheit) are also projected to increase substantially, placing additional burdens on the poor who may have limited access to air conditioning and on the well-being of the broader population when confronted by power disruptions that result from major storms.

2.6.2 Avoiding the Unmanageable

At the end of 2015, virtually all nations of the world endorsed the United Nations Paris Agreement, the guiding objective of which is to reduce net emissions of greenhouse gases from human activities in order to keep global warming well below an increase of 2 degrees Celsius in global mean temperature above preindustrial levels, with an ambition to limit it to 1.5 degrees Celsius (Rogelj et al. 2016). We are at about 1 degree Celsius above the preindustrial level today. The Paris Agreement recognizes that substantial adaptation to the changing climate will be still required but that as these levels of warming are exceeded, it will be very challenging for human society to adapt. In short, humankind must avoid the unmanageable, while managing the unavoidable.

Limiting global warming to less than 2 degrees Celsius will require the rapid reduction of global greenhouse gas emissions beginning very soon and reaching net zero emissions by mid-century or soon thereafter (Figueres et al. 2017). Absent dramatic breakthroughs in carbon capture and storage technologies, such large and rapid emission reductions would necessitate a transition from a fossil fuel-based economy far more quickly than the citizens and political leadership of south Louisiana may be ready to consider. And yet the fundamental conundrum is that such a global transition is as essential for the future habitation of coastal Louisiana as it is for an imperiled Pacific island nation.

The existential threat to future habitation in coastal Louisiana is global sea-level rise. First, keep in mind that the relative rate of sea-level rise there, half or more due to subsidence, already poses substantial adaptation challenges. To its credit, the 2017 Coastal Master Plan considers three scenarios of environmental changes over the next 50 years, representing sea-level rise (in addition to variable rates of subsidence) of 43, 63 and 83 cm by 2067 for the low, medium, and high scenarios (CPRA 2017). Although the Plan does not link these scenarios to greenhouse emission pathways, it should be obvious that the greater the greenhouse gas concentrations realized, the greater the warming of the atmosphere and oceans and the greater the sea-level rise.

If greenhouse gas emissions continue to grow through the century (the Representative Concentration Pathway 8.5 of the 2014 IPCC assessment), it is increasingly apparent that a very substantial and unstoppable loss of Antarctic ice would probably be triggered with dramatic effects on sea level later in the twenty-first century and beyond (Kopp et al. 2017). This would result in a range of possible sea-level rise by the end of the century that includes the 200 cm (6.6 feet) by 2100 on which Coastal Master Plan's high scenario is based. That would be just the beginning, as the likely sea-level rise during the next century would range between 600 and 900 cm (20–30 feet). The Gulf of Mexico shoreline would retreat to where it was 7000 years ago. Moreover, we would not be able to forecast this with great certainty until it is too late to slow the rate of ice loss by reducing our emissions.

If, on the other hand, global society were to rapidly reduce greenhouse gas emissions to meet the goals of the Paris Climate Agreement to keep the increase in global mean temperature below 2 degrees Celsius (RCP 2.6), catastrophic loss of Antarctic ice mass could be avoided. According to the recent probabilistic projections (Kopp et al. 2017), sea-level rise over the next 50 years would likely be less than what even the low scenario of the Coastal Master Plan assumes and substantially less than the 198 cm by 2100 on which scenario is based. In fact, there would be a 50/50 chance of sea-level rise being less than 100 cm even in 2200, giving the embattled Louisiana coast a fighting chance for adaptation that leads to "essential" social resilience (Laska 2012).

2.7 Implications for Social Resilience

2.7.1 Transient and Secular Disasters

The people, families, communities, and institutions of coastal Louisiana will continue to be confronted by transient disasters caused by river flooding, storm surges, and deluges. Within limits, they have been proudly resilient in the past, but many steps can yet be taken to improve social resilience in the future. However, now society is confronted with substantial secular (long duration) changes in the natural environment and their attendant risks in the form of rapid coastal disintegration of this geologically young territory, compounded by global climate change. These "slow motion disasters" require a different kind of approach to social resilience, one that fundamentally takes an intergenerational perspective but with substantial changes even happening fast enough to be experienced within a lifetime.

