Part II

Coastal Ecosystems and Climate Change

Chapter 6

Coastal Ecosystems of the Gulf of Mexico and Climate Change

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Summary

Coastal ecosystems in the Gulf of Mexico (GOM) are an important national and regional resource because of their many significant ecological functions. They support diverse life forms, including commercially-valuable fisheries species, provide recreational opportunities, storm protection, and are a home for millions of humans. The stressors on coastal resources have continued to increase over the last century under the intertwined pressures of population growth and intensified resource use. Now climate change (temperature, precipitation, discharge, sea-level rise, etc.) is an anticipated additional stressor in this century, and with sometimes clear, but often unclear, consequences.

This section provides a brief overview of some of the important ecological aspects of the Gulf of Mexico coastal ecosystems and major (but not all) changes. Subsequent sections discuss four key ecological behaviors that the anticipated future climate changes will likely impact: estuarine salinity, salt marsh sustainability, commercial fisheries (especially shrimp), and low oxygen zones. Each of these is representative of a key aspect of the health of the GOM coastal ecosystems.

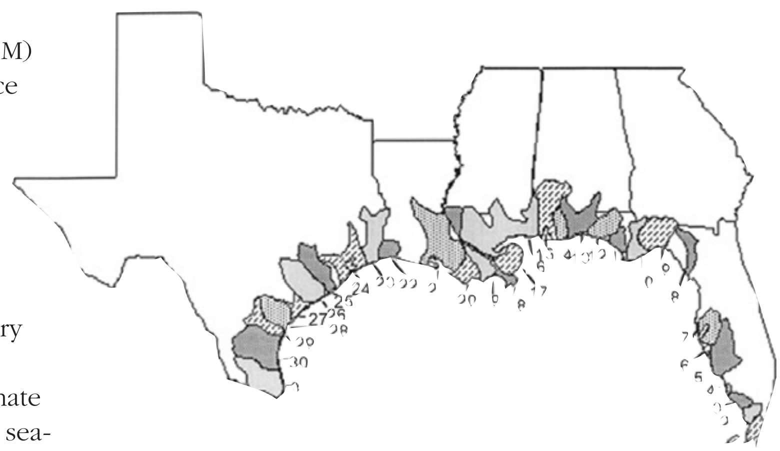

Figure 1. The major coastal watersheds in the Gulf of Mexico.

1 Florida Bay
2 South Ten Thousand Islands
3 North Ten Thousand Islands
4 Rookery Bay
5 Charlotte Harbor
6 Sarasota Bay
7 Tampa Bay
8 Suwanee River
9 Apalachee Bay
10 Apalachicola Bay
11 St. Andrew Bay
12 Choctawhatchee Bay
13 Pensacola Bay
14 Perdido Bay
15 Mobile Bay
16 Mississippi Sound
17 Breton/Chandeleur Sounds
18 Mississippi River
19 Barataria Bay
20 Terrebonne/Timbalier Bays
21 Atchafalaya/Vermilion Bays
22 Calcasiu Lake
23 Sabine Lake
24 Galveston Bay
25 Brazos River
26 Matagorda Bay
27 San Antonio Bay
28 Aransas Bay
29 Corpus Christi Bay
30 Upper Laguna Madre
31 Lower Laguna Madre

6.1 Current Status and Stresses

There are 31 major estuarine watersheds in the GOM (Figure 1). The Mississippi River and the Atchafalaya River (formed from the Red River and

Table 1 Wetland area (km²) and open water area (km²) for 125 major estuaries in the US. From Turner 2001.

Region	Wetland Area (km²) N	Wetland Area (km²) Average (% total)	Wetland Area (km²) Range	Open Water Area (km²) N	Open Water Area (km²) Average (% total)	Open Water Area (km²) Range
Northeast	13	252 (4%)	36 - 616	14	395 (7%)	16 - 1419
Middle Atlantic	11	848 (11%)	57 - 4033	21	1103 (28%)	52 - 9920
South Atlantic	17	1399 (28%)	101 - 4579	20	619 (15%)	23 - 7638
Gulf of Mexico	26	1654 (28%)	80 - 8762	35	945 (41%)	5 - 5403
Pacific	14	332 (6%)	5.2 - 2343	33	236 (9%)	3 - 2411
All	81	1079 (100%)	5.2 - 8762	123	666 (100%)	3 - 9920

the diverted one-third of the Mississippi River) drain 41% of the US. The other estuaries are largely regional watersheds of much smaller size. The coastal wetland and open water area in the GOM is 28 and 41 % of the US total, respectively (Table 1). Louisiana has 55% of the total wetland area in the GOM, most of which is marsh habitat (Table 2).

Estuaries in the southeast/Gulf of Mexico region tend to have lower freshwater turnover times than other US estuaries (Figure 2). The time it takes to turnover the freshwater content of these estuaries could decrease further with climate change. In other words, the flushing rate will increase. Further, some chaotic and episodic climate changes are likely introduced, e.g., drought and floods (Knox, 1993). As wetland losses accumulate, then the flushing rates may decrease as open water habitat increases and the estuary deepens. A lower flushing rate (e.g., from increased open water area) could lead to more harmful algal blooms (because of a longer residence time) or higher salinities (because of increased seawater mixing through the estuarine mouth. We do not know if these factors will compensate for each other and balance the effects of each so that equilibrium is maintained.

