Climate Change in Areas of the Gulf of Mexico With High Freshwater Input – A Review of Impacts and Potential Mitigation

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Resumen
El Golfo de México se extiende cubriendo la transición de ecosistemas costeros desde el trópico hasta climas templados, pero esto está cambiando conforme el norte del Golfo transita hacia una tropicalización y que lo volverá tropical por completo en este siglo. El objetivo de este artículo fue revisar información sobre los impactos del cambio climático en los ecosistemas costeros con grandes cantidades de entrada de agua dulce del golfo de México; y revisar las medidas de mitigación para abordar el cambio climático. Existen dos áreas de grandes descargas de agua dulce, una que rodea el río Mississippi en la parte centro-norte del Golfo y otra en el sur del Golfo, la cual está asociada con el río Grijalva-Usumacinta y los ríos adyacentes, así como la descarga de agua subterránea de la Península de Yucatán. Ambas zonas se caracterizan por contar con extensiones grandes de humedales y en el sur del Golfo, también se encuentra vegetación acuática sumergida. Estos ecosistemas costeros sustentan recursos naturales importantes, tienen una alta producción de petróleo, así como un intenso comercio marítimo. El cambio climático impactará ambas zonas fuertemente. La elevación del nivel del mar se proyecta que incremente un metro o más para el año 2100 y habrá más huracanes fuertes y grandes, con lluvias más intensas que se moverán más lento y la tasa de intensificación se incrementará. En el norte, la descarga pico del río Mississippi está proyectada que aumentará de un 10-60%. En el sur del Golfo, están proyectados decrementos en las precipitaciones y descarga de agua dulce, asociado con la región de Mesoamérica. El manejo costero para abordar el cambio climático deberá imitar el funcionamiento de los ecosistemas. Acciones específicas incluyen la protección de las áreas naturales, el uso completo de los recursos agua dulce y sedimentos, mantener las conexiones entre la entrada de agua dulce y los ecosistemas costeros, permitir la migración tierra adentro de los humedales y el manejo cuidadoso de los cambios de uso de la tierra.

Palabras clave: Golfo de México, impctos del cambio climáticos, ecosistemas costeros.

Abstract
The Gulf of Mexico currently spans the transition from tropical to temperate coastal ecosystems but this is changing as the northern Gulf undergoes tropicalization and the entire Gulf will become tropical in this century. The objective of this paper was to review information on climate change impacts on coastal ecosystems with high freshwater input for the Gulf of Mexico and review mitigation measures for dealing with climate change. There are two high freshwater discharge areas, one surrounding the Mississippi River in the north central Gulf and one in the southern Gulf, which is associated with the Grijalva-Usumacinta River and adjacent rivers and ground water discharge from the Yucatan Peninsula. Both of these areas are characterized by extensive coastal wetlands, and in the southern Gulf, submerged aquatic vegetation. These coastal ecosystems support important natural resources, have high petroleum production, and important maritime trade. Climate change will impact both of these areas strongly. Sea level is projected to increase by a meter or more by 2100 and there will be more strong hurricanes that will be larger, have more intense rainfall, will move slower, and the rate of intensification will increase. In the north, peak Mississippi River discharge is projected to increase by 10 to 60%. In the southern Gulf, it is projected that precipitation and freshwater discharge will decrease associated with the Mesoamerican climate hotspot. Coastal management to accommodate climate change should mimic ecosystem functioning. Specific actions include protection of natural areas, full use of freshwater and sediment resources, maintain connections between freshwater input and coastal systems, allow inland migration of coastal wetlands, and careful management of land use changes.

Keywords: Gulf of Mexico, climate change impacts, coastal ecosystems.
Introduction

The Gulf of Mexico (GOM) is one of the largest regional seas in the world covering an area of 1.6 million km$^2$ nearly half of which is shallow continental shelf waters. Historically, the GOM encompassed the transition from tropical in the south to sub-tropical/sub-tropical in the north. But this is changing rapidly due to climate change. The GOM is one of the most important petroleum producing regions of the world reflecting sustained high marine and coastal productivity over millions of years. It also supports some of the highest marine fisheries of the world. This is due to high freshwater input and expansive coastal wetlands and submerged aquatic vegetation beds, and large areas of shallow water. The two areas of the Gulf with the highest freshwater input are in the northern and southern GOM. In the north, this is associated mainly with the discharge of the Mississippi River. In the south, it is associated with the Grijalva-Usumacinta River and adjacent rivers and ground water discharge from the Yucatan Peninsula. Here, we review the characteristics of this regional sea, the growing impact of climate change in the area, and the potential for mitigation to deal with climate change. In doing so, we build on an extensive literature on the region especially a number of recent publications on the area (Day & Yáñez-Arancibia 2013 and chapters therein Kemp et al., 2016 a,b; Pérez-Caballos et al., 2017; Zaldívar-Jíménez et al., 2017; Day et al., 2019; Herre-rea-Silveria et al., 2019; Day & Rybczyk, 2019).