Enhancing intergenerational social resilience will require that the people of coastal Louisiana have a greater awareness and acceptance of the biophysical changes that will be confronting them. They will have to understand the accommodations and solutions that are possible and their limits in order to effectively participate in civil society. The people of coastal Louisiana can no longer afford to remain "strangers in their own land" as Hochshield (2016) framed the dilemma. While Louisiana's Coastal Protection and Restoration Authority has expended considerable effort to engage the public and has secured political support for the Coastal Master Plan to this point, much more extensive understanding by the public and incorporation of community concerns will be required. Because of the intergenerational nature of the challenge, there should be concerted efforts to raise the socio-environmental literacy of school children about their unique and dynamic coastal landscape and how and why it is being altered, including by climate change.

Enhancing resilience to disasters during an era of rapid change will also require a strategically developed capacity of natural and social scientists, engineers, designers and planners, and social workers. Higher education institutions should focus faculty development and research and training programs with this in mind. New kinds of boundary organizations (Cash et al. 2003) will have to evolve that link knowledge with practice, transcend public and private enterprises, and engage both citizens and decision makers.

2.7.2 Role of Natural Systems in Resilience

The concept of ecosystem services (Carpenter et al. 2009) has emerged with the growing recognition of the importance of natural environments to human well-being. The values of coastal wetlands for protection from hurricane waves and storm surges have been specifically assessed (Costanza et al. 2008; Barbier et al. 2013) and are among the many ecosystem services that support the socio-economy of coastal Louisiana. The natural ecosystem resilience of coastal Louisiana is increasingly recognized as an important contributor to social resilience.

Louisiana's consecutive Coastal Master Plans have taken major steps in the right direction by incorporating the benefits of coastal ecosystems in moderating wave and storm surge risks and in integrating protection and restoration. There is clearly much more work to be done on this front for project-specific design and integration. Future efforts will have to navigate the institutional obstacles regarding matching of funding sources, typically restricted to protection or to restoration, and coordination among disparate responsible agencies.

2.7.3 Limiting Climate Change Inseparable from Adaptation

While not expressly linked to global warming and greenhouse gas emissions, the sea-level rise rates embedded in the future scenarios of the Coastal Master Plan, together with their logical extensions beyond 2067 as discussed earlier, make it clear that the single most effective action to ensure the future well-being of people in coastal Louisiana is the rapid reduction in global greenhouse gas emissions consistent with the Paris Climate Agreement. This is urgent: with each 5-year delay in near-term peaking of carbon dioxide emissions, sea level in 2300 would increase by an estimated 20 cm (Mengel et al. 2018). From the perspective of people desiring to live in coastal Louisiana beyond the next 50 years, it is not an exaggeration to say that effective mitigation to limit climate change is a sine qua non. The benefits of most of the protection and restoration we have undertaken or are planning over the next 50 years would be rendered moot by 2 meters or more of sea-level rise. Climate change adaptation and mitigation are not separate issues but must go hand in hand in order to manage the unavoidable while avoiding the unmanageable.

Recognition of this reality by the public and political leadership in Louisiana is a challenging obstacle. Although there are some exceptions, many of those currently in political leadership at the state and federal level are stationed somewhere between denial (climate change is not happening or is mostly natural) and "lukewarmerism" (it will not be that bad or there is not much we can do about it). Improved public awareness of the scientific realities and the technological possibilities will be required to change this much.

