Please cite this article in press as: Day et al., Emerging climate threats to the Mississippi River Delta: Moving from restoration to adaptation, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.03.001

One Earth

CellPress

Perspective

Emerging climate threats to the Mississippi River Delta: Moving from restoration to adaptation

John W. Day,[1,*] Y. Jun Xu,[2] Barry D. Keim,[3] Vincent M. Brown,[3] Liviu Giosan,[4,5] Michael E. Mann,[6] and Jessica R. Stephens[7]
[1]Department of Oceanography and Coastal Science, Louisiana State University, Baton Rouge, LA, USA
[2]School of Renewable Natural Resources, Louisiana State University, Baton Rouge, LA, USA
[3]Department of Geography & Anthropology, Louisiana State University, Baton Rouge, LA, USA
[4]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, USA
[5]Institiul de Cercetare al Universitaitii din Buchuresti, Bucharest, Romania
[6]Department of Earth and Environmental Science, University of Pennsylvania, Philadelphia PA, USA
[7]Department of Environmental Sciences, Louisiana State University, Baton Rouge, LA, USA
*Correspondence: johnday@lsu.edu
https://doi.org/10.1016/j.oneear.2024.03.001

SUMMARY

The Mississippi River Delta (MRD) is a global natural and economic asset and socio-economic hub with an extensive fishery, major petrochemical complexes, and the largest global commodity port. During the twentieth century, >25% of MRD coastal wetlands were lost. Climate forcings threatening the MRD include extreme precipitation, increasing river discharge, tropical cyclones, and sea-level rise exacerbated by subsidence. We outline adaptation strategies to enhance the sustainability of the MRD. These include defining defensive baselines, diverting river water into the deltaic plain, protecting the crucial river corridor between Baton Rouge and New Orleans, strengthening protection for New Orleans, and sustaining the fishing industry. These strategies highlight potential challenges of existing "restoration" plans, which sometimes fail to address ongoing climate challenges. Management plans must be more adaptation focused. We offer suggestions for current restoration initiatives and put our findings into the context of global delta restoration.

INTRODUCTION

The Mississippi River Delta (MRD) is a prominent global natural asset and socio-economic hub. Located at approximately 30°N, 90°W, the MRD is one of the largest deltas by basin drainage area and freshwater and sediment discharge in a temperate climate.[1,2] However, over the past century, >25% of the wetlands were lost, primarily due to flood control levees along the river and pervasive alteration of the hydrology of the deltaic plain.[3–5]

The modern Mississippi River system is highly controlled through engineering measures. There are nearly continuous levees from the junction with the Ohio to the mouth of the river; dams and locks above the junction, especially on the Missouri River; and dikes and meander cutoffs below the junction. A control structure that limits flow in the Atchafalaya River, the only large functional distributary of the river, to about a third of total Mississippi plus Red River discharge. Figure 1 shows a general aspect of the deltaic plain and locations of issues discussed in the paper. These changes have reduced flood risk and allowed year-round navigation but have also reduced sediment flux by about half, prevented capture of river flow by the Atchafalaya, and prevented input of river water and sediments into most of the deltaic plain.

Sea surface temperatures (SST) from 1970–2020 increased by ~1°C across the Gulf of Mexico, a rate that is double the global SST average (Figure 2).[7] The rate of warming was greatest in spring and summer (Figure 3).[8,9] These Gulf of Mexico SSTs are higher than other SSTs at similar latitudes in the North Atlantic.[10] Furthermore, precipitation in the Mississippi River basin has increased by 10%–15% compared to the twentieth-century average, leading to increased discharge (Figure 4).

Sustained global warming is expected to intensify the four main climate stressors of the MRD (Figure 5): sea-level rise, extreme precipitation events, increasing river discharge, and tropical cyclones.[12] Notably, substantial land subsidence for the MRD, due to both geologic subsidence, compaction, and oxidation of drained soils, and petroleum production are exacerbating climate-controlled eustatic sea-level rise, leading to the highest rates of marine inundation in the United States.[13] This makes the MRD the most vulnerable region in the United States to climate change and among the most vulnerable locations worldwide to extreme events. For example, New Orleans faces the totality of these environmental threats. A levee system protects the city from the Mississippi River and storm surge from hurricanes; however, a large proportion of the bowl-shaped city has subsided and now sits below mean sea level, making the city more vulnerable to floods. Furthermore, when extreme precipitation events affect New Orleans, the runoff must be pumped uphill and outside the confines of the levees. Flooding from these sources (Mississippi River, storm surge, and precipitation),

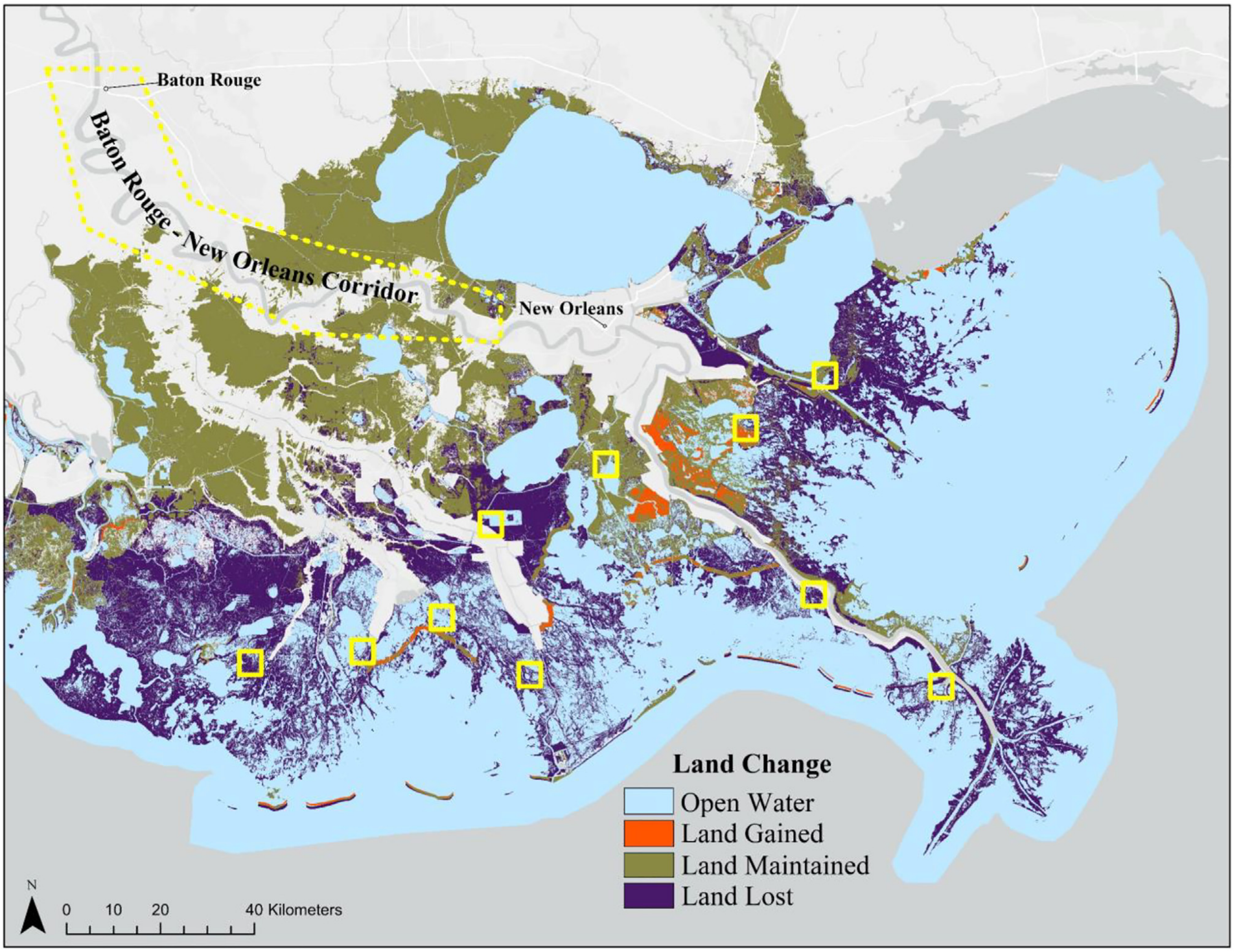

Figure 1. Mississippi River basin, the delta, and current conditions
The MRD with projected wetland loss this century (data for map retrieved from CPRA 2023 data viewer[6]). Highlighted on map are the Mississippi River corridor between Baton Rouge and New Orleans and suggested locations of fortified fishing villages (yellow squares), both discussed in the text. Land change from CPRA 2023 using high-end climate-change-impacts scenario. Orange, land gain due to river diversions and using dredged sediments to create new marsh; green, existing wetlands that are maintained; dark purple, wetlands that convert to open water.

which can occur simultaneously, are a constant concern and are likely to worsen with climate change.

The economic importance of the MRD for the United States and the world cannot be overstated. The MRD supports one of the largest global fisheries and is home to a vast petrochemical complex. As the largest commodity port globally, annual shipping in the MRD amounts to ca. 360 million tons of fossil fuels, other petrochemicals, and grain.[13,15] Food and energy shortages would occur globally if this maritime activity were disrupted or ceased. Because of the national importance of the MRD, the National Academies of Sciences, Engineering, and Medicine recently awarded a partnership between Louisiana State University and Tulane University with $22 million to launch a Mississippi River Delta Transition Initiative Consortium to find solutions to the complex problems.

Louisiana has implemented projects focused on coastal wetland restoration since the 1980s. Despite significant investment, considerable land loss continues. Although some wetlands have been created through marsh creation and barrier island restoration, it is unclear whether these are going to be sustained in the face of accelerating climate impacts. Therefore, climate adaptation should be essential to the state master plan. Here, we provide our perspectives on why adaptation strategies should also be considered in dealing with the complexity of coupled human-natural systems.