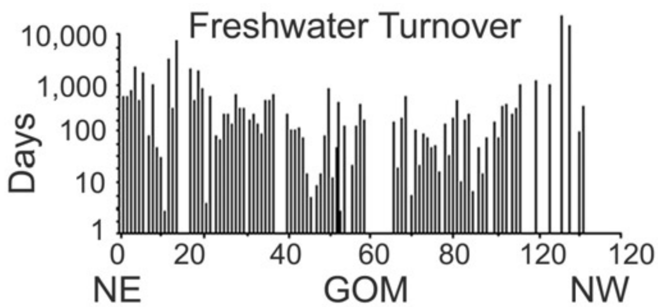

Figure 2. Variations in freshwater turnover times for US estuaries from the Northeast (NE) to the Gulf of Mexico (GOM) to the Northwest (NW). (Adapted from Turner, 2001).

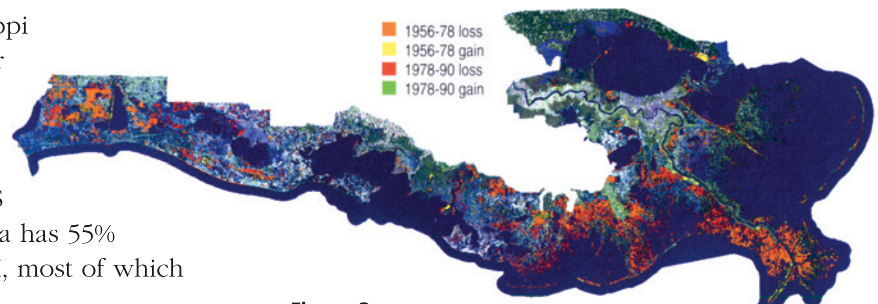

Figure 3.
Coastal landloss in Louisiana. From the USGS in Lafayette, Louisiana.

Two major habitat changes whose management will be further complicated by the anticipate global climate changes are wetland losses and barrier island erosion. Wetland losses are particularly severe in the northern Gulf of Mexico (Figure 3) because of a variety of human influences, including hydrologic change, eutrophication, and impoundment. Louisiana's wetland losses, for example, were 69% of the nation's coastal wetland losses from

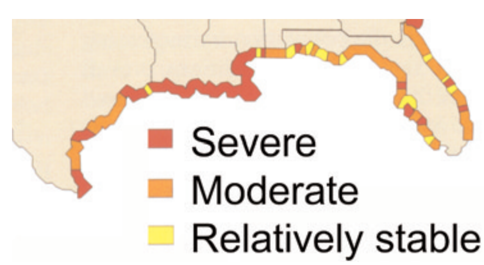

Figure 4. Annual shoreline change in the Gulf of Mexico. Adapted from USGS, 1985.

Table 2 Gulf of Mexico coastal wetland inventory (hectares). From NOAA, 1991.

	Marsh	Estuarine scrub-shrub	Forested and scrub-shrub	Total	% Total
Texas	183,900	1,100	3,000	188,000	14
Louisiana	723,500	4,100	1,900	729,500	55
Mississippi	23,800	400	-	24,200	2
Alabama	10,400	1,100	800	12,300	1
Florida	108,100	255,100	13,100	363,900	28
Total	1,049,700	255,100	13,100	1,317,900	100

1978 to 1990. Barrier islands form legal, physical and hydrological boundaries of importance to both natural and economic worlds. Barrier islands in the GOM are under considerable stress compared to the rest of the US because of either their use or their instability, including retreat (Figure 4).

6.2 Climate Variability and Change

Climate models predict an increase in temperature, variations (higher and lower) in precipitation, and higher riverine flow in major rivers. A summary of the predicted precipitation, temperature, and streamflow changes, by season expected to occur by the year 2100 as a result of global climate changes is in Table 3 (Swenson, Chapter 9). The scale of these changes is sufficient to anticipate impacts on the coastal ecosystems, although the magnitude and spatial distribution of impacts is somewhat speculative, given the sometimes conflicting model outputs for regional predictions. This uncertainty is an important area for research attention, since the interpretation of climate change impacts is driven by the magnitude of these changes, some of which might be synergistic, and others could be compensatory.

6.2.1 Estuarine salinity and climate change

Water turnover rates within the estuarine receiving basin will have two important effects on the physical environment of estuaries: the salinity regime will be altered, and the constituents will be diluted. The distribution and magnitude of effects will be indirectly realized through changes in estuarine salinity. A higher freshwater inflow will lower estuarine salinity and a lower net precipitation will raise salinities *if all other factors remain the same.*

Salinity in the northern Gulf of Mexico estuaries is influenced by (1) water exchange between the estuarine entrance and the coastal zone; and (2) local forcing (river discharge, precipitation) occurring

Table 3 Summary of predicted precipitation, temperature, and streamflow changes, by season expected to occur by the year 2100. The predictions are from the Hadley Model (HadCM2) as summarized by Ning and Addollahi (1999). Adapted from Swenson, Chapter 9.

Season	Parameter	Texas	Louisiana	Mississippi	Alabama	Florida
Winter	Precipitation	5-30% decrease	no change	no change	no change	no change
Spring	Precipitation	10% increase	no change	10% increase	10% increase	no change
Summer	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Fall	Precipitation	10% increase	10% increase	15% increase	15% increase	no change
Winter	Temperature	4° F increase	$<3^{\circ}$ F increase	2° F increase	2° F increase	$<3\text{-}4^{\circ}$ F increase
Spring	Temperature	3° F increase	3° F increase	3° F increase	3° F increase	$3\text{-}4^{\circ}$ F increase
Summer	Temperature	4° F increase	3° F increase	2° F increase	2° F increase	$3\text{-}4^{\circ}$ F increase
Fall	Temperature	4° F increase	$<3^{\circ}$ F increase	4° F increase	4° F increase	$3\text{-}4^{\circ}$ F increase
Winter	Streamflow	35% decrease	unknown	unknown	increase	unknown
Spring	Streamflow	35% decrease	unknown	unknown	increase	unknown
Summer	Streamflow	35% decrease	decrease	decrease	decrease	decrease
Fall	Streamflow	35% decrease	unknown	unknown	unknown	unknown

within the estuary proper. The Mississippi-Atchafalaya discharge dominates the input in the central portion of the Gulf, while the western (Texas) and eastern (Mississippi to Florida) portions of the Gulf are more heavily influence by local river flow (Table 4). The northern Gulf of Mexico precipitation-evaporation exhibits a general decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. The sum of these two patterns results in an overall precipitation deficit in the western part of the Gulf (and southern Florida) and a precipitation surplus in the central portion of the Gulf.