Contributing to this reticence are concerns about impacts on jobs and the regional economy of a phase out in the use of oil and gas as fuels. Production of petroleum hydrocarbons would still be required as feedstocks for chemicals and products that society would use. Existing industrial and technological capacities could be useful in developing renewable energy or in carbon sequestration in the vast deep saline aquifers lying under the northern Gulf of Mexico (DeSilva et al. 2015). For example, the support structures for offshore wind turbines recently installed off Rhode Island were built in an oil platform fabrication yard in Houma, Louisiana. Moving away from energy and transportation systems that rely on fossil fuels also opens up opportunities for creative approaches to coastal restoration and community resilience by the strategic brain trust mentioned above.

2.7.4 Defend, Adapt, or Relocate?

Difficult decisions are already here today regarding whether to structurally protect, improve resilience where structural protection is infeasible, or relocate vulnerable homes and communities (Bailey et al. 2014). Inclusive efforts that plan for the future such as LA SAFE are critical, and there is much that social scientists can contribute to and learn from these efforts and from planned relocations such as for

Isle de Jean Charles. After all, in coastal Louisiana the challenge is not just resilience to extreme weather events but also rational responses to substantial long-term biophysical changes that ensure human well-being and sustain the sociocultural fabric of communities.

2.7.5 Coastal Louisiana as a Harbinger

The Deltaic and Chenier plains that characterize the Louisiana coastal zone differ in many important ways from other coastal zones of the United States. They are younger, exceptionally low lying, and generally subsiding more rapidly than most coastal landforms. Yet, with relative sea-level rise accelerating and ocean storms and extreme precipitation likely to intensify along most of US coasts, Louisiana serves as a harbinger for the challenges to be faced in risk management for coastal communities elsewhere.

From the increase in the frequency of high tide or so-called nuisance flooding, even on sunny days, in cities such as Atlantic City, Annapolis, Norfolk, Charleston, and Miami (Sweet et al. 2018), to the damages associated with the exceptional storm surge of Superstorm Sandy (Halverson and Rabenhorst 2013), increased risks to communities are more evident, and planning is beginning to take this into account. Even California, which one does not usually think of having a low-lying coast, has updated its sea-level rise guidance (California Natural Resources Agency 2018) based on a rigorous scientific assessment (Griggs et al. 2017). With Louisiana's still massive, if underused, supplies of river-borne sediments, Louisiana might even have some advantages in contending with sea-level rise. South Florida, where huge populations and economies are at risk, has no muddy rivers, and the porous limestone platform that underlies it can render earthen levees ineffective.

What coastal Louisiana is confronting today defines challenges surely to be faced in other coastal regions around the globe. How can cities and towns contend with more regular tidal water flooding, as well as greater storm surges, while at the same time remove precipitation-driven stormwater? How can tidal wetlands be maintained not only for their natural resource values but also as a buffer to storm surges, during the coming period of more rapidly rising seas? How can state governments effectively integrate community hazard protection and coastal ecosystem restoration? How do communities and governments make rational and effective choices among structural storm surge protection, nonstructural adaptation, and relocation?

References

Bacon-Blood, L. (2018). St. John Parish is getting a new $760 million levee: Here are 10 things you need to know. *The Times-Picayune*. https://www.nola.com/environment/index.ssf/2018/07/10_things_to_know_about_st_joh.html

Bailey, D., Grambling, R., & Laska, S. B. (2014). Complexities of resilience: Adaptation and change within human communities in coastal Louisiana. In J. W. Day, G. P. Kemp, A. M.

Freeman, & D. P. Muth (Eds.), *Perspectives on the restoration of the Mississippi Delta* (pp. 125–140). Dordrecht: Springer.

Barbier, E. B., Georgiou, I. Y., Enchelmeyer, B., & Reed, D. J. (2013). The value of wetlands in protecting southeast Louisiana during hurricane storm surges. *PLoS ONE, 8*(3), e58715. https://doi.org/10.1371/journal.pone.0058715.

Barry, J. M. (1997). *Rising tide: The Great Mississippi River Flood of 1927 and how it changed America*. New York: Simon and Schuster.