North Central Gulf of Mexico - the Mississippi River and Delta

The Mississippi is one of the largest rivers in the world. Its watershed covers 3.2 million km$^2$, or about 40% of the area of the lower 48 U.S. states, and accounts for about 90% of river discharge to the Gulf of Mexico (Figure 1). Mean discharge is almost 20,000 m$^3$/sec. Major tributaries to the lower Mississippi include the Upper Mississippi, Missouri, Ohio, Arkansas and Red Rivers. As the Mississippi River (MR) approaches the ocean, water elevation rather than bed slope drives flow in the backwater zone that constitutes the MR delta, and for the last 724 km the bed of the river is actually below sea level; 4.6 m below sea level at Vicksburg, and over 52 m below sea level at New Orleans (Nittrouer et al., 2012).

The river built the Mississippi River Delta (MRD) across the continental shelf of the northern Gulf of Mexico over the past 6-7 thousand years. Delta formation was enhanced by a hierarchical series of forcing functions acting over different spatial and temporal scales during a period of stable sea level, predictable inputs from its basin, and as an extremely open system with strong interactions among river, delta plain and the coastal ocean (Table 1, Day et al., 1997, 2007, 2019; Baumann et al., 1984). This model applies equally to the Grijalva-Usumacinta delta. But within the last century, the MRD –like many deltas worldwide– has been profoundly altered by human activity including changes in hydrology, sediment supply, sea level rise, and land use that directly affect sustainability as sea level rise accelerates and other climate forcings intensify (Day et al., 2007, 2019; Couvillion et al., 2011; Colten & Day, 2018). Collectively, human actions changed the natural balance between land-building and land-loss toward a physical collapse with over 25% of delta wetlands lost since the 1930s (Figure 2).

The state of Louisiana is investing $50 billion in a 50-year Coastal Master Plan (CMP) of protection from flooding and restoring coastal wetlands and ecosystems (CPRA, 2017; Wiegman et al,
Figure 1. The Mississippi Delta was formed by a series of seven overlapping delta lobes. Along the main channel of the river, riverine input to the deltaic plain is prevented by levees. Only in the Atchafalaya Bay region does river water flow into shallow inshore areas. From J. Day et al. (2007), Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita. Science, 315: 1679-1684, reprinted with permission from AAAS.

Table 1. A hierarchy of forcings or pulsing events affecting the formation and sustainability of deltas (Modified from Day et al., 1997).

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Scale</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Changes in River Channels</td>
<td>500-1000 years</td>
<td>New delta lobe formation, major sediment deposition.</td>
</tr>
<tr>
<td>Major River Floods</td>
<td>50 - 100 yrs.</td>
<td>Avulsion enhancement, major sediment deposition, enhancement of crevasse formation and growth.</td>
</tr>
<tr>
<td>Major Storms</td>
<td>20-25 yrs.</td>
<td>Major sediment deposition, enhanced production.</td>
</tr>
<tr>
<td>Average River Floods</td>
<td>Annual</td>
<td>Enhanced sediment deposition, freshening (lower salinity), Nutrient input, Enhanced 1° and 2° production.</td>
</tr>
<tr>
<td>Normal Storm Events (Frontal Passage)</td>
<td>Weekly</td>
<td>Enhanced sediment deposition, Enhanced organism transport, Higher net materials transport.</td>
</tr>
<tr>
<td>Tides</td>
<td>Daily</td>
<td>Marsh drainage, Stimulated marsh production, Low net transport of water and materials.</td>
</tr>
</tbody>
</table>
2018). El plan combina estructuras duras como levantamiento y paredes de inundación con humedales construidos y sostenidos por la división del río y el aporte de vegetación, y mantenimiento de islas costeras. Acelerando los impactos climáticos y la escasez de recursos, hará que lograr los objetivos del plan sea más desafiante y costoso (Rutherford et al., 2018; Wiegman et al., 2017; Day et al., 2019). En todo caso, el CMP es ingeniería ecológica de gran escala, pero para que sea exitoso debe operar en consonancia con procesos biológicos y físicos complejos (por ejemplo, Colten & Day, 2018). Esto significará vivir en un sistema más abierto, aceptando limitaciones naturales y sociales, y utilizando más recursos del río.