The results of various climate change model predictions suggest that there will be increases in precipitation on the order of 10% for all of the Gulf states, except Florida. The predicted changes for streamflow are, in most cases, still uncertain. The effect of climate change on Mississippi River discharge is the most important consideration for the Louisiana estuaries, whose salinity is strongly affect-

Table 4 Summary of the major and secondary freshwater sources influencing salinities in the 26 northern Gulf of Mexico estuaries. The original data was taken from Orlando et al. (1995).

State	Estuarine system	Major freshwater source	Other freshwater source
Texas	Laguna Madre	Rainfall (65%)	Local riverflow (17%)
Texas	Corpus Christi Bay	Local riverflow (92%)	Rainfall (8%)
Texas	Aransas Bay	Local riverflow (54%)	Rainfall (46%)
Texas	San Antonio Bay	Local riverflow	Rainfall
Texas	Matagorda Bay	Local riverflow (25-80%)	Rainfall
Texas	Brazos River	Local riverflow	
Texas	Galveston Bay	Local riverflow	
Texas	Sabine Lake	Local riverflow	
Louisiana	Calcasieu Lake	Local riverflow	
Louisiana	Mermentau River	Local riverflow	
Louisiana	Atchafalaya/Vermilion	Atchafalaya River flow	
Louisiana	Terrebonne/Timbalier	Mississippi River flow	Rainfall
Louisiana	Barataria Bay	Mississippi River flow	Rainfall
Louisiana	Breton Sound	Mississippi River flow	Pearl River flow
Louisiana	Pontchartrain/Borgne	Local riverflow (90%)	Rainfall (5%)
Mississippi	Mississippi Sound	Local riverflow	Mississippi River flow
Alabama	Mobile Bay	Local riverflow	
Florida	Perdido Bay	Local riverflow	
Florida	Pensacola Bay	Local riverflow	
Florida	Choctawhatchee Bay	Local riverflow	
Florida	St. Andrew Bay	Rainfall	
Florida	Apalachicola Bay	Local riverflow	
Florida	Apalachee Bay	Local riverflow	
Florida	Suwannee River	Local riverflow	Groundwater flow
Florida	Tampa Bay	Local riverflow	Rainfall
Florida	Sarasota Bay	Rainfall	Local riverflow

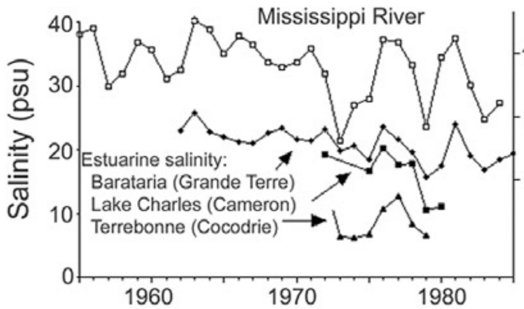

Figure 5. Time series plots of the combined annual mean flow of the Mississippi and Atchafalaya Rivers (open square) and plots of mean annual salinity from selected Louisiana Wildlife and Fisheries sampling stations within three Louisiana estuaries. River flow is in thousands of cubic feet per second (cfs) with a 15,000 cfs offset and is turned vertically to enhance visualization of the coherent patterns with estuarine salinity. It shows the effects of the river discharge variations on salinity in the estuarine bays. The relationship is dependent on freshwater entering through the open ocean passes during tidal excursions. Adapted from Wiseman et al., 1990.

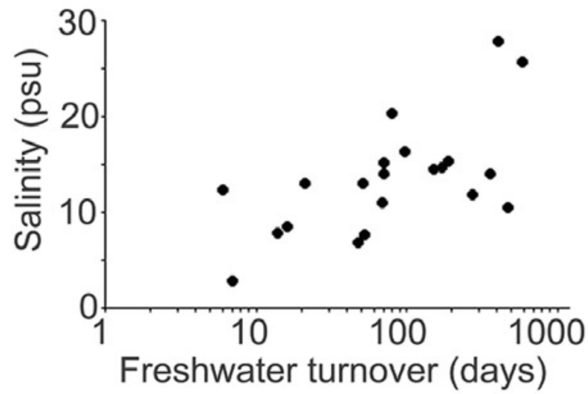

Figure 6. Freshwater inflow and salinity in Gulf of Mexico estuaries. Freshwater turnover is the estuarine volume divided by the freshwater inflow (from streams and precipitation) into the estuary. Increasing freshwater inflow will decrease the freshwater turnover time, leading to salinity reductions in the estuary. Adapted from Turner, 2001.

ed by salinity variations in the offshore waters (Figure 5). Boesch et al., (2000) present data indicating that the Hadley model predicts an increase of ~5%, and the Canadian Model predicts a decrease of ~35% for the Mississippi River discharge from 2025 through 2034. They further state that the Hadley model predicts an increase of ~50%, and the Canadian Model predicts a decrease of ~30% for the Mississippi River discharge from 2000 through 2099, and sea level is predicted to increase on the order of 30 centimeters by 2100.