CLIMATE STRESSORS OF THE MRD

The Mississippi River and Tributaries (MR&T) Project was established after the historic 1927 flood to manage flood control and navigation on the river.[16] The MR&T project flood was set at $\sim 85{,}000\ m^3\ s^{-1}$ (3 million $ft^3\ s^{-1}$) as a level considered greater than any flood that could occur. As we discuss below, climate change is leading to increasing river discharge. The design flood will likely be exceeded with increasing frequency in this century. As a result, the current infrastructure may be unlikely to contain

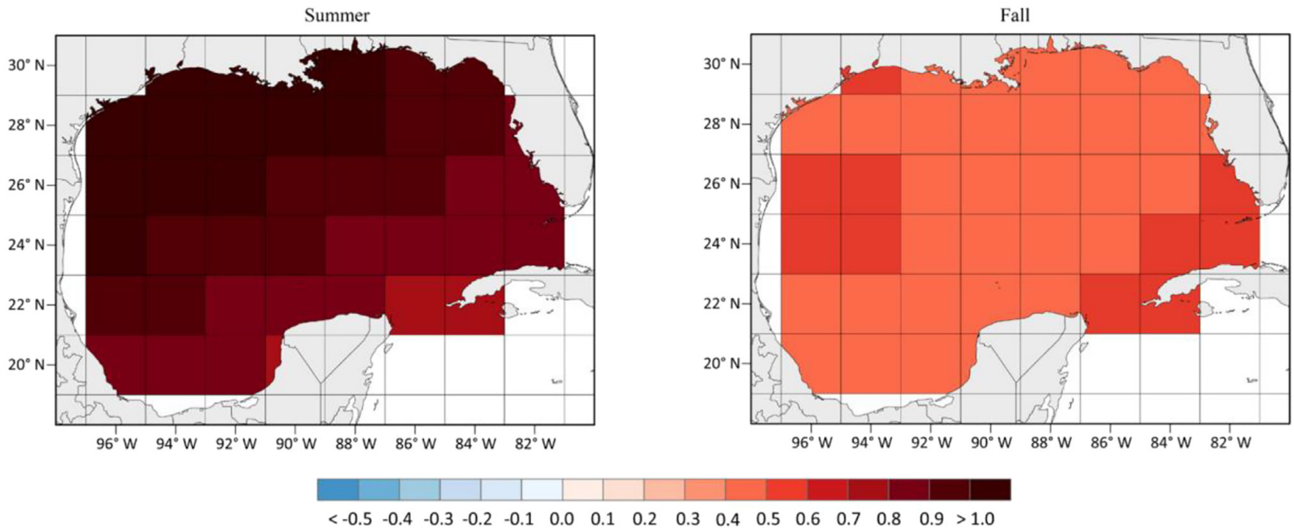

Figure 2. Sea surface temperatures in the Gulf of Mexico
Trends in sea surface temperatures in summer and fall from 1901 to 2010 in the Gulf of Mexico (from Allard et al.[8])

flows larger than the project flood. Current river management aims to maintain most flow in the main channel for flood control and navigation purposes. Increasing river discharge will complicate these objectives, as discussed below. Climate change has also led to extreme droughts across the Mississippi River basin, as occurred in 2022 and 2023, which resulted in very low flows on the river for these 2 years and in extensive saltwater intrusion in the lower river as far upstream as New Orleans.

Increasing precipitation extremes

During the twentieth century, the frequency and intensity of extreme precipitation events increased across many regions of the United States,[12,17] including the southeast[18] and southern Great Plains.[19] The frequency of recent extreme rainfall events, e.g., the South-Central Louisiana event in 2016 and Hurricane Harvey in 2017,[20,21] combined with the severity of the resulting floods, have raised questions as to whether changes in the global climate have affected extreme precipitation climatology.[22–25] There is a direct relationship between global temperatures and precipitation because the water-holding capacity of the atmosphere is a function of temperature[24]; thus, as global temperatures increase, storms may be provided with more moisture, assuming no change in moisture availability or convergence mechanisms, that may produce more intense and higher magnitude events.[25]

It has been predicted that heavy and extreme precipitation events will become more frequent.[12,17,26] Changes in tropical cyclone (TC)-induced rainfall are particularly important to coastal regions because accumulations from TCs in a single location, during certain events, can contribute 50%–100% of mean annual precipitation in just a few days.[27] Knutson et al.[28] projected future increases in TC rainfall rates of 6%–22% with 2°C global warming, roughly consistent with expectations from the Clausius-Clapeyron equation[22] (7% K^{-1} local temperature increase) based on experiments with an earlier version of the Geophysical Fluid Dynamics Laboratory (GFDL) model. More recent simulations by Liu et al.[29] with the HiFLOR version of the GFDL model show larger increases with warming, with an increase of 19%–29% for a roughly 1.5°C local SST increase. This "super Clausius-Clapeyron" scaling is tied to a positive-feedback loop wherein local increases in SST lead both to increased moisture content through Clausius-Clapeyron and intensification. Stronger winds more effectively entrain water vapor into storms, increasing moisture content. These estimates might be conservative, since the HiFLOR model only produces a 2%–5.4% increase in intensity per °C, while observational studies[30] suggest an ∼11% increase in wind speed per °C among the strongest storms, amounting to a ∼37% increase in intensity.

Moreover, these modeling studies do not consider an additional effect that leads to increased local rainfall from TCs. Hall and Kossin[31] showed that North Atlantic TCs had increased residence time in confined coastal regions because of slower translation speed and abrupt changes in direction. The observed "slowdown" of TCs was associated with a statistically significant increase in coastal annual mean rainfall in the second half of the twentieth and into the twenty-first century.[32] Consequently, events such as Hurricane Harvey, which have been linked to a changing climate,[33] are projected to become more likely in the coastal zone. For example, recent estimates show Hurricane Harvey produced roughly 1,213 mm (47.75 in) of rainfall across 1,036 km^2 (400 square miles), an area exceeding the size of Orleans Parish, in 120 h.[34] Similar storms will likely occur in the future over the low-lying deltaic City of New Orleans and cause catastrophic loss (Figure 6).

Increasing river discharge

Over the past 80 years, the discharge of the Mississippi River and its artificially controlled distributary, the Atchafalaya, has increased by 25% and 75%, respectively[16,35] (Figures 2 and 5). More than 90% of the increase originates in the upper Mississippi and Ohio basins. Discharge is projected to be further enhanced by 11%–61% by the end of this century.[36] Upstream of New Orleans is a flood-relief outlet, the Bonnet Carré Spillway,

Please cite this article in press as: Day et al., Emerging climate threats to the Mississippi River Delta: Moving from restoration to adaptation, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.03.001

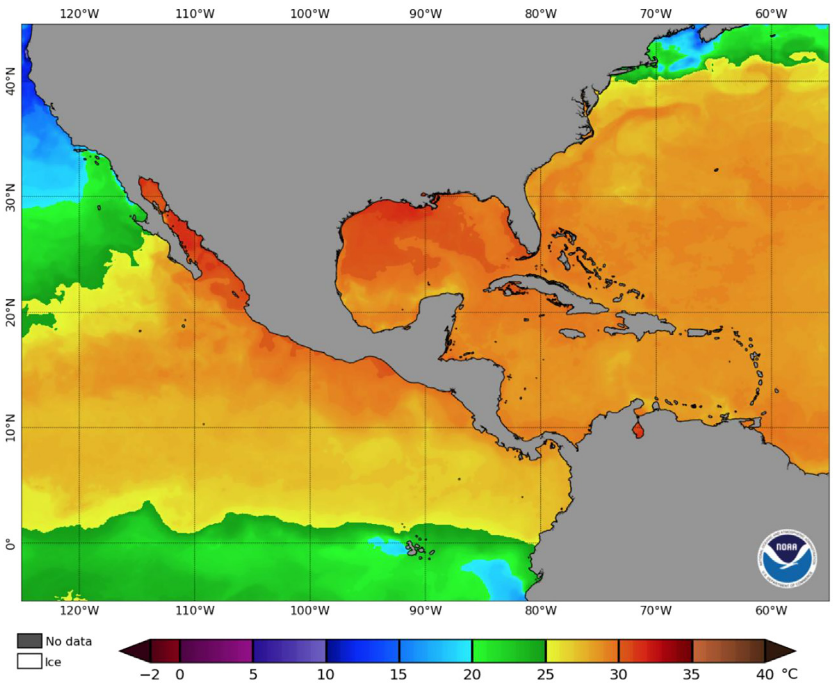

Figure 3. Surface temperatures in the Gulf of Mexico and adjacent North Atlantic
Surface temperature on August 26, 2021, 3 days before landfall of Hurricane Ida.

built after the 1927 flood. The structure has been opened 15 times since its completion in 1931 and was first used in 1937. The discharge criteria to justify an opening have not changed since the structure was built, which is to prevent the Mississippi River flows at New Orleans from exceeding about 35,400 $m^3\ s^{-1}$ (1.25 million $ft^3\ s^{-1}$). However, 10 of the 15 openings have occurred in the second half of its operational history, and five have occurred since 2016. The spillway was opened twice during 2019 due to the unprecedented long-duration flooding that extended the flooding conditions into hurricane season. This led to serious concerns about Hurricane Barry pushing a storm surge up the Mississippi River, which could have flooded New Orleans given the already swollen river.[12] The recent frequent need for water release through the Bonnet Carré Spillway reflects the occurrence of larger floods, which are becoming more common on the lower Mississippi River.

Increasing hurricane frequency and intensity

The frequency and intensity of TC strikes on the United States gulf and east coasts are depicted in Keim et al.[37] The MRD has a 3-year return frequency for TCs, including all tropical storms and hurricanes. On average, the region gets struck by hurricanes once every 7 years and major hurricanes (category 3–5 only) once every 26 years. There is still debate in the scientific community about the impact of climate change on North Atlantic TCs. Some researchers have argued for fewer TCs based on a global climate modeling approach,[38] while others have argued for more based on a downscaling approach applied to global climate model simulations.[39] There seems to be consensus, however, that the storms that do form will likely be more intense, leading to more major hurricanes. Even here, though, there is a substantial difference between the former studies, which project an increase in the intensity of a few percent with CO_2 doubling, and the latter, which predict a 30% increase. Emanuel[39] attributes these discrepancies to an insufficient spatial resolution to capture the most intense TCs in global modeling studies. Nevertheless, several researchers conclude that an increase in the most intense TCs is already observable.[30,40–44] For example, in Louisiana, between Hurricane Laura in 2020 and Ida in 2021 (368 days), seven named storms affected the state, five of which were hurricanes, including two category-4 storms. Also, Hurricane Laura produced the highest known storm surge in Louisiana at 6.37 m (20.9 ft).[45] These storms demonstrate what is possible in the region in the future. Accompanied by large surge events,[46] cyclones are also intensifying more rapidly[47] and losing strength more slowly over land.[48,49] The combination of increased storm surge from more hurricanes and sea-level rise has led to a substantial increase in coastal flood risk over the past century and is projected to lead to further increases with additional warming. The primary uncertainty in projected future flood risk is tied to uncertainties in sea-level rise from ice-sheet collapse[50].