Baxter, V. (2014). Rent, real estate, and flood mitigation in New Orleans East. *Antipode, 46*(4), 1014–1031. https://doi.org/10.1111/anti.12080.

Bentley, S. J. S., Blum, M. D., Maloney, J., Pond, L., & Paulsell, R. (2016). The Mississippi River source-to-sink system: Perspectives on tectonic, climatic, and anthropogenic influences, Miocene to Antropocene. *Earth-Science Reviews, 153*, 139–174.

Bernard, S. K. (2016). *Teche: A history of Louisana's most famous bayou*. Oxford: University of Mississippi Press.

Bevan, J. L. I. I., Avila, L. A., Blake, E. S., Brown, D. P., Franklin, J. L., Knabb, R. D., et al. (2008). Atlantic hurricane season of 2005. *Monthly Weather Review*, 1009–1117. https://doi.org/10.1175/2007MWR2074.1.

Blum, M. D., & Roberts, H. H. (2009). Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. *Nature Geoscience, 2*(7), 488–491.

Blum, M. D., & Roberts, H. H. (2012). The Mississippi delta region: Past, present, and future. *Annual Review of Earth and Planetary Sciences, 40*, 655–683.

Boesch, D. F., Josselyn, M. N., Mehta, A. J., Morris, J. T., Nuttle, W. K., Simenstad, C. A., et al. (1994). Scientific assessment of coastal wetland loss restoration and management in Louisiana. *Journal of Coastal Research, Spec Issue, 20*, 1–103.

Brasseaux, C. A., & Davis, D. W. (2017). *Ain’t there no more: Louisiana’s disappearing coastal plain*. Oxford: University of Mississippi Press.

California Natural Resources Agency. (2018). *State of California sea-level rise guidance*. Sacramento: California Natural Resources Agency.

Campanella, R. (2008). *Bienville's dilemma: A historical geography of New Orleans*. Lafayette: Center for Louisiana Studies, University of Louisiana, Lafayette.

Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Diaz, S., et al. (2009). Science for managing ecosystem services: Beyond the millennium ecosystem assessment. *Proceedings of the National Academy of Sciences, 106*(5), 1305–1312.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. W., et al. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences, 100*(14), 8086–8091.

Chamberlain, E. L., Törnqvist, R. E., Shen, Z., Mauz, B., & Wallinga, J. (2018). Anatomy of Mississippi Delta growth and its implications for coastal restoration. *Science Advances, 4*, eaar4740. https://doi.org/10.1126/sciadv.aar4740.

Changing Course. (2016). *Changing course: navigating the future of the Lower Mississippi River Delta*. http://changingcourse.us

Coastal Protection and Restoration Authority of Louisiana (CPRA). (2017). *Louisiana’s comprehensive master plan for a sustainable coast*. Baton Rouge: Coastal Protection and Restoration Authority of Louisiana.

Colton, C. E. (2005). *Unnatural metropolis: Wresting New Orleans from nature*. Baton Rouge: Louisiana State University Press.

Corthell, E. (1897). The delta of the Mississippi River. *National Geographic, 12*, 351–354.

Costanza, R., Pérez-Maqueo, O., Martinez, M. L., Sutton, P., Anderson, S. J., & Mulder, K. (2008). The value of coastal wetlands for hurricane protection. *Ambio, 37*(4), 241.

Couvillion, B. R., Beck, H., Schoolmaster, D., & Fischer, M. (2017). Land area change in coastal Louisiana. In *Scientific investigations map 3381*. Reston: U.S. Geological Survey.

Dangendorf, S., Maros, M., Woppelmann, G., Conrad, C. P., Frederiske, T., & Riva, R. (2017). Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences, 114*(23), 5946–5951. https://doi.org/10.1038/ncomms14792.

Day, J. W., Britsch, L. D., Hawes, S. R., Schaffer, G. P., Reed, D. J., & Cahoon, D. (2000). Pattern and process of land loss in the Mississippi Delta: A spatial and temporal analysis of wetland habitat change. *Estuaries, 23*(4), 425–438.