Statistical models (Swenson Chapter 9) were developed describing the observed salinity at three stations (a "coastal station", a "mid-estuary station", and an "upper estuary station") in the Barataria estuary, Louisiana, in terms of the major forcing functions (Mississippi River discharge, local precipitation, and coastal water levels). The most successful models used an autoregressive term in addition to the forcing function values. These models were able to account for 72, 74, and 63 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations, respectively. The non-autoregressive portion of the model accounted for 48, 41, and 16 percent of the observed salinity signal at the coast, mid-estuary, and upper estuary stations, respectively.

The models were then used to predict the average salinity for each station using the data from 1990 through 2000 as an "index" period. The models reproduced the average annual salinity at each of the stations. The potential salinity changes that might occur with global climate changes in the forcing functions were estimated by changing the forcing functions during the index period to correspond to various climate change scenarios (increased or decreased precipitation and Mississippi River discharge). The resulting change in the annual pattern was then compared to the baseline condition. The results yield a potential change of ~3 psu (= 3 ppt) for the salt marsh, and ~1 psu for the intermediate to brackish areas of the Barataria system.

A separate analysis of the relationship between freshwater inflow and average salinity supports these model predictions and inferences. A doubling of freshwater inflow decreases the time it takes to turnover the water volume of an estuary. The relationship between freshwater turnover (X) and salinity (Y) for 26 Gulf of Mexico (GOM) estuaries is shown in Figure 6. It suggests that halving the freshwater turnover time (a doubling of freshwater inflow) will result in a salinity decrease of only a few psu (on the average).

The potential impacts of these changes are difficult to assess because the present climate models give conflicting results on the expected changes in runoff (there is general agreement on precipitation changes). However, if changes are about 3 psu, then the potential impacts would most likely be limited to small scale vegetation community changes at the boundaries of the major vegetation types. Larger

Table 5 Classification for Gulf of Mexico estuaries based on salinity variability as it relates to the character of the forcing functions. Listed, for each estuary type, is the stability level the forcing function and salinity variability characteristics, and example estuaries. Adapted from Swenson, Chapter 9.

Type	Description	Characteristics	Examples
1	Stable	1. Salinity controlled by one factor 2. Lack of dominant and continuous freshwater sources. 3. Salinity always at or near Gulf Salinities. 4. Very low to low salinity variability at all time scales.	Tampa Bay, FL Corpus Christie Bay, TX Sarasota Bay, FL Laguna Madre, TX
2	Variable 1	1. Salinity controlled by multiple factors. 2. Riverflow component important, tidal flow dominates. 3. Medium to high variability at day-week time scales. 4. Low variability at day-week time scales. 5. Low to medium salinity variability at yearly time scales.	San Antonio Bay, TX Terrebonne/Timbalier, LA Aransas Bay, TX Barataria Bay, LA Apalachee Bay, FL
3	Variable 2	1. Salinity controlled by multiple factors. 2. Riverflow and tidal flow are equal. 3. Medium variability at day-week scales. 4. High variability at day-week time scales. 5. Medium salinity variability at yearly time scales.	Suwannee River, FL Perdido Bay, FL Pensacola Bay, FL Apalachicola Bay, FL Mermantau River, LA
4	Variable 3	1. Salinity controlled by multiple factors. 2. Tidal flow component important, river flow dominates. 3. Low variability at day-week time scales 4. Medium variability at day-week time scales. 5. Low to medium salinity variability at yearly time scales.	Sabine Lake, LA-TX Mobile Bay, AL Breton Sound, LA Galveston Bay, TX Calcasieu Lake, LA
5	Stable	1. Salinity controlled by one factor. 2. Lack of dominant saltwater source. 3. Salinity values always quite low except for extreme events. 4. Low salinity variability at all time scales.	Atchafalaya Bay, LA Lake Pontchartrain, LA Chandeleur Sound, LA Mississippi Sound, MS

salinity changes would be needed in order to see dramatic vegetation shifts in the coastal salt marshes.

The two climate models (Hadley and Canadian) used for the basis for this study give conflicting estimates of the potential changes in the hydrologic cycle (Boesch et al., 2000). In general, there is low confidence in the predicted precipitation changes on a regional level (Adams and Gleick, 2000). This makes it difficult to assess the impacts around the Gulf of Mexico without detailed data from each estuarine system as was utilized in the Barataria assessment. However, some general statements regarding possible impacts can be made (Table 5). Stable systems such as Laguna Madre, Texas, or Atchafalaya Bay, Louisiana should not be affected by changes in the forcing functions that may result from global climate change, provided the changes are on the order of those predicted for the Barataria estuary (1 - 3 psu). These systems will only be effected by extremely large changes in the environmental forcing functions. The Types 2, 3, and 4 systems are the systems that would exhibit the greatest response to climate change due to their dynamic nature. In these systems, however, a negative change in one forcing function may be offset by a positive change in another forcing function. For example, in the Barataria System, a decrease in the local precipitation would lead to an increase in estuarine salinity, however, an increase in Mississippi River discharge occurring at the same time could offset this hypothetical salinity increase.