Accelerating sea-level rise

Eustatic, climatically driven sea-level rise is projected to increase significantly this century, even in a scenario of substantial mitigation.[12] Coastal regions with large areas of near-sea level, such as the MRD, are especially vulnerable.[1,2] For example, at the Grand Isle, LA gauging station, water levels have risen by +7 mm $year^{-1}$ over the past 15 years (Figure 5), and relative sea-level rise will likely exceed 100 cm this century. A recent federal report on United States coastal sea-level rise predicts that sea-level rise will be highest for the United States in the MRD, with 49–69 cm of relative sea-level rise by 2050.[12] Eustatic rise is compounded with high land subsidence rates in the MRD, caused by compaction and consolidation of deltaic sediments, and these processes are exacerbated by human activities such as reclamation, hydrologic alteration, and fluid withdrawal primarily associated with oil and gas production.

COURSE CHANGE NEEDED

How to better protect the manifold functions of the MRD in the face of combined and intensifying climatic stressors such as those mentioned above has thus become a crucial problem that requires novel adaptation strategies. Here, we outline ideas for such new strategies.

Although hundreds of projects have already been implemented to protect and restore deltaic coastal land areas in Louisiana,[48,51] land loss continues, and floods are becoming more frequent and more substantial.[52] Coastal flooding from TCs,

One Earth
Perspective

CellPress

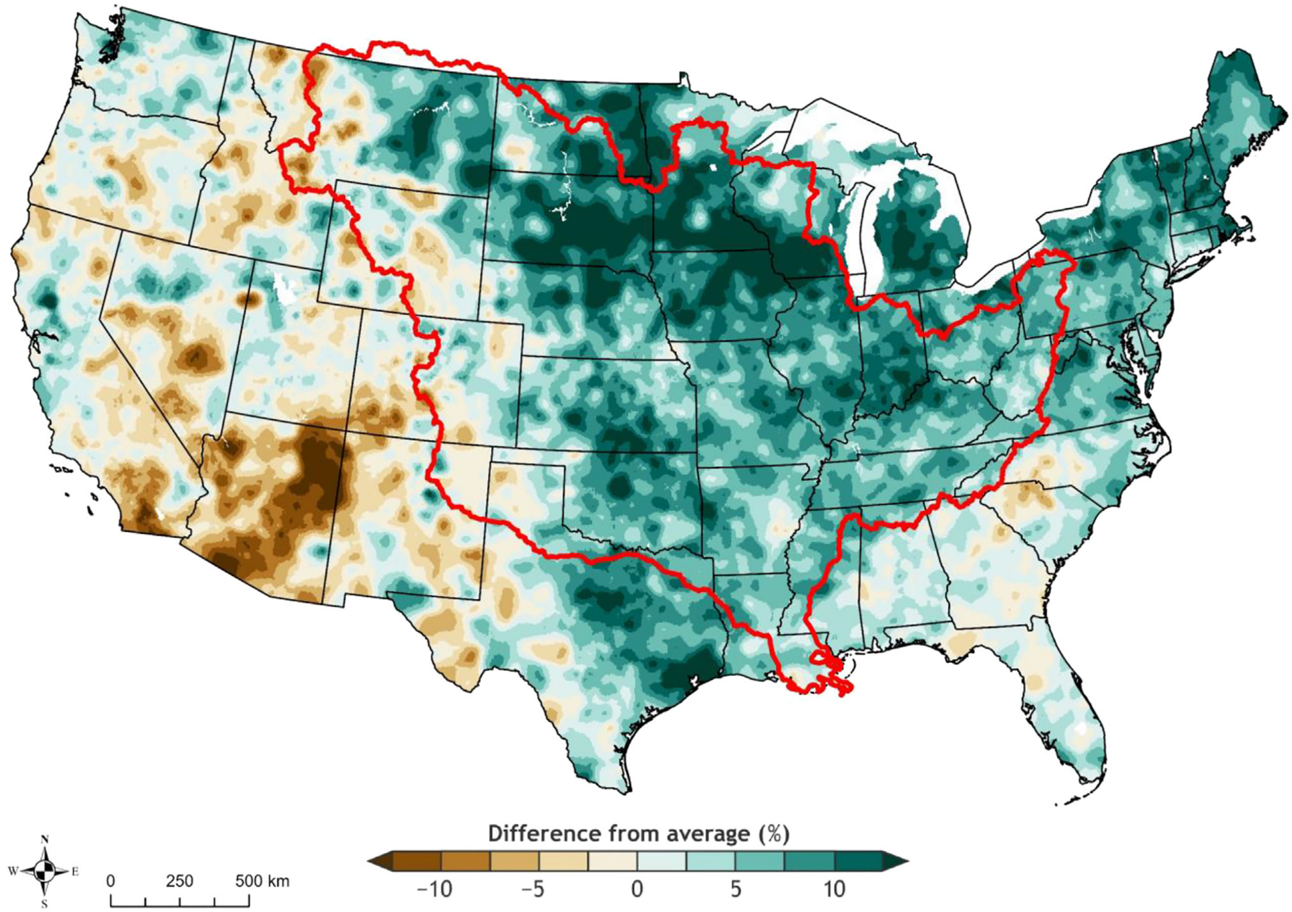

Figure 4. Precipitation trends in the Mississippi River basin
Annual precipitation from 1991 to 2020 compared to the twentieth-century average. Red line delineates the Mississippi River basin (NOAA[11] modified by V. Brown).

flooding during intense rainfall events, and river floods from increased river discharge are all exacerbated by rising sea levels. The current restoration plan developed by the Coastal Protection and Restoration Authority (CPRA)[6,14] includes many notable restoration measures and flood protection (e.g., Mississippi River diversions, improved levees, and marsh creation); however, a clear goal as to which specific conditions the MRD should be restored to is missing. For example, are marsh ecosystems to be returned to conditions that existed in the mid-twentieth century? Should nature-based solutions be incorporated to a greater extent? Moreover, climatic impacts discussed here are not fully integrated into the restoration plans, although they may overwhelm restoration efforts in this century. For example, relative sea-level rise at Grand Isle, LA, increased at a rate of 9.16 mm/year (±0.37 mm) since 1947, equivalent to a rate of 0.92 m (3.01 ft) per 100 years (National Oceanic and Atmospheric Administration [NOAA] Tides and Currents, 2023). The best-case (intermediate-low scenario) for this location at the base of the MRD from the latest sea-level rise scenarios[12] estimates a rise of 1.26 m (4.13 ft) by 2100, while the worst-case scenario (high scenario) estimates 2.7 m (8.86 ft) by 2100, which would completely overwhelm current CPRA efforts. Extreme precipitation and increasing Mississippi River discharge are not addressed meaningfully in current restoration and protection planning. This justifies fears and raises legitimate questions about the sustainability of MRD's current restoration strategy. Adaptation plans must be developed for the delta to meet the challenges of climate change.

A WAY FORWARD: CLIMATE ADAPTATION

Defining defensive baselines for the MRD

The current state of the MRD is already beyond the point of restoration to the pristine delta before European contact or even to early twentieth-century conditions. A course change from favoring a restoration-focused strategy to a more realistic adaptation-directed strategy is urgently needed. First and foremost, geographically defined boundaries for the MRD should be defined based on the topography and elevation of deltaic regions that are higher than a threshold level, such as 0.5 or 1.0 m above mean sea level (MSL), as well as how far future inland threats may extend (Figure 5). All future industrial and urban development in the coastal region of the MRD should be adapted to conditions within such boundaries.