Day, J. W., Jr., Barras, J., Clairain, E., Johnston, J., Justic, D., Kemp, G. P., et al. (2005). Implications of global climate change and energy cost and availability for the restoration of the Mississippi delta. *Ecological Engineering, 24*, 253–265.

Day, J. W., Jr., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., et al. (2007). Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. *Science, 315*(5819), 1679–1684.

De Silva, G. P. D., Ranjith, P. G., & Perera, M. S. A. (2015). Geochemical aspects of CO_2 sequestration in deep saline aquifers: A review. *Fuel, 155*, 128–143.

Dixon, B. (2009). *Last days of Last Island: The hurricane of 1856, Louisiana's first great storm*. Lafayette: University of Louisiana at Lafayette Press.

Dixon, T. H., Amelung, F., Ferretti, A., Novali, F., Rocca, F., Dokka, R., et al. (2006). Subsidence and flooding in New Orleans. *Nature, 441*, 587–588.

Figueres, C., Schellnhuber, H. J., Whiteman, G., Rockström Hobley, A., & Rahmstorf, S. (2017). Three years to safeguard our climate. *Nature, 546*, 593–595.

Freudenburg, W. R., Gramling, R., Laska, S., & Erikson, K. (2009a). *Catastrophe in the making: The engineering of Katrina and the disasters of tomorrow* (2nd ed.). Washington, D.C.: Island Press.

Freudenburg, W. R., Gramling, R., Laska, S., & Erikson, K. (2009b). Disproportionality and disaster: Hurricane Katrina and the Mississippi River-Gulf Outlet. *Social Science Quarterly, 90*, 497–515.

Gagliano, S. M., Meyer-Arendt, K. J., & Wicker, K. M. (1981). Land loss in the Mississippi River deltaic plain. *Transactions, Gulf Coast Association of Geological Societies, 31*, 295–300.

Griggs, G., Árvai, J., Cayan, D., DeConto, R., Fox, J., Fricker, H. A., et al. (2017). *Rising seas in California: An update on sea-level rise science*. Oakland: California Ocean Science Trust.

Halverson, J. B., & Rabenhorst, T. (2013). Hurricane Sandy: The science and impacts of a superstorm. *Weatherwise, 66*, 14–23.

Heimann, D. C., Sprague, L. A., & Blevins, D. W. (2011). *Trends in suspended-sediment loads and concentrations in the Mississippi River Basin, 1950–2009. Scientific Investigations Report* (pp. 2011–5200). Reston: U.S. Geological Survey.

Hochschield, A. R. (2016). *Strangers in their own land: Anger and mourning on the American right*. New York: The New Press.

Intergovernmental Panel on Climate Change (IPCC). (2014). *Climate change 2014: Synthesis report*. Geneva: Intergovernmental Panel on Climate Change.

Janowski, K. L., Törnqvist, T. E., & Fernandes, A. M. (2017). Vulnerability of Louisiana's coastal wetlands to present-day rates of relative sea-level rise. *Nature Communications, 8*, 14792. https://doi.org/10.1038/ncomms14792.

Kemp, A. C., Horton, B. C., Donnelly, J. P., Mann, M. E., Vermeer, M., & Rahmstorf, S. (2011). Climate related sea-level variations over the past two millennia. *Proceedings of the National Academy of Sciences, 108*, 11017–11022.

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., et al. (2010). Tropical cyclones and climate change. *Nature Geoscience, 157-163*(2010), 3. https://doi.org/10.1038/ngeo779.

Kolker, A. S., Allison, M. A., & Hameed, S. An evaluation of subsidence rates and sea- level variability in the northern Gulf of Mexico. *Geophysical Research Letters, 2011*. https://doi.org/10.1029/2011GL049458.