6.2.2 Sustaining salt marshes amidst climate changes

Salt marshes, located at the seaward edge of the estuary must maintain their relative elevational position as sea level rises. If the plant is flooded too often, then the soil salt marsh plants grow on may become a hostile environment, and the plants will become physiologically stressed. If the soils do not accumulate enough organic and inorganic materials to compensate for both sea level rise and for the lowering of the marsh soil (subsidence), then the marsh becomes open water. A healthy salt marsh accumulates just enough sediment over several years to survive the seasonal and annual fluctuations in

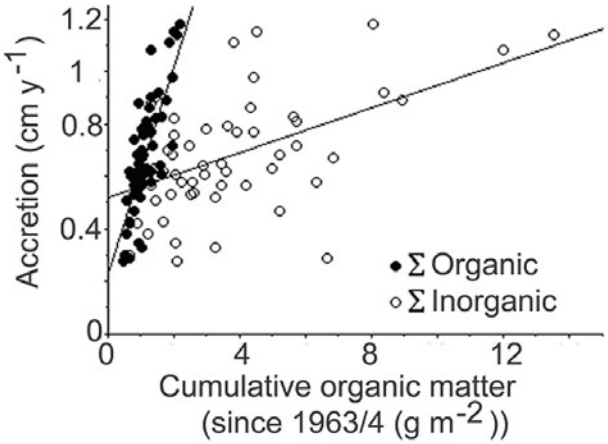

Figure 7. The relationship between the vertical accretion rate and the accumulated organic (left panel) and inorganic material (right panel). The data are for post 1963/4 accumulations. Adapted from data in Turner et al., 2001b.

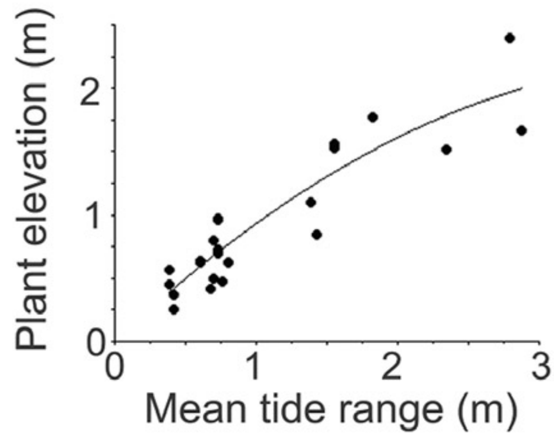

Figure 8. The relationship between the tidal range (X axis) and the elevation range within which the emergent salt marsh macrophyte Spartina alterniflora occupies. The tidal range at different locations within the Gulf of Mexico varies between 30 to 100 cm. Adapted from data in Mckee and Patrick, 1988.

water level. Most of this material is organic matter, not inorganic matter. Inorganic material makes up less than 5% of the soil volume in salt marshes. The rest of the soil is water, which is held there by the organic material. Thus the relationship between vertical accretion and organic matter is stronger than between vertical accretion and inorganic material (Figure 7).

GOM salt marshes occupy a rather narrow range (30 to 100 cm) within the intertidal zone, which is smaller than on the East Coast (Figure 8). A small change in a plant's elevation can make a big difference on whether or not its habitat is suitable, especially for plants living near the limits of its physiological tolerances. GOM salt marshes appear to be more susceptible to changes in subsidence, and sea level rise - a climate induced change. The marsh, in other words, is responsive to the seen (above ground) and unseen (belowground) environmental factors affecting plant health.

What this means is that the health of the salt marsh plant, especially belowground, is probably the major factor determining whether or not salt marshes can survive in the face of rising sea level and the sinking of the land upon which the plant is embedded. Most of the vertical adaptations that salt marsh plants must make are for subsidence, which is dominated by changes in the upper 2 meters (Turner 1991). The changes from global sea-level rise (present and future) are usually less than half of this subsidence rates (Figure 9). However, not all plants occupy an 'average' position in the landscape. Plants on the lower end of the tidal range shown in Figure 8 can be quite susceptible to even small changes in their flooding frequency.

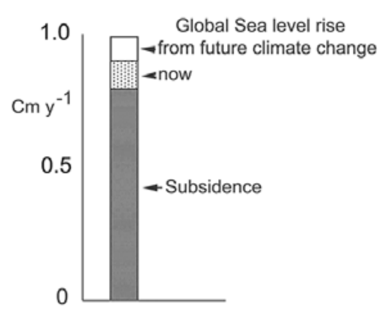

Figure 9. An example of the relative water level changes in a salt marsh due to subsidence from soil compaction and geological shifts and sinking (dark fill), present sea level rise (gray fill) and projected additional future sea level rise resulting from global climate change (unfilled). The total relative water level changes varies around the Gulf of Mexico, from zero to >1.3 cm y^{-1}.

There are other factors that interact with climate to influence the survivability of salt marshes. Some striking and novel results of other effects on coastal marshes arose from field experiments by Silliman and Zieman (2001) who demonstrated control of salt marsh macrophytic vegetation by snails. The common periwinkle, Littorina irrorata, has a profound effect on the health of the living salt marsh plant by grazing periphytic algae off the leaves that are damaged in the process. This effect increased with increasing nitrogen availability. Presumably, predation on periwinkles affects the amount of damage done by the whole snail population, and this predation could be influenced by commercial fishing pressure or interspecific competition by crabs, birds and fish (all of which might be influenced by climate). In addition, nutrient availability, including too much nitrogen, can increase the decomposition of the belowground organic material (Morris and Bradley, 1999), perhaps leading to marsh collapse. Thus, the survivability of salt marshes is not dependent on one factor, but the interaction of many factors, including those affected by global climate changes. These complex relationships between habitat sustainability and ecosystem health can be cumulative and long-term in nature.

The upland side of the salt marshes is also sensitive to flooding, and also other factors, reflecting the interactive nature of multiple influences. For example, Sasser (1977) documented how four brackish and salt marsh plants were sensitive to both salinity and flooding (Figure 10). A plant might exist, or not, because of either too high a salinity, or an intolerance to the in situ flooding regime.