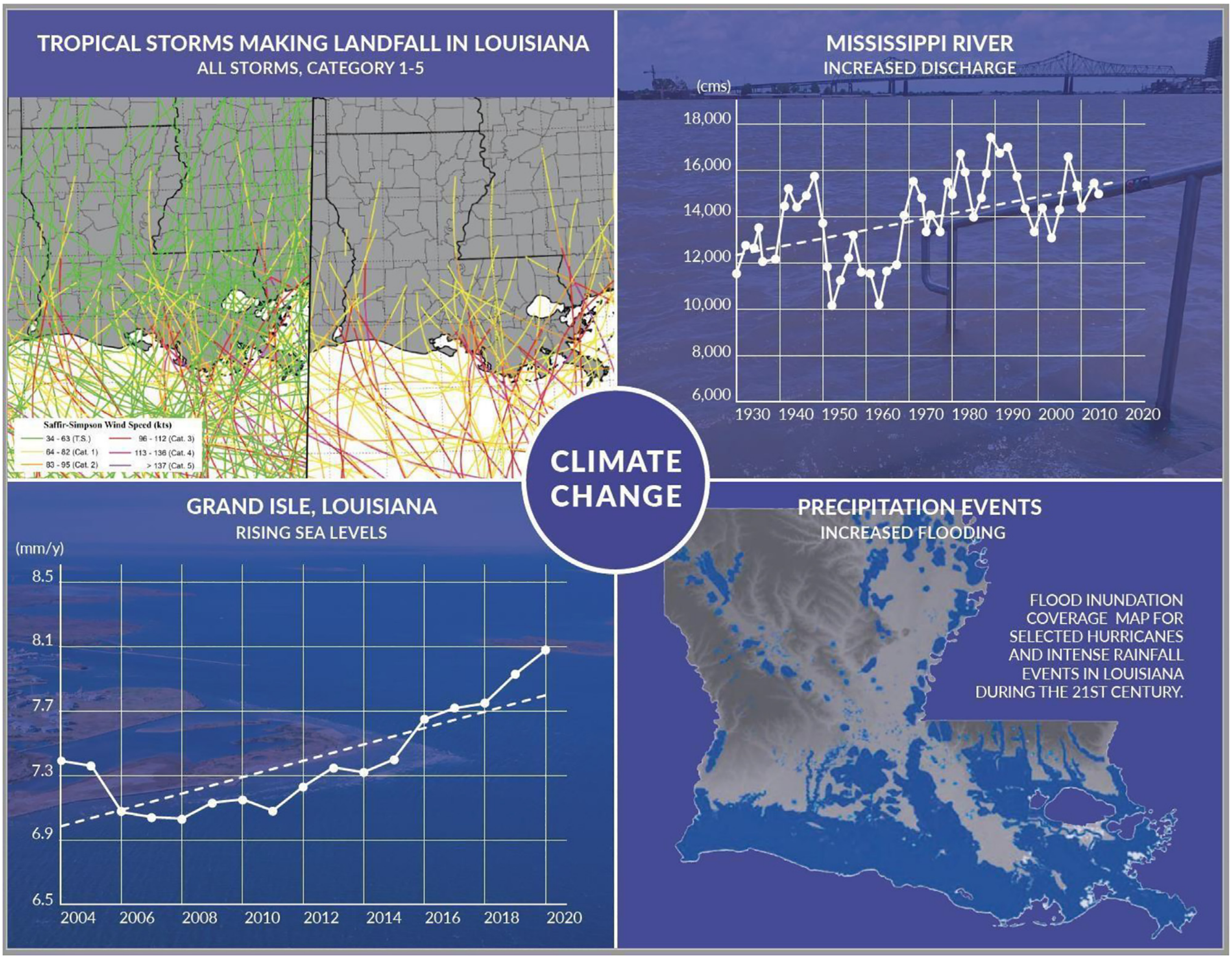

Figure 5. Climate forcings affecting the Mississippi Delta

Tropical cyclone tracks 1851–2021 (upper left). Source NOAA Digital GeoZone. (Lower left) Water level rise through 2020 at Grand Isle, LA due to both subsidence and eustatic sea-level rise (ESLR), such that relative sea-level rise (RSLR) is greater than ESLR (lower left, data source: United States, Sea-Level Report Cards). Increasing trend of Mississippi River discharge (upper right, USACE). Flooding due to extreme precipitation events in Louisiana from 2005 to 2017 (lower right[14]).

Zhong and Xu[53] show a potential elevation-based geographical seaward defensive boundary for the MRD, separating areas below and above 2 m above mean sea level (Figure 7). The most inland geographical defensive boundary should be considered above the highest of all coastal flooding projections, including rising sea levels. For hurricane surges, the NOAA has run models providing worst-case scenario storm surge flood levels for thousands of synthetic category 3 hurricanes (Figure 8). As average hurricane intensity will likely increase in this century, the projected flooding for any modeled location could be worse than shown and perhaps become more likely by the end of the century.

The inland extent of tropical storm-force winds and flooding from rainfall can extend throughout Louisiana, and category 1–5 winds can occur throughout the coastal region (Figure 5; top left). River floods from the Mississippi and local rivers, coupled with extreme rainfall events, also pose threats. In a composite flood map linked to extreme precipitation events and storm surge inundation from 2005–2017,[54] almost all of south Louisiana experienced flooding (Figure 5 bottom right). Defensive boundaries would provide a pragmatic way to calibrate adaptive measures for all delta regions. To the extent possible, these boundaries should inform planning and adaptation concerning policies such as abandonment of specific areas, retreat, and investment in sustainable and defensible areas.

Diverting river water upstream of New Orleans

Climate-enhanced river discharge will likely exceed the MR&T project design flood of ~85,000 $m^3\ s^{-1}$ (3 million $ft^3\ s^{-1}$) at the latitude of the Red River landing (the U.S. Army Corps of Engineers, USACE, 2007), with growing frequency this century. The Corps of Engineers defined the project flood in the 1930s as carrying a significantly larger peak flow than during the 1927 flood disaster, then the flood of record. The current flood control system will likely be overwhelmed by growing climate impacts. This trend is already happening at the Bonnet Carré Spillway, which was opened eight times from 1931 to 2000 and seven times from 2001 to 2023. Because the spillway does not lower water

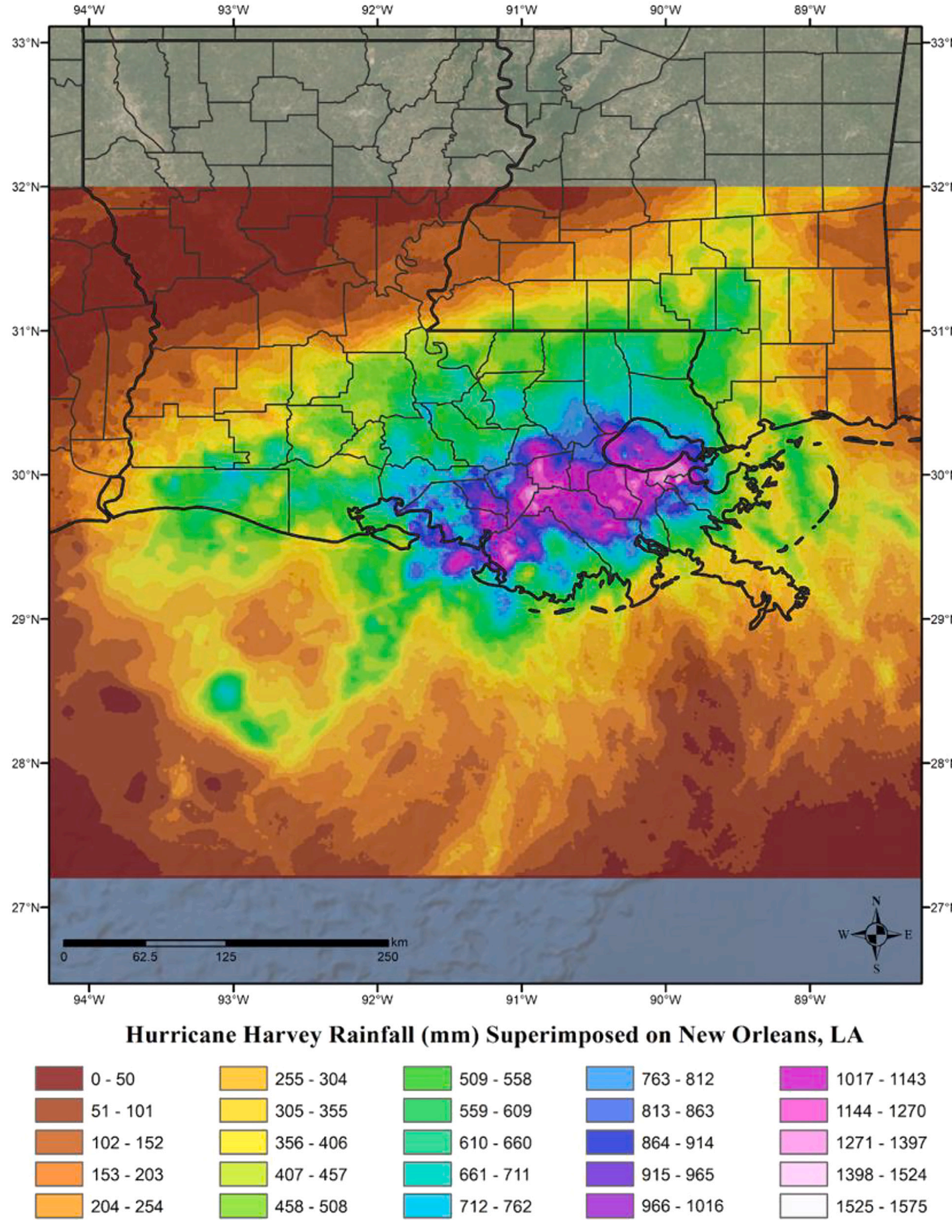

Figure 6. Hurricane Harvey rainfall over New Orleans
Footprint of Hurricane Harvey rainfall in southeast Texas centered over southeast Louisiana.[33]

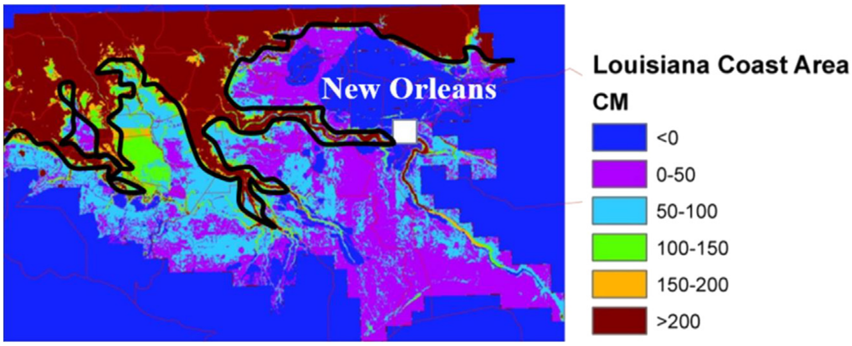

Figure 7. Topography of coastal Louisiana
Elevation in southeastern Louisiana. Black line represents 2 m MSL.[53]

levels upriver, more outlets will likely be needed to contain large floods within the current levee system without causing catastrophic levee breaches. The excess flood water that will likely leave the river can be used for coastal restoration, because diversions are part of the Coastal Master Plan.[6,14] Diverting Mississippi River water during a flood can serve several purposes. For instance, the flood water can be channeled to the Atchafalaya River to increase sediment delivery to the Atchafalaya Bay, potentially creating new land. The diverted water will provide sediments to existing wetlands and result in the establishment of new wetlands. The flood water can be used to recharge surface water to combat saltwater intrusion in southern Louisiana. The flood water can also be channeled to agricultural cropping areas that require irrigation during droughts.