Dos de las actividades de restauración más importantes son las divisiones del río y la creación de humedales para la construcción de tierra en la zona costera. La creación de humedales utiliza sedimentos excavados que son bombeados a través de tuberías, a menudo por largas distancias, para construir humedales (Wiegman et al., 2017). Sin embargo, el crecimiento de los impactos climáticos y el aumento de los costos energéticos hará que la creación de humedales sea muy costosa y probablemente inaccesible en la segunda mitad de este siglo. Las divisiones introducirán agua del río en la zona costera para crear y restaurar humedales (Day et al., 2014; Twilley et al., 2016; Rutherford et al., 2018); esto será mucho más efectivo si la reducción de la transportación de sedimentos finos en el río se restaura (Kemp et al., 2016a).

Después de la gran inundación de 1927 que provocó inundaciones y pérdidas de vida y propiedad a lo largo del valle del río Mississippi, el Gobierno federal comenzó un esfuerzo de control de inundaciones y navegación área a toda la分级ie (MR&T). El sistema MR&T está diseñado para el proyecto de inundación con un caudal pico de alrededor de 85,000 m$^3$ sec$^{-1}$ (3 millones ft$^3$ sec$^{-1}$). El caudal pico del río Mississippi en Vicksburg fue de 64,000 m$^3$ sec$^{-1}$ (2,278,000 cfs) en 1927 y 65,000 m$^3$ sec$^{-1}$ (2,310,000 cfs) en 2011. Las inundaciones grandes están volviéndose más comunes en el río Mississippi. Por ejemplo, el Bonnet Carré Spillway es un punto de escape situado a unos 40 km arriba de Nueva Orleans. Se diseñó para bajar el nivel del río en la ciudad permitiendo que el agua fluya del río a Lake Pontchartrain (Day et al., 2012).
ed in 1933 after the great flood of 1927 and has been opened 14 times beginning in 1937 with the last opening in 2019. Nine of the 14 openings occurred in the second half of its operational history and the spillway was opened four times from 2016 to 2019, including twice in 2019, indicating that large floods are becoming more common. Tao et al. (2014) modeled the combined effects of climate change, land use, and river management on discharge of the Mississippi River and projected that peak river discharge may increase by 10-60% during this century. Assuming that peak discharge would increase by the same amounts, we plotted the peak discharge of the 2011 flood and added 10% to 60%. An increase of 60% over the peak discharge for the 2011 flood would result in a peak discharge of 104,000 m$^3$sec$^{-1}$ (3.70 million ft$^3$ sec$^{-1}$) exceeding the project flood by about 20% (Figure 3). Peak flow increases of this magnitude may compromise the MR&T flood control system on the Mississippi River (Kemp et al., 2014). Kemp et al. (2016a) concluded that Delta restoration will be more sustainable if sediment input from the basin could be increased to the lower river.

![Figure 3. Potential increase in peak Mississippi River discharge due to climate change and land use changes in the basin (based on model projections from Tao et al., 2014). MR&T is the Mississippi River and Tributaries project flood. From Day et al. (2019), used by permission.](image-url)
Comprehensive planning – The importance of global change in Mississippi Delta restoration

There is a pressing need to carry out planning for coastal restoration and protection to a much greater extent within a comprehensive plan that takes into consideration 21st century global change megatrends including climate change, energy scarcity, ecosystem degradation, economic constraints, and the local cultural context. There is a need to recognize the extremely high ecosystem services and their role in the future ecological, economic, and social health of the region and how these goods and services can be sustained. There is also a need to really consider what is possible, what is not, and what it will take to have a sustainable system in the Mississippi delta. There needs to be an acceptance that the delta will shrink considerably (Chambers et al., 2018), that there will be significant population shifts accompanying managed retreat (Colten & Day, 2018), and that the river will have to be used to the maximum extent possible. As this century progresses, much of what is being planned for coastal protection and restoration will become more expensive, perhaps prohibitively so (Tessler et al., 2015; Wiegman et al., 2017; Day et al., 2018, 2019). Society will have to adapt to a much more dynamic river and delta system that cannot be controlled as it has been for the last century. The energies of nature must play a much more important role in delta management. This is ecological engineering on a grand scale, that must operate in synchronization with complex social processes. This will mean living in a much more open system, accepting natural and social limitations, and utilizing the resources of the river more fully.

The high freshwater discharge region of the Southern Gulf of Mexico

In the southern Gulf of Mexico, there is an extensive coastal system high freshwater input, extensive coastal lagoons and wetlands and coastal, rich fisheries, and human urban systems whose economy is supported by the rich natural resources of the area and maritime trade (Figure 4).

The Grijalva-Usumacinta River (GUR) is the largest river in Mesoamerica and one of the most significant shared water resources in North America (Bestermeyer & Alonso, 2000; Yáñez-Arancibia & Day, 2004a, 2006; Yáñez-Arancibia & Day, 2004b). The average discharge of the GUR is 3,000 to nearly 5,000 m³ sec⁻¹ with peak discharge as high as 9,000 m³ sec⁻¹, and is second only to the Mississippi River for discharge to the Gulf. The highest discharge is from September through November and the lowest occurs in April-May.