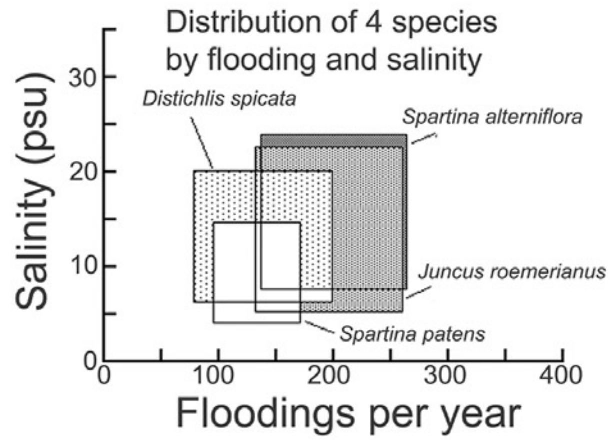

Figure 10. The distribution of four species of emergent estuarine plants described according to the flooding frequency and average salinity at each site. Note the close overlap for some species, and that a change in either salinity or flooding can change the competitive outcome for two species trying to occupy one location. Adapted from Sasser, 1977.

6.2.3 Commercial Shrimp Harvests and Climate Change

There has been considerable research on how temperature and salinity govern estuarine communities, especially species of substantial economic interest. Estuaries are often called 'nursery grounds' because of the role they play in providing juveniles a relatively food-rich niche of reduced predation pressure. A slight reduction in mortality while young can be quite important in determining the size of the adult population. Thus estuarine conditions have been used to predict future harvest success. Empirically-defined analyses of species composition, survival, or harvest over varying salinity and temperature ranges in Gulf of Mexico estuaries have been quite successful (e.g., Gunter, 1950; Gunter et al., 1964, Copeland and Bechtel, 1974; Armstrong, 1982). Based on these analyses, it is quite clear that the effects of climate change will be significant. The temperature of slow moving or stagnant shallow waters is strongly influenced by air temperatures, which are postulated to increase by 3 – 5°F as atmospheric carbon dioxide doubles. Estuaries with limited mixing will be more stratified as temperature rises (also affecting bottom water oxygen concentration), especially during summer.

The commercial shrimp fisheries of the northern Gulf of Mexico are based on the capture of brown and white shrimp, and much smaller quantities of pink and red shrimp. The general life cycle of brown and white shrimp includes an offshore spawning stock. One female may release one million eggs, which suggests a very high mortality rate. The free-floating larvae make their way into coastal estuaries and may have some ability to move vertically to maximize differential current flows within a stratified water column. Once in the estuary they live at the wetland edge and within the wetland (depending on water levels) where they grow large enough over several months to eventually migrate offshore as post-larvae or juveniles and be caught, eaten and/or reproduce. The entire cycle from birth to harvest is ordinarily 12 months.

The large annual variations in shrimp harvest from year to year are associated with changes in estuarine conditions when the juveniles are in the estuary. Variation in estuarine salinity and temperature at the time of estuarine use by the shrimp is documented world-wide for significant climatic influence on shrimp mortality (Table 7), although the frequency and intensity of passages of meteorological fronts, may also be important. Copeland and Bechtel (1974) analyzed the salinity and temperature preferences of several penaeid (shrimp) species in estuaries of the northern Gulf of Mexico. They clearly demonstrated the interactive optimal preferences by shrimp for temperature and salinity, rather than linear relationships dominated by one factor. The result is that several state fish and game agencies predict

Models of the effects of doubling sea-level rise on coastal wetland loss in Louisiana.

A computer model of the coastal Louisiana landscape was used to explore the effects of climate change on wetland loss rates (in Reyes et al., Chapter 7). Two watersheds were examined (Figure 11). One landscape (Western Basin) had a prograding delta and the other a regressive delta (Barataria). The 6100 km^2 Barataria estuarine system is located between the natural levees of the Mississippi River and Bayou Lafourche. The Western Basin is bordered by Freshwater Bayou on the west and the Atchafalaya River on the east and occupies about 6765 km^2. The models attempted to link habitat interactions within these two basins across spatial and temporal scales using three coupled modules: a vertically integrated hydrodynamic module; a process-based biological module of above and below ground primary productivity; and a module for soil dynamics.

The models were run using present sea-level rise rates and also a doubling of sea level rise (0.18 and 0.40 cm y^{-1}, respectively). The assumptions inherent to the model have varying levels of confidence, and there is no direct experimental mechanism to test their accuracy. Hindcasting model results against pre-1988 conditions is used, therefore, to test the model's accuracy. A minimum usefulness of the model is to teach scientists about the uncertainties in the model's assumptions, and, to predict the relative proportional changes in the two basins, and to estimate the relative changes in land loss with and without a doubling of sea level rise. The predictions (Table 6) suggest that the two basins behave differently, which the authors attribute to the presence of the Atchafalaya River debouching into the Western Basin, in contrast to the Mississippi River delta's retreat in the other site (located offshore of the Barataria Estuarine system). Interestingly, land loss in the Western Basin is predicted to be less than 5 % from 1988 to 2058 (70 years), and also that coastal land loss therein is unlikely to be dramatically affected by a doubling of sea level rise. Land loss in the Barataria Basin was predicted to be 37% over the same interval, and to increase by and additional 9% if sea level rise doubles (and additional 25% above the rates with a stable sea level rise).

Figure 11. Location of the two basins included in the computer model of coastal land loss and sea level rise changes.

Table 6 Results from a computer model that explores the effects on coastal wetland loss using two assumptions: with and without a doubling of sea level rise (SL) from 0.17 to 0.4 cm y^{-1}.