The conveyance capacity of the receiving basins will limit the amount of water that can be diverted on the west bank compared to the east bank between Baton Rouge and New Orleans. On the east bank, the two outlets to the Gulf of Mexico from Lake Pontchartrain have a combined cross-section area of 11,250 m^2 (~70% of the river at New Orleans) and a mean depth of about 12 m. On the west bank near New Orleans, the outlets draining to the Gulf of Mexico have a cross-section area of less than a few hundred square meters, limiting large diversions to the west above New Orleans without causing extensive flooding. Thus, if large flow volumes must leave the river during large floods, it must be to the east. Lower discharge diversions with very high sediment concentrations could target forested wetlands on both sides of the river that are mostly permanently flooded and not sustainable.[54]

Freshwater will also provide a buffer against saltwater intrusion into these forested wetlands. Thus, more water must be redirected from the river upstream of the city as the discharge increases with climate change to protect New Orleans. Such river diversions will reduce flood risks and human vulnerability and trap sediment in areas with the highest retention rates in upstream regions of the delta. One problem is that total sediment discharge has decreased by >75% due to retention behind large Missouri River dams.[55] However, managing dams on the lower Missouri River could increase sediment transport by 100–200 million tons per year.[55]

Protecting the crucial river corridor between Baton Rouge and New Orleans

The river corridor between the two largest metropolitan areas of Louisiana and the area north of Lake Pontchartrain (Figures 1 and 9) should be a priority for flood protection as it is vital to the economy and well-being of the region. It includes Louisiana's two largest metro areas, the capital city, and the most important educational institutions. The overwhelming majority of Louisiana's industry, port-related activities, and tourism occur in this region. Eighty percent of the state gross domestic product (GDP) and 70% of the state's population is in the metropolitan statistical areas on the I-10 and I-12 corridor, with 60% of the state GDP (including 75% of tourism income) in the Baton Rouge to New Orleans corridor. Much of this activity is located on the highest part of the natural levees of the Mississippi River, where flood control levees are prone to catastrophic breaches. South of Baton Rouge, development should be concentrated on the highest parts of the natural levees and protected with ring levees, if necessary, as is the case for the New Orleans metro area. Engineering multiple outlets between Baton Rouge and New Orleans will reduce the danger of levee failure, protect economically important infrastructure adjacent to the river, and provide riverine resources for enhanced coastal restoration.

Strengthening protection of New Orleans

New Orleans presents a unique challenge for flood protection in the MRD (Figure 8). It is the largest metropolitan area in the state and, economically and culturally, of the highest relevance for the state and nation. In the nineteenth century, New Orleans expanded along the relatively high-elevation natural river levee above sea level, albeit by only a few meters. The subsequent sprawling over the twentieth century from the natural levees out (to lower elevations) toward the backswamp and Lake Pontchartrain and up and down the Mississippi River required drainage of nearby wetlands and the construction of extensively engineered levees and pump systems. Unfortunately, the expansion of cities into lowlands had two unintended and ultimately catastrophic consequences. First, the draining of highly organic wetland soils exposed them to oxidation and subsidence, and their accelerated demise reduced hurricane surge and wave protection. As a result, large city areas are now below sea level, with some regions >3 m below sea level and one point in the city along I-10 >6 m below sea level, and pumping capacity is often exceeded in heavy rainfall events causing frequent nuisance flooding with depths exceeding 1 m in some places (e.g., Mid-City) during specific events (e.g., August 2017). Since the mid-twentieth century, catastrophic flooding from hurricanes has occurred three times (in 1965 from Hurricane Betsy and in 2005 from Hurricanes Katrina and Rita), but the probability of such events is increasing.

Hurricane Katrina's landfall in the eastern Mississippi Delta provides the textbook example of unintended catastrophic consequences of urban development within regions

Please cite this article in press as: Day et al., Emerging climate threats to the Mississippi River Delta: Moving from restoration to adaptation, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.03.001

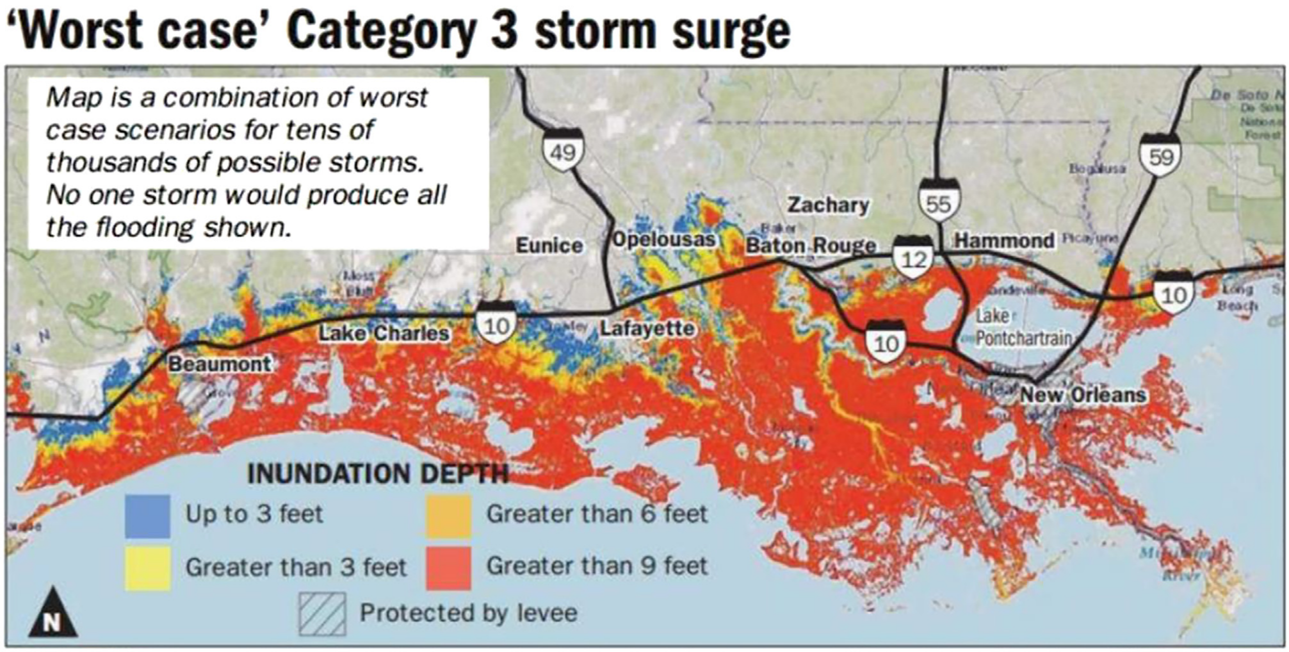

Figure 8. Hurricane storm surge risk in coastal Louisiana
The map projects modeled worst-case flooding for a category 3 storm at any given location in coastal Louisiana[12] (3 ft is approximately 1 m).

vulnerable to climate change. Still, almost two decades after the event, the New Orleans metro area remains among the most threatened urban areas in the United States. The region has not fully recovered after the catastrophic flooding and loss of life due to levee breaches in 2005.[56] Most buildings were repaired in place, and very few flooded structures were raised above flood levels.[57] Maintenance of the complex protection infrastructure around the city may become increasingly untenable as the threat of flooding intensifies. Even with the recent strengthening of the perimeter levees, the city is still susceptible to extreme rainfall events, as occurred in Houston during Hurricane Harvey. Without radical rethinking of the adaptation strategy to living within a deltaic environment, it is virtually certain that New Orleans will flood catastrophically again in this century (see Figure 6). New approaches are needed to integrate resilience into the metropolitan area's long-term sustainability planning. It is critically important that residents and infrastructure intolerant of flooding be raised above sea level.

Erdman et al.[58] proposed a bold new vision to make New Orleans resilient in the twenty-first century and beyond by providing additional protection along the Lake Pontchartrain shoreline. Ideally, the plan would raise most living areas at least 5 m above sea level (Figure 8). Their two-part strategy includes reinforcing the lake edge (known as the lakefront) along Lake Pontchartrain using infill to extend the higher ground by an additional 65 km^2 and fronted by a cypress swamp. Subsequently, a series of leveed polders would be developed by filling with river sediment, raising structures inside the polder, or managing them for aquatic and wetland systems that could serve as floodwater detention reservoirs. The cost of implementing this plan is estimated at $5–7 billion.[58]

Protecting and sustaining the fishing industry

Coastal Louisiana supports a multibillion-dollar commercial and recreational fishery, one of the largest fisheries in North America.[17] Much of the fishing industry population and infrastructure is located along low-lying abandoned distributary ridges. Some of the lower coast will have to be abandoned for permanent habitation. A central question is what can be truly protected in place and what must be relocated. Many commercial saltwater and estuarine fisheries (oysters, shrimp, crabs, and finfish) are conducted by individual fishers with a home base in the delta along the seaward tips of abandoned distributary channels. These areas are strategic because they are close to major fishing areas, but almost none have fully effective flood protection. As a result, these communities are exposed to hurricane winds and surges, and each major storm causes significant damage to fishing vessels and other infrastructure. For example, during Hurricane Katrina, the communities of Hopedale, Shell Beach, and Yscloskey in St. Bernard Parish experienced a storm surge of 5.7 m,[45] and 1-min sustained winds near 160 kph, as estimated by NOAA's Atlantic Oceanographic and Meteorological Laboratory.

Adequate hurricane protection for these linear communities is difficult and expensive. We suggest the idea of fortified fishing communities (Figure 9) to withstand major hurricanes. Enclosure by high, hurricane-proof levees with strong gates would protect settlements of 100 fishing vessels with processing facilities and temporary housing. Buried natural gas and electrical power lines would be provided to complement solar and wind energy. Facilities would be closed during storms, and most anglers would move to safe, higher ground. Additionally, there must be plans for the "up-the-bayou" movement of local populations to areas safe from flooding.

Please cite this article in press as: Day et al., Emerging climate threats to the Mississippi River Delta: Moving from restoration to adaptation, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.03.001