Laguna de Términos is the largest coastal lagoon-mangrove-freshwater wetland ecosystem in Mexico and one of the largest in Latin America (Yáñez-Arancibia & Day, 1982, 1988; Figure 5). For much of the year, there is a net east to west flow caused by prevailing easterly trade winds with a net seawater inflow the eastern Puerto Real inlet and a net outflow of mixed estuarine waters through the western El Carmen inlet. Annual precipitation is from 1650 to 1850 mm yr⁻¹. The southwestern lagoon has more than 50% of freshwater discharge,
mainly from the Palizada River, a distributary of the Usumacinta River. River discharge into the lagoon in the mid 20th century was $6 \times 10^9$ m$^3$ yr$^{-1}$ (Phleger and Ayala-Castanares, 1971). This results in saline clear water in the eastern part of the lagoon and turbid lower salinity in the western part. These interactions result in strong seasonal and spatial water quality patterns. Environmental gradients and local habitats (i.e. mangroves, oyster reefs, submerged aquatic vegetation) adjacent to the fluvial lagoon subsystems influence nutrient levels, and water quality, and biota. These patterns are stronger in the rainy season with high river discharge.

**Habitat diversity**

There is high habitat diversity in Laguna de Términos. There are large areas of sea grass beds in the eastern part of the lagoon and the inner littoral of Carmen Island due to clearer high salinity waters. Extensive oyster reefs occur in the western part of the lagoon in lower salinity waters near the river mouths (Figure 5). Aquatic habitats include open waters of the near-shore Gulf, brackish lagoon waters, and freshwater areas in the fluvial lagoon systems. Terrigenous sediments occur off the western part of Carmen island while carbonate sediments occur off the eastern end of the island. There are variety of mangrove and freshwater wetland habitats including all of the mangrove community types described by Lugo and Snedakar (1974). Riverine forests occur near the river mouths. Fringe forests exist along tidal channels and on the lagoon side of Carmen Island and scrub and basin forests are located where circulation is restricted. The forests are composed of red (*Rhizophora mangle*), black (*Avicennia germinans*) and white (*Laguncularia racemosa*) mangroves and button bush (*Conocarpus*...
Figure 5. Top. Laguna de Términos showing the location of major vegetation habitats and oyster reefs, direction of net flow through the lagoon, and rivers entering the lagoon. Letters indicate sampling locations for nekton discussed in the text. Mid. Location of major subsystems offshore of Laguna de Términos. Left terrigenous sediments, right carbonate sediments. Bottom. Major habitats of Laguna de Términos. I Lagoon side of Carmen Island, II Central Basin, III Fluvial-deltaic systems, C Carmen Inlet, P Puerto Real Inlet. From Yáñez-Arancibia et al. (2013), used by permission.
erectus). Submerged aquatic vegetation dominated by *Thalassia testudinum* occurs in clear, high salinity waters while freshwater species such as *Valisneria Americana* and *Cabomba palaeformis* are in lagoons associated with the fluvial lagoon systems.

There are spatial and temporal patterns of primary productivity for all major producer groups of the Términos ecosystem (Day *et al.*, 1982, 1987, 1988, 1996, and summarized by Rojas-Galaviz *et al.*, 1992; Figure 6). Mangrove litterfall is highest in the rainy and early nortes seasons. Aquatic primary productivity (APP) is also highest in this period when water clarity is moderate and nutrients are abundant (Day *et al.*, 1982). Submerged aquatic vegetation biomass is most abundant during the dry season in areas of high water clarity (Rojas-Galaviz *et al.*, 1992). Because the different primary producers have peak production periods in different seasons, there is high year-round productivity but peak productivity shifts seasonally among different habitats in the lagoon (Figure 6).

A series of studies in Laguna de Términos reviewed successful restoration of black mangroves after hydrologic restoration. Hydrological restoration was carried out at a mangrove site on the lagoon side of Carmen Island. Micro-typography was restored by opening tidal channels into basin mangroves that lowered salinity (Pérez-Ceballos *et al.*, 2017). This enhanced natural recruitment via enhanced propagule dispersal and survival and enhanced growth (Echeverría *et al.*, 2019). Natural areas close to the restoration site were important as a source of propagules. After initial restoration, fine root production was low but increased over several years and was related to nutrient levels and the frequency and duration of tidal inundation (Pérez-Ceballos *et al.*, 2018). Zaldívar *et al.* (2017) reported that community-based hydrologic restoration involving both academic institutions and government agencies was important to the success of long-term restoration at the site. They reported that identifying economic alternatives and ecological monitoring were critical to successful implementation.