From 1988 to 2058:	Total Land (KM^2)	Open Water (KM^2)	Land loss 1988-2058	
Western Basin				
1988	2157	6465		
projected without 2X SL rise in 2058	2057	6565	4.64%	Difference
projected with 2X SL rise by 2058	2056	6566	4.68%	+ 0.05%
Barataria Basin				
1988	2971	2952		
projected without 2X SL rise in 2058	1866	4057	37.19%	Difference
projected with 2X SL rise by 2058	1604	4319	46.01%	+ 8.82%

shrimp fisheries harvest on the basis of spring salinity and temperature, or from surrogate measures of salinity, such as riverflow. An example is the annual variations in the Gulf of Mexico shrimp catch which are negatively related to annual variations in riverflow (Figure 12), implying a riverine control on estuarine salinity. The higher yield at the same discharge in recent years may be the result of the greater fishing effort, gear changes, improved fishing knowledge, increased wetland 'edge' (resulting from wetland fragmentation), economic incentives, or, improved reporting of the actual catch. These predictive efforts are successful because larval recruitment from the spawning sites offshore into estuaries is so high that postlarval growth and survival in the estuary are probably the most important factors affecting the harvestable adult population size. Estuarine salinity and temperature changes affect the variations in annual postlarval survival, perhaps for physiological reasons, or for the indirect influences on food supply or predators. Nevertheless, it is clear that variations in climate affect fisheries yields.

Table 7 Examples of the effects of climate on coastal penaeid shrimp stocks. Adapted from Turner, 1989.

Location	Species	Effect on yields
North Carolina	*P. duorarum*	temperature (-)
Louisiana	*P. setiferus*	salinity (-) temperature (+)
	P. aztecus	salinity (+) temperature (+)
Northern Gulf of Mexico (USA)	*P. setiferus*	salinity (-) temperature (+)
	P. aztecus	salinity (+) temperature (+)
Florida	*P. duorarum*	water level (+)
Laguna Madre, Texas (periodically hypersaline)	*P. fluviatilis* *P. aztecus*	rainfall (+)
Australia	*P. merguiensis*	rainfall (+)
Indonesia	*P. merguiensis* *P. monodon*	riverflow (+)
Senegal	*P. duorarum*	salinity (+)

Although postlarval growth and survival in the estuary are the most important factors affecting the harvestable adult population size from year-to-year, the long-term yields are directly related to both the quantity and quality of intertidal habitat. This conclusion is supported by the strong linear relationship between shrimp and the area of estuarine vegetation, from Louisiana to Florida (Figure 13). There is no obvious relationship between harvest and open estuarine water surface area, except for a possible inverse relationship. In addition, the species of shrimp caught are directly related to the kinds of intertidal coastal vegetation within that hydrologic unit. The implication of this conclusion is that habitat changes in the estuary (e.g., from any source including climate change) will affect shrimp yields.

Model predictions for climate change in the northern Gulf of Mexico suggest that both temperature and riverflow will increase. The present relationship between riverflow and commercial yields is negative (Figure 12). The short term effect of higher discharge rates will be a decrease in overall yields, therefore. There may be some adjustments as the estuarine watershed vegetation changes with lower salinities. The longer term prospects are, however, even worse. This result will because of the consequential dependency of the shrimp on the intertidal vegetation. It might seem that the fresher part of the estuary will move inland. However, the elevation gradient increases in many parts of the Gulf of Mexico, which will cause a squeezing of space for intertidal habitat. The result of these interacting forces will be lower shrimp yields for the same amount of fishing effort. The implication of the relationship between riverflow and shrimp yields shown in Figure 12 is that a 30% rise in river discharge might result in a 15 to 20 % reduction in shrimp yields in the northern Gulf of Mexico.

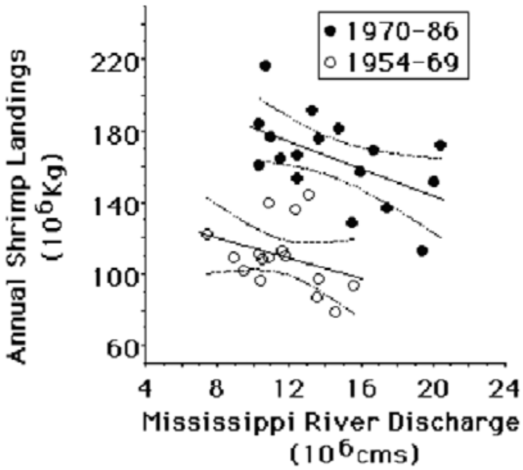

Figure 12. The relationship between the annual yields of shrimp in the Gulf of Mexico and discharge of the Mississippi river. The 95% confidence limit for the y value of each linear regression is shown. Temperature is also an important covariable. (Adapted from Turner, 1992).

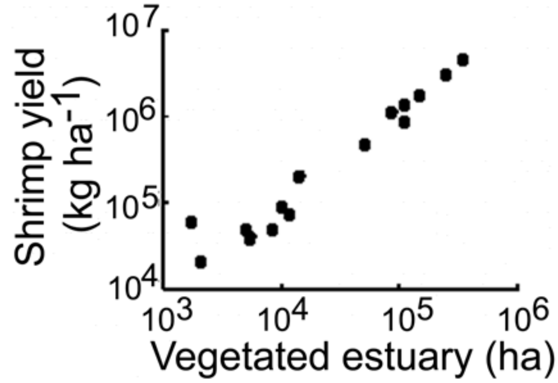

Figure 13. The relationship between intertidal vegetation and penaeid shrimp yields from the estuaries of the northern Gulf of Mexico (adapted from Turner, 1977).

6.2.4 Hypoxia and climate change

Hypoxia occurs when the oxygen content of bottom waters fall below 2 mg l^{-1}. This cut-off point is the empirically-defined limit below which shrimp and fish are usually absent. Anoxia occurs where there is no oxygen in bottom layers.