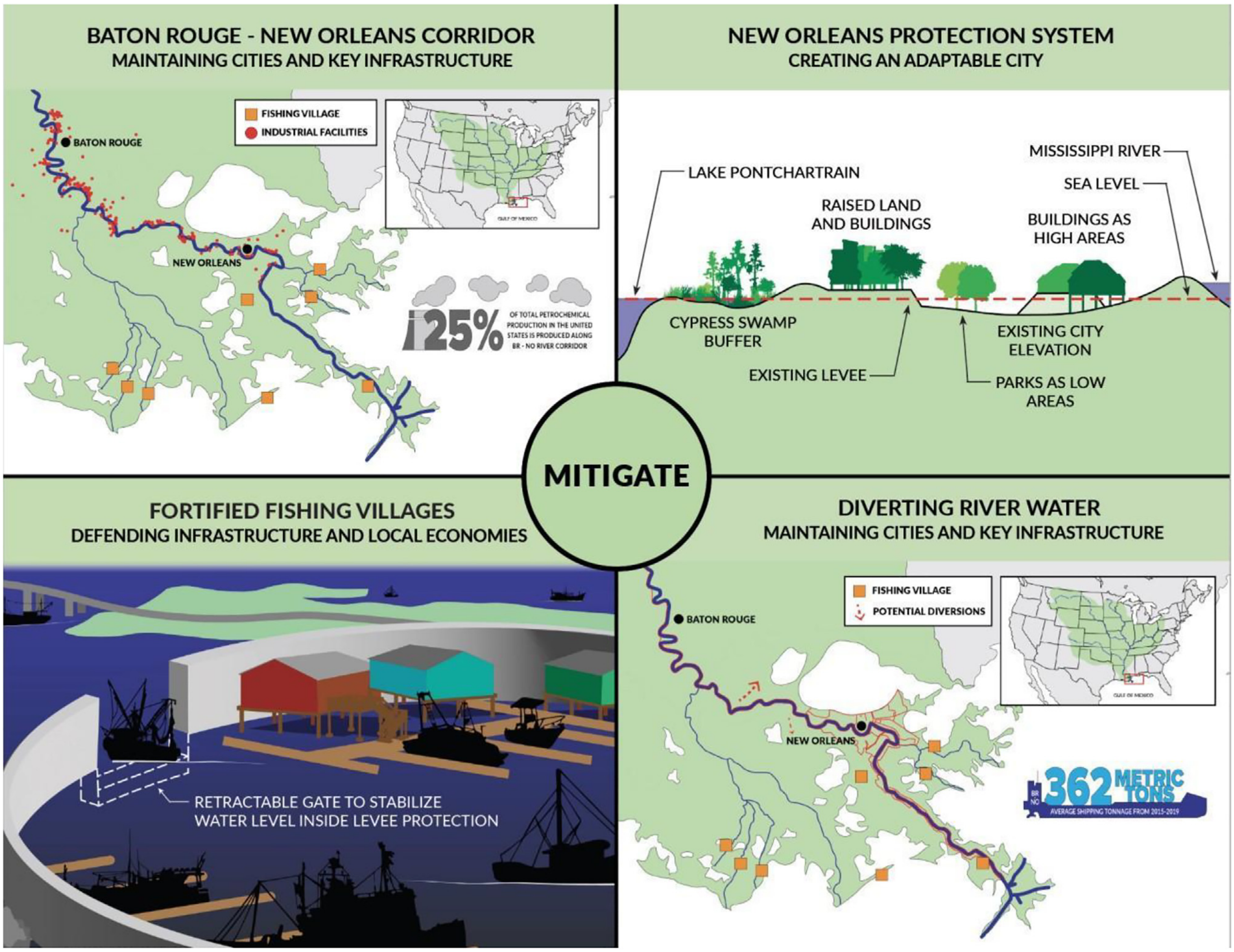

Figure 9. Climate adaptation strategies for the Mississippi River Delta
Key infrastructure along the Mississippi River and fortified fishing villages (upper left). Conceptual diagram of a fortified fishing village (bottom left). Floodproofing New Orleans by raising infrastructure (upper right, modified from Erdman et al.[58]). Proposed locations for Mississippi River diversions (lower right). Image prepared by Joshua Crawford.

Although no development is specifically designed to protect fishing infrastructure, several small communities and agricultural lands are ring-leveed to various degrees of protection. Generally, these areas are at least partially below sea level. For example, there is a plan to provide a ring levee for the town of Lafitte south of New Orleans on the west bank of the river, which experienced extensive damage in 2021 when category 4 Hurricane Ida passed over the area. This plan includes about 46 km of earthen levees and T-wall levees, seven gates, and various other features. The Lafitte plan would cost \$1.2–1.5 billion. The idea of protected areas for fishing infrastructure has been discussed for some time in the context of storm-proofing living areas.[59,60] Based on the above considerations, ring-leveed protection with a circumference of about 1.5 km could be built for $\leq$\$100 million. Louisiana's commercial and recreational fishing industry has a value of several billion dollars annually. Thus, fortified fishing villages seem a reasonable investment given the value of the fishing industry to Louisiana and the nation. Such facilities would not be below sea level because they are designed to accommodate boats floating at sea level and built infrastructure would be built above sea level.

GLOBAL IMPLICATIONS

The perspectives of this paper have broad implications for deltas worldwide, as they are at the forefront of climate effects and are among the most threatened natural systems. The MRD has one of the most comprehensive restoration plans globally, and lessons learned will be applicable globally.

Here, we compare human impacts and management suggestions for several global deltas. The Ebro Delta and basin in northeastern Spain receives most of its water from the southern flank of the Pyrenees, but much of the basin is semi-arid. Large dams on the Ebro River have reduced sediment discharge to the delta by more than 95%, and freshwater reaching the delta has been greatly reduced.[61] As in the Mississippi River, where Kemp et al.[55] showed that sediment delivery could be substantially increased by sediment bypassing, this is necessary for the

Ebro if the delta is to survive. Interestingly, most wetlands in the delta have been converted to rice fields. Before the construction of the large dams on the Ebro River, sediment-laden water was delivered to much of the delta via a network of irrigation canals, which offset subsidence.[61] The loss of riverine sediments has resulted in a loss of elevation, and the fringes of the delta are sinking below sea level. As with the Mississippi Delta, sediment bypassing will be necessary if the Ebro Delta is to survive. A rethinking of the Spanish National Hydrological Plan will be necessary if sufficient sediment and freshwater discharge to ensure a more sustainable delta.[62] For the Po, Rhone, and Ebro deltas, areas with active riverine input had surface elevation gain greater than relative sea-level rise, while impounded areas had elevation gain almost 10 times less.[63] In the Rhone Delta, Pont et al.[64] reported that two large floods that breached the levees led to much greater levels of sediment deposition, showing the importance of high levels of riverine input to delta sustainability.

Up-basin-down-basin competition for freshwater is challenging within a single country such as Spain but is much more complicated if river basins span several countries. In the Nile basin, most water comes from tropical precipitation in the highlands of tropical Africa. The seasonal floods of the Nile sustained not only Egyptian civilization but also the Nile Delta.[4,65] With the construction of the Aswan High Dam, sediment discharge was dramatically reduced, and much water was lost via evaporation. The new Grand Ethiopian Renaissance Dam (GERD) will further reduce freshwater and sediment discharge in the Nile and has increased tensions between Ethiopia, and Egypt, and Sudan. Such conflicts are common, especially in semi-arid basins that are shared with several countries. Examples include the Nile, Colorado, Tigris-Euphrates, and Indus basins.[4,65] Water availability in arid basins is declining due to growing demand for water and climate change, leading to more drought. Even in water-rich basins, the construction of dams results in less sediment transport downstream. The Mekong is a case in point. Until relatively recently, the Mekong had few dams, but there has been a dramatic increase in dam construction, resulting in reduced sediment transport.[66] The Three Gorges Dam in China has also significantly reduced sediment transport to the coast. There is a need to implement sediment bypassing to increase sediment transport to coastal deltas.

Within deltas, there is a need to reconnect rivers to the deltaic plain. In the Mississippi Delta, levees have prevented most riverine input, leading to widespread wetland loss. In deltas with high rainfall basins (most topical deltas and the Mississippi), increasing discharge due to climate change and river basin management will threaten flood control systems. Clearly, providing managed outlets to the river floodplain and deltaic plain will become necessary. One additional issue is the viability of maintaining areas below sea level with climate forcings (TCs, extreme precipitation events, larger river floods). Deltas with areas below sea level include the Mississippi, Rhine, Ebro, Po, Nile, and Yangtze. Consideration should be given to raising or relocating critical infrastructure.

CONCLUSIONS

The MRD is one of the largest deltas in the world. It sustains the world's largest commodity port, supports many energy infrastructure facilities and petrochemical plants that are of national importance, and nurtures a historic American port city and tourist destination. However, its existence is seriously threatened by climate change and human impacts. The stressors include increasing Mississippi River discharge, accelerating climatically controlled sea-level rise exacerbated by high subsidence rates, intensifying hurricane impacts, and more extreme precipitation events. Human activities such as the isolation of much of the deltaic plain by levees and pervasive hydrologic alteration of the deltaic plain have further contributed to the magnitude of the stressors. These impacts affect the economically important river corridor between Baton Rouge and New Orleans and threaten the fishing industry's viability. We urge an immediate shift from the current restoration-centered approach to climate-adaptation-focused planning. We offer suggestions for protecting the vital river corridor and the City of New Orleans, building fortified fishing villages, and making difficult decisions about what can be protected. Large diversions upstream of New Orleans will likely be necessary to alleviate pressure on the flood control system due to increasing river discharge and to protect the city. These diversions would also build new wetlands and protect existing ones.

There are several large-scale ongoing initiatives that we believe could benefit from the information presented in our review, including the Corps of Engineers Mississippi River Hydrodynamics and Delta Management Study; the CPRA Coastal Lowermost Mississippi River Management Program; and the recently funded National Academies of Sciences, Engineering, and Medicine Mississippi River Delta Transition Initiative Consortium. These programs seek to enhance sustainable restoration of the lower Mississippi and delta, but the strategies developed in these programs and our perspectives can be also transferable to dealing with the complexity of coupled human and natural systems in other river deltas.

We believe the findings of our paper provide insights for these initiatives. A range of future trajectories identified in our paper must be addressed in such studies. Climate change is leading to dramatic changes for the region, including accelerating sea-level rise, increased frequency of stronger hurricanes, more extreme precipitation events, and increased discharge of the Mississippi River but lower sediment discharge. The MR&T project flood will likely be exceeded due to increased river discharge and extreme precipitation. This means more water will have to leave the river below and above New Orleans. Where will outlets be, and how many? These outlets can benefit coastal restoration through wetland creation and offsetting subsidence if properly designed. Kemp et al.[55] suggested that enhancement of sediment bypassing from lower Missouri River dams could enhance sediment transport by 100–200 million metric tons per year. Consideration should also be given to the larger dams on the upper Missouri. A central issue is how to repair damage to the delta due to flood control, navigation, and energy industry activities. How will a future with less fossil energy affect restoration activities? Finally, the study must consider that areas below sea level, especially the New Orleans metropolitan area, will likely become untenable in this century. A failure of New Orleans is likely under current management and would lead to dramatic economic impacts in southeast Louisiana. Erdman et al.[58] outlined an approach that includes raised structures, raised land, and using areas to store excess water.