García-Ríos *et al.* (2013) carried out a coastal condition index analysis of the Laguna de Térmi-
The results of the analysis indicated that the overall environmental condition of the lagoon was fair; water quality and benthic indices were fair; sediment contaminant index was good; and the coastal habitat and fish tissue contaminants indices and biomarkers were poor.

There is a high diversity of consumers including over 250 nekton species and a high diversity of benthos and avifauna. Migratory nekton utilize the full range of habitats in the lagoon from tidal freshwater through the lagoon to the near shore Gulf. Nekton tend to use the different habitats when rates of primary productivity are highest. Thus, nekton exhibit small scale migration patterns tied to resource availability. Fishery resources in the lagoon and the nearshore Campeche Sound are dependent on food availability, high habitat diversity, and the movement of nekton pre-adults from the lagoon-estuarine system to the sea (Yáñez-Arancibia et al., 1980; Yáñez-Arancibia & Day, 1982; Dee gan et al., 1986; Sánchez-Gil et al., 2008).

The high productivity and habitat diversity support a high diversity, multi-stock fishery resource in Campeche Sound where 75% of dominant species are either estuarine-dependent or estuarine-related in the juvenile and pre-adult stages (Yáñez-Arancibia et al., 1980; Yáñez-Arancibia & Sánchez-Gil, 1986; Sánchez-Gil & Yáñez-Arancibia, 1997).

The Yucatán Peninsula has one of the largest karst aquifer systems globally. The peninsula is a carbonate platform with an extensive continental shelf with high fresh ground water discharge along much of the coast (Ward et al., 1985; Herrera-Silveira, 1994; Perry et al., 1995). The aquifer system is a nearly horizontal, highly-permeable system with high hydrological connectivity between terrestrial and coastal systems which is strongly controlled by climatic variability. The aquifer covers an area of over 165,000 km² in México, Guatemala, and Belize. This groundwater resource supports diverse groundwater-dependent coastal ecosystems. The aquifer is the only available freshwater resource because there almost no surface water.

There are karstic freshwater lakes, brackish lagoons, coastal lagoons and reef lagoons, which form the largest and most diverse coastal ecosystems of the peninsula. Spatial and temporal patterns of this complex ecosystem can be used to characterize hydrological, biogeochemical, and ecological dynamics using the “Transverse Coastal Corridor” conceptual model (Herrera-Silveira & Comín, 2000; Herrera-Silveira et al., 2004; Hernández-Arana et al., 2015).

The factors affecting Yucatan coastal ecosystems are variable due to (1) size and shape of coastal lagoons (2) regional forcings change considerably by location; (3) tidal range, freshwater input, and human impacts vary in different parts of the coast; (4) the climate is tropical but ranges from arid to more humid; and (5) the impact of natural forcings such as hurricanes varies with coastal location (Herrera-Silveira & Comín, 2000; Herrera-Silveira et al., 2013).

The structure and functioning of Yucatan coastal ecosystems are controlled by regional (i.e., Yucatan Current) and local (i.e., upwelling and groundwater discharges) drivers, as well as pulsing events ranging from high-frequency low-intensity events (i.e., tides) to low-frequency high-intensity events (i.e., hurricanes). Additionally, human impacts interact with natural drivers to variably affect specific coastal ecosystems (Herrera-Silveira et al., 2013; Figure 7). In general, the Yucatan coast can be divided into East, North, and West coast sub-regions.

Ecosystem assessment and management of coastal ecosystems of the Yucatan can be guided by three core concepts. Connectivity integrates biogeochemical, biological, and hydrological interactions. Dynamic land-sea interactions influence system productivity, biodiversity, responses to disturbance, and overall functioning. Ecological stability is the timing and mechanisms by which ecosystems recover after disturbance and their resistance to disturbances (Herrera-Silveira et al., 1999; Morales-Ojeda et al., 2010).
The Gulf of Mexico is being impacted by climate change and impacts will grow significantly during this century. Here we review the projected impacts of climate change.

Temperature
Global temperatures are projected rise 1-5°C during the 21st century (IPCC, 2007, 2013) compared to an increase of about a degree since the latter part of the 18th century. Over the same period CO₂ levels increased from about 280 ppm to over 400 ppm between 1880 and 2010 (IPCC, 2013). Increasing temperatures will affect precipitation, sea-level rise, the intensity and frequency of hurricane and other storms, the frequency of extreme weather events, and biological processes. Friedlingstein et al. (2014, see also IPCC, 2017) reported that atmospheric CO₂ levels are growing at rates consistent with the highest IPCC scenarios. CO₂ levels have reached 415 ppm, the highest levels for at least the last 3 million years (Willeit et al., 2019).
Many tropical coastal species, such as mangroves, are limited in their distribution by cold temperatures and severe freezes. Changes in regional temperature regimes will cause a variety of ecological responses including local extinctions, shifts in geographic ranges, and changes in biodiversity and rates of ecosystem metabolism primary production. Many tropical species will extend their ranges to higher latitudes as is the case of mangroves worldwide (e.g., Yáñez-Arancibia et al., 2010, Twilley & Day 2013; Osland et al., 2016; Dangremond & Feller, 2016; Doughty et al., 2014; Saintilan et al., 2014). Areas in the northern Gulf that are now sub-temperate will become fully tropical in this century in a process called tropicalization (Day et al., 2010; Day & Rybczyk, 2019).