Kopp, R. E., DeConto, R. M., Bader, D. A., Hay, C. C., Horton, R. M., Kulp, S., et al. (2017). Evolving understanding of Antarctic ice-sheet physics and ambiguity in probabilistic sea-level projections. *Earth's Future*. https://doi.org/10.1002/2017EF000663.

Kunkel, K. E., Stevens, L. E., Stevens, S. E., Sun, L., Janssen, E., Wuebbles, D., et al. (2013). *Regional climate trends and scenarios for the U.S. National Climate Assessment. Part 2. Climate of the Southeast U.S. technical report NESDIS* (pp. 142–142). Silver Spring: National Oceanic and Atmospheric Administration.

Laska, S. (2012). Dimensions of resiliency: Essential resiliency, exceptional recovery and scale. *International Journal of Critical Infrastructures, 8*(1), 47–62.

Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority. (1998). *Coast 2050: Toward a sustainable coastal Louisiana*. Baton Rouge: Louisiana Department of Natural Resources.

Louisiana Office of Community Development Disaster Recovery Unit. (2017). *LA SAFE: Louisiana's strategic adaptations for future environments*. Baton Rouge: Louisiana Office of Community Development.

McBride, R. A., et al. (2007). A geomorphic process-response model for chenier-plain evolution in southwestern Louisiana, USA. In *Coastal Sediments' 07* (pp. 762–775).

McIntire, W. G. (1958). *Prehistoric indian settlements of the changing Mississippi River delta*. Baton Rouge: Louisiana State University Press.

McQuaid, J., & Schleifstein, M. (2006). *Path of destruction: The devastation of New Orleans and the coming age of superstorms*. New York: Little, Brown.

Meade, R. H., & Moody, J. A. (2010). Causes for the decline of suspended-sediment discharge in the Mississippi River system, 1940–2007. *Hydrological Processes, 24*, 35–49.

Mengel, M., Nauels, A., Rogelj, J., & Schleussner, D. F. (2018). Committed sea-level rise under the Paris agreement and the legacy of delayed mitigation action. *Nature Communications*. https://doi.org/10.1038/s41467-018-02985-8.

Morton, R. A., Bernier, J. C., & Barras, J. A. (2006). Evidence of regional subsidence and associated interior wetland loss induced by hydrocarbon production, Gulf Coast region, USA. *Environmental Geology, 50*, 261. https://doi.org/10.1007/s00254-006-0207-3.

Munoz, S. E., Giosan, L., Therrell, M. S., Remo, J. W. F., Shen, Z., Sullivan, R. M., et al. (2018). Climactic control of Mississippi River flood hazard amplified by river engineering. *Nature, 556*, 95–98.

Muth, D. P. (2014). The once and future delta. In J. W. Day, G. P. Kemp, A. M. Freeman, & D. P. Muth (Eds.), *Perspectives on the restoration of the Mississippi Delta* (pp. 9–27). Dordrecht: Springer.

Nerem, R. S., Buckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change-driven accelerated sea-level rise detected in the altimeter data. *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.1717312115.

Penland, S., & Suter, J. R. (1989). The geomorphology of the Mississippi River chenier plain. *Marine Geology, 90*, 231–240, 243–258.

Penland, S., Mendelssohn, I., Wayne, L., & Britsch, D. (1996). *Natural and human causes of coastal land loss in Louisiana*. Baton Rouge: Coastal Studies Institute and Wetland Biogeochemistry Institute, Louisiana State University.

Perry, C. L., & Mendelssohn, I. A. (2009). Ecosystem effects of expanding populations of *Avicennia germinans* in a Louisiana salt marsh. *Wetlands, 29*(1), 396–406. https://doi.org/10.1672/08-100.1.

Piazza, B. P. (2014). *The Atchafalaya River Basin: History and ecology of an American wet land*. College Station: Texas A&M University Press.

Reed, D. J. (1989). Patterns of sediment deposition in subsiding coastal salt marshes, Terrebonne Bay, Louisiana: The role of winter storms. *Estuaries and Coasts, 4*, 222–227.