New options for sustainable management must consider escalating climate threats, the degree to which the most important economic activities can be protected, sustaining the fishing industry, and the viability of different coastal regions. A fundamental problem underlying the multiple threats in the MRD is that the environmental baseline that existed for centuries and millennia for the formation and growth of the delta, and human habitation, whether Native Americans or Europeans and other immigrants, has shifted dramatically recently. Such baseline conditions are no longer suitable for the delta and its human inhabitants.[67] Despite a highly dynamic coastal system for centuries, natural ecosystems and human communities coexisted sustainably. The fluvial system maintained the natural deltaic system, and human communities developed lifestyles and enhanced resilience adapted to a dynamic coast. The new anthropogenic baselines during the twenty-first century, which are attributable to climate change in conjunction with human development and growing resource scarcity, will reflect conditions never experienced before by the MRD.

The sustainability and resilience of the delta will depend on new adaptation strategies tailored for a future outside of the historic norm for this coupled natural-human system. Nevertheless, a sustainable future is possible for the MRD. Its communities will differ from the past and depend on difficult decisions of what to protect and abandon. Our objective in this paper has been to describe actions that can replicate the conditions that will allow the delta and its inhabitants to survive.

This investigation of the Mississippi Delta demonstrates that impacts on the delta result from changes in basin inputs and direct impacts on the deltaic plain. Insights gained from the MRD lead to implications for other coupled natural-human delta systems. Basin-level impacts on deltas include changes in freshwater and sediment discharge and changes in the biogeochemistry of river waters. These changes come into clearer focus because changes in basin-level inputs have occurred over just the past two centuries as opposed to many European and Asian deltas that have been affected for much longer periods, such as the Nile and Rhine.[68] In the Mississippi Delta, sediment discharge has been reduced by about half, while there has been a significant increase in freshwater discharge over the past half-century, albeit with high variability ranging to extremely low water years (e.g., 2023).

DATA AND CODE AVAILABILITY

All data are publicly available in the cited references in this manuscript. Additionally, data are available from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

J.W.D contributed writing and editing. Y.J.X. contributed writing, editing, and formatting. B.D.K. contributed writing and editing. V.M.B. contributed writing and graphics support. L.G. contributed writing and editing. M.E.M. contributed writing and editing. J.R.S. contributed to writing, formatting, and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Bentley, S.J., Blum, M.D., Maloney, J., Pond, L., and Paulsell, R. (2016). The Mississippi River source-to-sink system: Perspectives on tectonic, climatic, and anthropogenic influences, Miocene to Anthropocene. Earth Sci. Rev. *153*, 139–174. https://doi.org/10.1016/j.earscirev.2015.11.001.
2. Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., and Nicholls, R.J. (2009). Sinking deltas due to human activities. Nature Ge *2*, 681–686. https://doi.org/10.1038/ngeo629.
3. Day, J.W., Jr., Boesch, D.F., Clairain, E.J., Kemp, G.P., Laska, S.B., Mitsch, W.J., Orth, K., Mashriqui, H., Reed, D.J., Shabman, L., et al. (2007). Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. Science *315*, 1679–1684. https://doi.org/10.1126/science.1137030.
4. Couvillion, B.R., Beck, H., Schoolmaster, D., and Fischer, M. (2017). *Land area Change in Coastal Louisiana (1932 to 2016)* (No. 3381) (US Geological Survey).
5. Fluet-Chouinard, E., Stocker, B.D., Zhang, Z., Malhotra, A., Melton, J.R., Poulter, B., Kaplan, J.O., Goldewijk, K.K., Siebert, S., Minayeva, T., et al. (2023). Extensive global wetland loss over the past three centuries. Nature *614*, 281–286. https://doi.org/10.1038/s41586-022-05572-6.
6. Coastal Protection and Restoration Authority of Louisiana (2023). Draft Master Plan: Louisiana's Comprehensive Master Plan for a Sustainable Coast, 4th Edition. Draft Plan. Baton Rouge, LA. URL: https://coastal.la.gov/wp-content/uploads/2023/06/230531_CPRA_MP_Final-for-web_spreads.pdf
7. Wang, Z., Boyer, T., Reagan, J., and Hogan, P. (2023). Upper-Oceanic Warming in the Gulf of Mexico between 1950 and 2020. J. Clim. *36*, 2721–2734. https://doi.org/10.1175/JCLI-D-22-0409.1.
8. Allard, J., Clarke III, J.V., and Keim, B.D. (2016). Spatial and temporal patterns of in situ sea surface temperatures within the Gulf of Mexico from 1901-2010. Am. J. Clim. Change *05*, 314–343. https://doi.org/10.4236/ajcc.2016.53025.
9. Li, G., Wang, Z., and Wang, B. (2022). Multidecade trends of sea surface temperature, chlorophyll-a concentration, and ocean eddies in the Gulf of Mexico. Rem. Sens. *14*, 3754. https://doi.org/10.3390/rs14153754.
10. Ochoa, J., Ferreira-Bartrina, V., Candela, J., Sheinbaum, J., López, M., Pérez-Brunius, P., Herzka, S., and Amon, R.M. (2021). Deep-Water Warming in the Gulf of Mexico from 2003 to 2019. J. Phys. Oceanogr. *51*, 1021–1035. https://doi.org/10.1175/JPO-D-19-0295.1.
11. (2021). Climate Change and the 1991-2020 U.S. Climate Normals. https://www.climate.gov/news-features/understanding-climate/climate-change-and-1991-2020-us-climate-normals.
12. IPCC (2022). In Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, and V. Möller, et al., eds. (Cambridge University Press. In Press).
13. Sweet, W.V., Hamlington, B.D., Kopp, R.E., Weaver, C.P., Barnard, P.L., Bekaert, D., Brooks, W., Craghan, M., Dusek, G., T., et al. (2022). Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. Retrieved on February 23, 2024. https://ntrs.nasa.gov/api/citations/20180001857/downloads/20180001857.pdf.
14. Coastal Protection and Restoration Authority of Louisiana (2017). Louisiana's Comprehensive Master Plan for a Sustainable Coast. Coastal Protection and Restoration Authority of Louisiana. Baton Rouge, LA. URL: https://coastal.la.gov/wp-content/uploads/2017/04/2017-Coastal-Master-Plan_Web-Book_CFinal-with-Effective-Date-06092017.pdf
15. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf
16. Yin, S., Gao, G., Li, Y., Xu, Y.J., Turner, R.E., Ran, L., Wang, X., and Fu, B. (2023). Long-term trends of streamflow, sediment load and nutrient fluxes from the Mississippi River Basin: Impacts of climate change and human activities. J. Hydrol. *616*, 128822. https://doi.org/10.1016/j.jhydrol.2022.128822.
17. Easterling, D.R., Kunkel, K.E., Arnold, J.R., Knutson, T., LeGrande, A.N., Leung, L.R., Vose, R.S., Waliser, D.E., and Wehner, M.F. (2017). Precipitation change in the United States. In Climate Science Special Report: Fourth National Climate Assessment, Volume I [Wuebbles, D.J.., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock, eds. (Washington, DC, USA: U.S. Global Change Research Program), pp. 207–230. https://doi.org/10.7930/J0H993CC.

18. Brown, V.M., Keim, B.D., and Black, A.W. (2019). Climatology and Trends in Hourly Precipitation for the Southeast United States. J. Hydrometeorol. *20*, 1737–1755. https://doi.org/10.1175/JHM-D19-0004.1.

19. Van Der Wiel, K., Kapnick, S.B., Van Oldenborgh, G.J., Whan, K., Philip, S., Vecchi, G.A., Singh, R.K., Arrighi, J., and Cullen, H. (2017). Rapid attribution of the August 2016 flood-inducing extreme precipitation in south Louisiana to climate change. Hydrol. Earth Syst. Sci. *21*, 897–921. https://doi.org/10.5194/hess-21-897-2017.

20. Trenberth, K.E., Cheng, L., Jacobs, P., Zhang, Y., and Fasullo, J. (2018). Hurricane Harvey links to ocean heat content and climate change adaptation. Earth's Future *6*, 730–744. https://doi.org/10.1029/2018EF000825.

21. Min, S.K., Zhang, X., Zwiers, F.W., and Hegerl, G.C. (2011). Human contribution to more intense precipitation extremes. Nature *470*, 378–381. https://doi.org/10.1038/nature09763.

22. Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D., and Allen, M.R. (2011). Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. Nature *470*, 382–385. https://doi.org/10.1038/nature09762.

23. Keim, B.D., Kappel, W.D., Muhlestein, G.A., Hultstrand, D.M., Parzybok, T.W., Lewis, A.B., Tomlinson, E.M., and Black, A.W. (2018). Assessment of the extreme rainfall event at Nashville, TN and the surrounding region on May 1–3, 2010. J. American Water Resour. Assoc. *54*, 1001–1010. https://doi.org/10.1111/1752-1688.12657.

24. Trenberth, K.E., Dai, A., Rasmussen, R.M., and Parsons, D.B. (2003). The changing character of precipitation. Bull. Am. Meteorol. Soc. *84*, 1205–1218. https://doi.org/10.1175/BAMS84-9-1205.

25. Trenberth, K.E. (2011). Changes in precipitation with climate change. Clim. Res. *47*, 123–138. https://doi.org/10.3354/cr00953.

26. Prein, A.F., Rasmussen, R.M., Ikeda, K., Liu, C., Clark, M.P., and Holland, G.J. (2017). The future intensification of hourly precipitation extremes. Nat. Clim. Chang. *7*, 48–52. https://doi.org/10.1038/nclimate3168.

27. Nogueira, R.C., and Keim, B.D. (2011). Contributions of Atlantic tropical cyclones to monthly and seasonal rainfall in the eastern United States 1960–2007. Theor. Appl. Climatol. *103*, 213–227. https://doi.org/10.1007/s00704-010-0292-9.

28. Knutson, T.R., Sirutis, J.J., Zhao, M., Tuleya, R.E., Bender, M., Vecchi, G.A., Villarini, G., and Chavas, D. (2015). Global projections of intense tropical cyclone activity for the late twenty-first century from dynamical downscaling of CMIP5/RCP4.5 scenarios. J. Clim. *28*, 7203–7224. https://doi.org/10.1175/JCLI-D-15-0129.1.

29. Liu, M., Vecchi, G.A., Smith, J.A., and Knutson, T.R. (2019). Causes of large projected increases in hurricane precipitation rates with global warming. npj Clim. Atmos. Sci. *2*, 38. https://doi.org/10.1038/s41612-019-0095-3.

30. Elsner, J.B., Strazzo, S.E., Jagger, T.H., LaRow, T., and Zhao, M. (2013). Sensitivity of Limiting Hurricane Intensity to SST in the Atlantic from Observations and GCM. J. Clim. *26*, 5949–5957. https://doi.org/10.1175/JCLI-D-12-00433.1.