Sea-level rise
Accelerated sea-level rise will impact coastal ecosystems and society in the Gulf of Mexico during the 21st century. During the last ice age, sea level was over 100 meters below current levels but rose at the end of the last glacial epoch. There is enough water locked in land-based ice to raise sea levels by 80 meters (Emery & Aubrey, 1991).

Sea-level rise was 0.6 mm/yr between 1900 and 1939, averaged about 1.7 mm/yr for much of the 20th century (FitzGerald et al., 2008; Hansen et al., 2015; Figure 8) and was 3-4 mm yr^-1 from 1993 to 2010 (Nerem et al., 2010) and 3.3 mm/yr between 1993 and 2015 (Figure 1). Thus, the rate for the past two decades was nearly twice the average of the 20th century as a whole and over five times higher than the beginning of the 20th century. Total sea-level rise will likely be between 1 and 2 meters in the 21st century (IPCC, 2017; Rahmstorf, 2007; Vermeer & Rahmstorf, 2009; Horton et al., 2014; Koop et al., 2016).

Relative sea level rise (RSLR) is the combination of eustatic sea-level rise and subsidence. High rates of subsidence commonly occur in deltas due to compaction, consolidation, and dewatering of sediments (Syvitski et al., 2009; Day et al., 2016). Both the Mississippi and the Grijalva-Usumacinta delta are experiencing RSLR (Baumann et al., 1984; Day et al., 2007; Lara Domínguez et al.,

![Global Mean Sea Level Change](image)

**Figure 8.** Rates of sea-level rise from 1900 to 2015 (figure from Hansen et al., 2015, used by permission).
2013) and in the Mississippi RSLR is in excess of 10 mm yr\(^{-1}\). Thus, these two deltas will be especially impacted by accelerated ESLR (Syvitski et al., 2009; Giosan et al., 2014; Day et al., 2019; Herrera-Silveira et al., 2019).

Increasing warming of ocean surface waters has impacted tropical cyclones in a number of ways. Tropical cyclones have become more frequent in the North Atlantic and globally (Webster et al., 2005). Emanuel (2005) reported that total hurricane intensity or power increased by about 80% over the last 50 years and there was a 1°C increase in sea surface temperature in the tropics over the same period. There has also been an increase in the frequency of category 4 and 5 storms over recent decades (Webster et al., 2005). A number of studies have concluded that the frequency of category 4 and 5 tropical cyclones will increase during the 21st century (Hoyos et al., 2006; Elsner et al., 2008; Bender et al., 2010). Mei et al. (2015) reported that typhoon intensity has increased in the Pacific region and predicted climate change will increase average typhoon intensity in the Pacific area by 14% by 2100. Bhatia et al. (2019) reported that the rate of intensification of tropical cyclones has increased significantly over the past 3 decades. These studies indicate that stronger hurricanes will increase in frequency, there will be more intense precipitation, storms will be larger and slower moving, and the rate of intensification will increase. All of this indicates that hurricanes will have a growing impact on coastal ecosystems during the 21st century.

Globally there will be both increases and decreases in precipitation in the 21st century (IPCC, 2013, 2017). In general, the outer tropics and sub-tropical zone will be drier, the inner tropics will be wetter, and high latitudes will become wetter as warmer temperatures lead to the movement of greater amounts of water vapour away from tropical and sub-tropical regions. Dry areas will likely become drier. In general, this indicates that freshwater runoff to coastal areas will decrease in mid latitudes and increase around the equator and at higher latitudes. Heavy precipitation events, and consequently flooding, are expected to increase in intensity with climate change (Groisman et al., 2005; Min et al., 2011; Pall et al., 2011; Prein et al., 2016). Tao et al. (2014) reported that peak discharge of the Mississippi River will likely increase by 10-60% during this century due to interactive effects of climate change and land use even given the presence of many dams, mainly on the Missouri River. Such large increases may compromise the flood control system on the Mississippi River (Kemp et al., 2014; Day et al., 2019). A great threat to coastal ecosystems in the southern GOM is the severe drying predicted for the entire Mesoamerican “climate change hot-spot” (Fuentes Franco et al., 2015; Imbach et al., 2012). This means that freshwater discharge to the coastal Gulf and Caribbean will decrease both for surface and ground water discharges. This will threaten the sustainability of coastal ecosystems.