Risser, M. D., & Wehner, M. F. (2017). Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. *Geophysical Research Letters, 44*, 12457–12464. https://doi.org/10.1002/2017GL075888.

Roberts, H. H. (1997). Dynamic changes of the Holocene Mississippi River Delta Plain: The delta cycle. *Journal of Coastal Research, 13*(3), 605–627.

Roberts, H. H., Coleman, J. M., Bentley, S. J., & Walker, N. (2003). Embryonic major delta lobe: A new generation of delta studies in the Atchafalaya-Wax Lake delta system. *Gulf Coast Association of Geological Societies Transactions, 53*, 690–703.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., et al. (2016). Paris agreement climate proposals been a boost to keep warming well below 2°C. *Nature*. https://doi.org/10.1038/nature18307.

Roth, D. (2010). *Louisiana hurricane history*. Camp Springs, Maryland: National Weather Service.

Salinas, L. M., DeLaune, R. D., & Patrick, W. H., Jr. (1986). Changes occurring along a rapidly submerging coastal area: Louisiana, USA. *Journal of Coastal Research, 2*(3), 269–284.

Saucier, R. T. (1994). *Geomorphology and Quaternary geologic history of the Lower Mississippi Valley*. Vicksburg: Mississippi River Commission.

Stanford, J. D., Hemingway, R., Rohling, E. J., Challenor, P. G., Medina-Elizalde, M., & Lester, A. J. (2010). Sea-level probability for the last deglaciation: A statistical analysis of far-field records. *Global and Planetary Change, 79*, 193–203.

Sweet, W. V., Dusek, G., Obeysekera, J., & Marra, J. J. (2018). *Patterns and projections of high tide flooding along the U.S. coastline using a common impact threshold. NOAA technical report NOS CO-OPS 086*. Silver Spring: National Oceanic and Atmospheric Administration.

Turner, R. E. (1997). Wetland loss in the northern Gulf of Mexico: Multiple working hypotheses. *Estuaries, 20*(1), 13.

Twilley, R., Allison, M., Capozzoli, L., Laska, S., McKee, L., Meselhe, E., et al. (2008). Morganza-to-the-Gulf Technical Panel review final report. In *Duxbury*. Massachusetts: Battelle.

Twilley, R. R., Bentley, S. J., Sr., Chen, Q., Edmonds, D. A., Hagen, S. C., Lam, N. S. N., et al. (2016). Co-evolution of wetlands landscapes, flooding, and human settlement in the Mississippi River Delta Plain. *Sustainability Science, 11*, 711–731.

U.S. Army Corps of Engineers (USACE). (2004). Louisiana Coastal Area (LCA), Louisiana: Ecosystem restoration study. In *New Orleans*. Louisiana: U.S. Army Corps of Engineers New Orleans District.

U.S. Army Corps of Engineers (USACE). (2009). Louisiana Coastal Protection and Restoration (LACPR): Final technical report. In *New Orleans*. Louisiana: U.S. Army Corps of Engineers New Orleans District.

U.S. Global Change Research Program (USGCRP). (2017). *Climate science special report: Fourth National Climate Assessment, Volume I*. Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/J0J964J6.

van der Wiel, K., Kapnick, S. B., van Oldenborgh, G. J., Whan, K., Phillipm, S., Vecchi, G. A., et al. (2017). Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. *Hydrology and Earth System Sciences, 897-92*(2017), 21. https://doi.org/10.5194/hess-21-1631-2017.

van Oldenborgh, G. J., van der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., et al. (2017). Attribution of extreme rainfall from Hurricane Harvey, August 2017. *Environmental Research Letters, 12*, 124009. https://doi.org/10.1088/1748/aa9ef2.

Visser, J. M., Sasser, C. E., Chabreck, R. H., & Linscombe, R. G. (2002). The impact of a severe drought on the vegetation of a subtropical estuary. *Estuaries, 25*(6A), 1184–1195.