31. Hall, T.M., and Kossin, J.P. (2019). Hurricane stalling along the North American coast and implications for rainfall. npj Clim. Atmos. Sci. *2*, 17–19. https://doi.org/10.1038/s41612-0190074-8.

32. Tu, S., Chan, J.C.L., Xu, J., Zhong, Q., Zhou, W., and Zhang, Y. (2022). Increase in tropical cyclone rain rate with translation speed. Nat. Commun. *13*, 7325–7328. https://doi.org/10.1038/s41467-022-35113-8.

33. Van Oldenborgh, G.J., Van Der Wiel, K., Sebastian, A., Singh, R., Arrighi, J., Otto, F., Haustein, K., Li, S., Vecchi, G., and Cullen, H. (2017). Attribution of extreme rainfall from Hurricane Harvey. Environ. Res. Lett. *12*, 124009. https://doi.org/10.1088/1748-9326/aa9ef2.

34. Applied Weather Associates, L.L.C. (2019). Regional probable maximum precipitation study for Oklahoma, Arkansas, Louisiana, and Mississippi final report. Tech. rep. URL. https://www.owrb.ok.gov/damsafety/pdf/2019RegionalPMPStudy.pdf.

35. Reiman, J.H., and Xu, Y.J. (2019). Dissolved carbon export and CO_2 outgassing from the Lower Mississippi River – Implications of future river carbon fluxes. J. Hydrol. *578*, 124093. https://doi.org/10.1016/j.jhydrol.2019.124093.

36. Tao, B., Tian, H., Ren, W., Yang, J., Yang, Q., He, R., Cai, W., and Lohrenz, S. (2014). Increasing Mississippi river discharge throughout the 21st century influenced by changes in climate, land use, and atmospheric CO2. Geophys. Res. Lett. *41*, 4978–4986. https://doi.org/10.1002/2014GL060361.

37. Keim, B.D., Muller, R.A., and Stone, G.W. (2007). Spatiotemporal Patterns and Return Periods of Tropical Storm and Hurricane Strikes from Texas to Maine. J. Clim. *20*, 3498–3509. https://doi.org/10.1175/JCLI4187.1.

38. Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C.H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., and Wu, L. (2020). Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. Bull. Am. Meteorol. Soc. *101*, 303–322. https://doi.org/10.1175/BAMS-D-18-0194.1.

39. Emanuel, K. (2021). Response of Global Tropical Cyclone Activity to Increasing CO2: Results from Downscaling CMIP6 Models. J. Clim. *34*, 57–70. https://doi.org/10.1175/JCLI-D-20-0367.1.

40. Mei, W., Xie, S.P., Primeau, F., McWilliams, J.C., and Pasquero, C. (2015). Northwestern Pacific typhoon intensity controlled by changes in ocean temperatures. Sci. Adv. *1*, 1500014. https://doi.org/10.1126/sciadv.1500014.

41. Webster, J., Holland, G., Curry, J., and Chang, H. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. Science *309*, 1844.

42. Hoyos, C., Agudelo, P., Webster, P., and Curry, J. (2006). Deconvolution of the factors contributing to the increase in global hurricane intensity. Sci. *312*, 94–97.

43. Bender, M., Knutson, T., Tuleya, R., Sirutis, J.J., Vecchi, G.A., Garner, S.T., and Held, I.M. (2010). Modeled impact of anthropogenic warming on the frequency of intense Atlantic hurricanes. Sci. *327*, 454–458.

44. Elsner, J. B., Kossin, J. P., and Jagger, T. H. (2008). The increasing intensity of the strongest tropical cyclones. Nature *455*, 92–95.

45. Needham, H.F., and Keim, B.D. (2012). A Storm Surge Database for the U.S. Gulf Coast. Int. J. Climatol. *32*, 2108–2123. https://doi.org/10.1002/joc.2425.

46. Grinsted, A., Moore, J.C., and Jevrejeva, S. (2012). Homogeneous record of Atlantic hurricane surge threat since 1923. Proc. Natl. Acad. Sci. *109*, 19601–19605. https://doi.org/10.1073/pnas.1209542109//DCSupplemental.

47. Bhatia, K.T., Vecchi, G.A., Knutson, T.R., Murakami, H., Kossin, J., Dixon, K.W., and Whitlock, C.E. (2019). Recent increases in tropical cyclone intensification. Nat. Commun. *10*, 635. https://doi.org/10.1038/s41467-019-08471-z.

48. Li, L., and Chakraborty, P. (2020). Slower decay of landfalling hurricanes in a warming world. Nature *587*, 230–234. https://doi.org/10.1038/s41586-020-2867-7.

49. Gori, A., Lin, N., Xi, D., et al. (2022). Tropical cyclone climatology change greatly exacerbates US extreme rainfall–surge hazard. Nat. Clim. Chang. *12*, 171–178. https://doi.org/10.1038/s41558-021-01272-7.

50. Garner, A.J., Mann, M.E., Emanuel, K.A., Kopp, R.E., Lin, N., Alley, R.B., Horton, B.P., DeConto, R.M., Donnelly, J.P., and Pollard, D. (2017). Impact of climate change on New York City's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 CE. Proc. Natl. Acad. Sci. *114*, 11861–11866.

51. Freeman, A.M., Pahl, J.W., White, E.D., Langlois, S., Lindquist, D.C., Raynie, R.C., and Sharp, L.A. (2021). A Review of How Uncertainties in Management Decisions Are Addressed in Coastal Louisiana Restoration. Water *13*, 1528. https://doi.org/10.3390/w13111528.

52. Day, J., Hunter, R., Kemp, G., Moerschbaecher, M., and Brantley, C. (2021). The ''problem'' of New Orleans and diminishing sustainability of Mississippi River management – Future options. Water *13*, 813. https://doi.org/10.3390/w13060813.

53. Zhong, B., and Xu, Y.J. (2011). Risk of inundation to coastal wetlands and soil organic carbon and organic nitrogen accounting in Louisiana, USA. Environ. Sci. Technol. *45*, 8241–8246. https://doi.org/10.1021/es200909g.

54. Laska, S. (2020). Louisiana's Response to Extreme Weather: A Coastal State's Adaptation Challenges and Successes (Cham, Switzerland: Springer Nature). https://doi.org/10.1007/978-3-030-27205-0.

55. Kemp, G.P., Day, J.W., Rogers, J.D., Giosan, L., and Peyronnin, N. (2016). Enhancing mud supply to the Mississippi River delta: Dam bypassing and coastal restoration. Estuar. Coast Shelf Sci. *183*, 304–313. https://doi.org/10.1016/j.ecss.2016.07.008.

56. Glavovic, B.C. (2014). Waves of Adversity, Layers of Resilience: Floods, Hurricanes, Oil Spills and Climate Change in the Mississippi Delta. In Adapting to Climate Change: Lessons from Natural Hazards Planning, B.C. Glavovic and G.P. Smith, eds. (Dordrecht, The Netherlands: Springer), pp. 369–403. https://doi.org/10.1007/978-94-017-8631-7_15.

57. Colten, C. (2021). State of Disaster: A Historical Geography of Louisiana's Land Loss Crisis (Baton Rouge, LA.: LSU Press), p. 187.

58. Erdman, J.A., James, C.W., Croakley, G.P., and Williams, E.A. (2018). Raising New Orleans: The Marais Design Strategy. In Mississippi Delta Restoration, J. Day and J. Erdman, eds. (New York, NY, USA: Springer), pp. 171–200. https://doi.org/10.1007/978-3-319-65663-2_11.

59. J.W. Day and J.A. Erdman, eds. (2018). Mississippi delta restoration: pathways to a sustainable future (Springer). https://doi.org/10.1007/978-3-319-65663-2.

60. Day, J., Colten, C., and Kemp, P. (2019). Mississippi delta restoration and protection: Shifting baselines, diminishing resilience, and growing non-sustainability. In Coasts and Estuaries - The Future, E. Wolanski, J. Day, M. Elliott, and R. Ramachandran, eds. (Amsterdam: Elsevier), pp. 173–192. Chapter 10. https://doi.org/10.1016/B978-0-12-814003-1.00010-1.

61. Ibàñez, C., Canicio, A., Day, J.W., and Curcó, A. (1997). Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebre Delta, Spain. J. Coast Conserv. *3*, 191–202.

62. Day, J.W., Abrami, G., Rybczyk, J., and Mitsch, W. (2005). Venice Lagoon and the Po Delta; system functioning as a basis for sustainable management. In Flooding and environmental challenges for Venice and its lagoon; state of knowledge (Cambridge University Press), pp. 445–459.

63. Day, J., Ibáñez, C., Scarton, F., Pont, D., Hensel, P., Day, J., and Lane, R. (2011). Sustainability of Mediterranean deltaic and lagoon wetlands with sea-level rise: the importance of river input. Estuar. Coast *34*, 483–493. https://doi.org/10.1007/s12237-011-9390-x.

64. Pont, D., Day, J.W., and Ibáñez, C. (2017). The impact of two large floods (1993–1994) on sediment deposition in the Rhône delta: Implications for sustainable management. Sci. Total Environ. *609*, 251–262. https://doi.org/10.1016/j.scitotenv.2017.07.155.

65. Chen, Z. (2019). A Brief Overview of Ecological Degradation of the Nile Delta: What We Can Learn. Coasts and Estuaries, 233–236. https://doi.org/10.1016/B978-0-12-814003-1.00013-7.

66. Nhan, N.H., and Cao, N.B. (2019). Damming the Mekong: Impacts in Vietnam and solutions. In Coasts and Estuaries (Elsevier), pp. 321–340. https://doi.org/10.1016/B978-0-12-814003-1.00019-8.

67. Colten, C., and Day, J. (2018). Resilience of natural systems and human communities in the Mississippi Delta: Moving beyond adaptability due to shifting baselines. In Sustainable Coastal Design and Planning, E. Mossop, ed. (CRC Press). https://doi.org/10.1201/9780429458057-16.

68. Syvitski, J., Anthony, E., Saito, Y., Zăinescu, F., Day, J., Bhattacharya, J.P., and Giosan, L. (2022). Large deltas, small deltas: Toward a more rigorous understanding of coastal marine deltas. Global Planet. Change *218*, 103958. https://doi.org/10.1016/j.gloplacha.2022.103958.