Several recent examples of intense weather events are available for both the northern and southern Gulf of Mexico. In 2000-2001, an extreme drought raised salinities in western Lake Pontchartrain and Lake Maurepas from an average of 2-3 psu to 10-12 psu and led to mortality of cypress over a wide area (Day et al., 2012; Shaffer et al., 2016). Such droughts, in combination with increasing sea level and strong hurricanes, will lead to salinity stress on broad areas of freshwater wetlands. In August, 2016, nearly a meter of rain fell in three days in southeast Louisiana during a stalled front that was not associated with a hurricane led to extensive flooding east of the Mississippi River. Rainfall totaled about 1.5 m during Hurricane Harvey in the Houston in 2017 in 4 days when its forward movement was stalled by a frontal system. Over the last two decades, hurricanes have caused widespread damage in coastal areas of the Gulf of Mexico including Katrina, Rita, Michael, and Florence. In Mexico, hurricanes and tropical depressions have led to intense rainfall. For example, in 2005 Emily (Cat 4-5) in July led to rainfall accumulations of nearly 500 mm Tamaulipas and Wilma (Cat 4-5) had peak accumulation of 770 mm in Quintana...
Roo. Other notable storms were Hanna in October 2014 (Quintana Roo, tropical depression, 430 mm), Arlene in June 2010 (Veracruz, tropical depression, 679 mm), Ingrid in September 2013 (Tamaulipas, tropical depression, 743 mm) and Franklin in August 2017 (Veracruz, Cat 1, 410 mm).

In summary, increasing temperatures will lead to tropicalization of the entire Gulf of Mexico. Climate change is projected to lead to higher freshwater input in the northern Gulf due to increased Mississippi River discharge while decreased precipitation in the southern due to the Mesoamerican climate hotspot will lead to a reduction of freshwater input. Sea-level rise will stress the ability of coastal wetlands to keep up with rising water levels. This will be exacerbated by increasing salinity in the southern Gulf due to increasing drought. This will especially threaten mangroves due to increased flooding duration and increased salinity. Growing frequency and strength of hurricanes as well as intense precipitation will threaten both natural and human systems.

**Mitigation and management for climate change**

As discussed above, climate change will strongly impact the high freshwater discharge areas of the northern and southern Gulf of Mexico. These impacts include increasing temperature, sea-level rise, stronger and more frequent hurricanes, more intense rainfall events, and changes in freshwater and sediment input. An important difference between the two regions is that freshwater input is projected to increase in the northern Gulf while it is predicted to decrease significantly in the southern Gulf. In both regions, a guiding principle is that system functioning should form the basis for sustainable management in the high freshwater input areas of the GOM (Day et al., 1997, 2007) and focus on important aspects of the system including wetland preservation, hydrologic restoration, and fully using resources of freshwater and sediments to enhance coastal ecosystems. Coastal restoration efforts will have to be more intense to offset the impacts of climate change (Day et al., 2018; Day & Rybczyn, 2019; Herrera-Silveira et al., 2019). Restoration and management of coastal ecosystems in the southern Gulf of Mexico should include (Day & Yáñez-Arancibia, 1988; Herrera-Silveira et al., 2019): (1) protect structure and functioning of regional ecosystems, (2) utilize natural energies and freshwater resources to the fullest extent possible, (3) carefully plan urban and industrial development in harmony with nature, (4) manage for optimal yield of biotic resources, and (5) monitor changes in resources and habitats and use adaptive management to enhance sustainability. Restoration of a black mangrove site in the Laguna de Términos demonstrated the importance of hydrological restoration and community involvement (Zaldívar et al., 2017).

Increasing temperature will lead to the tropicalization of the entire Gulf of Mexico in the 21st century. Because of this, mangroves will increasingly dominate intertidal vegetation. Mangrove establishment should be accelerated by planting. In general, management of mangroves in the Mississippi delta region should build on the many studies that have been carried out in the southern Gulf and other tropical areas. In both the northern and southern Gulf of Mexico, full use of freshwater, sediment, and nutrient resources should be done to enhance the productivity and vertical accretion. These types of studies are more advanced in the Mississippi delta and provide information and experience for management for climate change in the southern Gulf region. This will be especially important in the southern Gulf of Mexico where economic resources are lower than for the Mississippi
delta. This will enhance the ability of mangroves to significantly reduce hurricane storm surge, increase accretion to offset sea-level rise and increase the value of ecosystem goods and services.

Sea-level rise will strongly impact coastal wetlands, especially in areas where there are broad areas of near sea level wetlands such as in the Mississippi and Grijalva-Usumacinta deltas. Wise use of freshwater and sediment resources can enhance the resilience of coastal ecosystems, especially wetlands, in both the northern and southern GOM. An important mechanism to accomplish this is re-mobilization of sediments trapped by dams. Kemp et al. (2016a) suggested that 100 to 200 million metric tons of fine sediment could be mobilized from lower Missouri River reservoirs. Sand transport to the Mississippi delta is sufficient to build wetlands in shallow, sheltered coastal bays receiving engineered diversions (Allison et al., 2012, Nittrouer & Viparelli, 2014). But suspended mud (silt & clay) transport by the Mississippi has dropped from nearly 400 Mt y\(^{-1}\) in the early 1950s, to 100 Mt y\(^{-1}\) since 1970 (Meade & Moody, 2010). Fine-grained sediments can be transported deep into receiving estuarine basins because they can be easily resuspended by wind waves and play a critical role in sustaining existing wetlands. Most sediment input to the Mississippi delta was from the Missouri River Basin prior to the construction of nearly 100 dams on the Missouri. About 100 Mt y\(^{-1}\) is currently trapped in large Upper Missouri dams completed by the mid 1950s. About 200 Mt y\(^{-1}\) is trapped in impoundments on the lower Missouri in the 1950s and 1960s. Sediment bypassing on lower Missouri impoundments is part of current river management. Sediment flux during discharge years of 1973, 1993 and 2011 approached pre-dam levels when Lower Missouri tributaries contributed significantly to flood flows. These streams drain a large, semi-arid part of the Great Plains dominated by highly erodible loess soils. Reducing the continued decline in Missouri fine-grained sediment flux is very important now that river diversions are being built for coastal wetland restoration in the Mississippi delta. Kemp et al. (2016a) concluded that bypassing in the Lower Missouri tributaries could increase mud supply to the Mississippi delta by 100-200 Mt y\(^{-1}\) within 1-2 decades. Such management should be considered for present and planned reservoirs on the Grijalva-Usumacinta and adjacent rivers.

Within the Mississippi delta, construction of levees isolated much of delta plain from riverine input and contributed to the high levels of wetland loss (Day et al., 2000, 2007, 2019). The construction of river diversions that reintroduce river water and sediments is a core objective of the restoration plan for the delta as part of the Louisiana Coastal Master Plan (CPRA 2017; Day et al., 2019). In contrast to the Mississippi delta, the Grijalva-Usumacinta remains largely un-leveed. It is important to design any flood control levees with care so that sediment input to the coastal floodplains in the southern GOM can be maximized. This will help avoid the problems that have occurred in the Mississippi delta.

Inland migration of coastal wetlands is a way to replace wetlands on the seaward edge of coastal systems that are being lost to sea-level rise. For the Mississippi delta, this will be difficult because of both the broad area of wetlands in the delta that are near sea level and the presence of levees and other built up infrastructure that prevent inland migration. However, this is likely more possible for the southern Gulf of Mexico. Along the west coast of the Yucatan Peninsula there is a broad area of freshwater wetlands called the Petenes. These wetlands are on a gently sloping coastal areas inland of mangroves. The topography of much of this coast can accommodate inland migration of coastal wetlands. The same is true for much of the area surrounding Laguna de Términos and the Grijalva-Usumacinta delta.

From a regional context in both the northern and southern GOM, Kemp et al. (2016b) concluded that continental shelf river and groundwater plumes promote ecological resilience in the face of climate change. These riverine and groundwa
ter inflows to the coastal zone sustain coastal ecosystems of the area. The most important rivers in the southern Gulf are those in the broader Grijalva-Usumacinta region. These systems owe much of their natural resilience to a coastal geomorphology that spreads risk across the coast while providing ecosystem connectivity through shelf plumes that connect estuaries. These shelf plumes extend along all of the Yucatan Peninsula due to ground water input. Freshwater input generates large plumes that extend estuarine conditions onto the nearshore shelf and strongly influence fisheries of the adjacent continental shelf. Recent global change models indicate that that precipitation and freshwater input to the southern Gulf of Mexico region may significantly decline in the 21st century. Reconnecting rivers to coastal ecosystems and releasing fine-grained sediments trapped behind dams are ways to counter the impacts of climate change in both the northern and southern high freshwater discharge areas. Careful management of land use changes can enhance sustainability and resilience of coastal ecosystems.

The recognition that multiple threats endanger coastal ecosystems in the southern Gulf of Mexico has led Mexico to protect intact coastal ecosystems via the establishment of 17 natural protected areas in the region (see Herrera-Silveira et al., 2019). These include Biosphere Reserves, Flora and Fauna Protection areas, State Reserves, National Marine Parks, and National Parks. The total area of these reserves is about 2.8 million ha in Tabasco, Campeche, Yucatan, and Quintana Roo. Maintaining large areas of the coastal landscape in these protected areas makes coastal management more sustainable and feasible.

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