What Causes Hypoxia

Two principal factors lead to the development and maintenance of hypoxia in coastal waters: (1) a physically stratified water column, and, (2) decomposition of organic matter in the bottom layer. The water column must be stratified so that the bottom layer is isolated from the surface layer with the result that normal diffusion of oxygen from surface to bottom layers is reduced. Fresher waters derived from rivers and seasonally-warmed surface waters are less dense and reside above the saltier, cooler and more dense water masses near the bottom. This isolation reduces the reaeration of oxygen from atmosphere to surface layer to bottom waters. The stratified system may be interrupted by wind-mixing events, notably tropical storms and winter cold fronts.

The decomposition of organic matter in the bottom layer consumes oxygen, but stratification prevents an equilibrium concentration that is sufficient to maintain oxygen concentrations sufficient to support many life forms, including fish and shrimp. The source of this organic matter is mostly from phytoplankton growth in surface water. Phytoplankton not incorporated into the food web and fecal material generated via the food web sink into bottom waters where they are decomposed by aerobic bacteria, and oxygen is depleted. The concentrations and total loads of nitrogen, phosphorus and silica influence the quantity and quality of phytoplankton community and, ultimately, the flux of phytoplankton-derived organic matter.

The relative influence of the physical features of the system and the progression of biological processes varies spatially and over an annual cycle. In the northern Gulf of Mexico the physical and biological processes are complexly inter-related and directly linked with the dynamics of rivers, atmospheric sources, and groundwater.

Where is Hypoxia/Anoxia in the Gulf of Mexico

Decreased concentration of dissolved oxygen (=hypoxia) occurs in many parts of the world's aquatic environments. Hypoxic and anoxic (no oxygen) waters have existed throughout geologic time and presently occur in many of the ocean's deeper environs, but their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities (Diaz and Rosenberg, 1995).

The second largest zone of coastal hypoxia (= oxygen depleted waters) in the world is found on the northern Gulf of Mexico continental shelf adjacent to the outflows of the Mississippi and Atchafalaya rivers (Figure 14). The mid-summer bottom areal extent of hypoxic waters (< 2 mg l^{-1} O_2, or ppm) in 1985 – 1992 averaged 8,000 to 9,000 km^2, but increased to 16,000 to 20,000 km^2 in 1993 - 1999 (Rabalais and Turner, 2000). The estimated extent was 12,500 km^2 in mid-summer of 1998, and 4,400 km^2 in 2000 and reached a record size of 20,700 km^2 in mid-summer 2001 (Rabalais 2001). Hypoxia is not found just a thin lens overlying bottom sediments, but occurs well up into the water column depending on the location of the pycnocline(s). Depending on the depth of the water, hypoxia may encompass from 10% to over 80% of the total water column, but is normally only 20 to 50% of the water column. At the high end of this range, hypoxic waters may reach to within 2 m of the surface in a 10-m water column, or to within 6 m of the surface in a 20-m water column.

Hypoxia or anoxia is also found in most of the Gulf of Mexico estuaries (Figure 15). When hypoxia occurs in Mobile Bay or nearby coastal waters, fish can be trapped along the shore where they are easily capture (and sometimes moribund). These events are called "Jubilees" if the fish are moribund when captured, but not dying. Jubilees also happen in Louisiana along barrier island beaches.

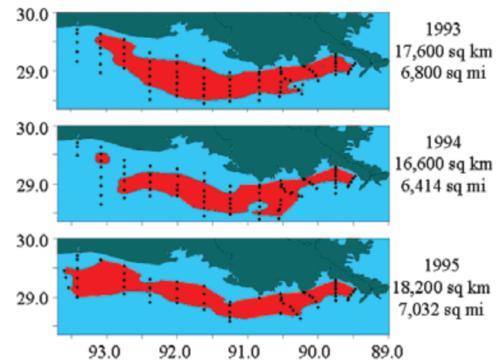

Figure 14. Hypoxia in bottom waters during the summer west of the Mississippi River delta. Graphics provided by N. N. Rabalais and colleagues and are described in Rabalais et al., 1999.

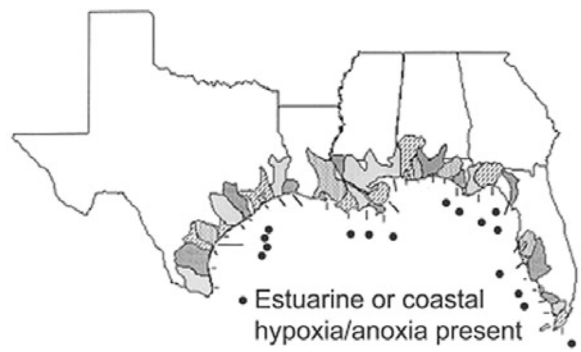

Figure 15. Estuaries in the Gulf of Mexico that have a record of periodic hypoxia or anoxia.

Some Biological Effects of Hypoxia

The hypoxic zone off Louisiana is often referred to as the "Dead Zone" in the popular press and literature. The term "dead zone" refers to the failure to capture fish, shrimp, and crabs in bottom-dragging trawls when the oxygen concentration falls below 2 mg l^{-1} in the water covering the seabed (Leming and Stuntz, 1984; Renaud, 1986). The numbers of stressed or dying benthic infaunal organisms within the sediments increase substantially when the oxygen levels remain low for prolonged periods (Rabalais et al. 2001). Higher up in the water column and in the surface mixed layer, however, there is sufficient oxygen to support sizable populations of swimming fish and crabs. Also, there are anaerobic or hypoxia-adapted organisms that survive in sediments overlain by hypoxic or anoxic waters, so that the term "dead zone" is not entirely applicable to the whole of the area designated "hypoxic" (several chapters in Rabalais and Turner, 2001). Still, the area is large, approaching the size of the state of Massachusetts in 2001, and garners public attention primarily because of the loss of catchable fish and shrimp.

Mass mortalities are likely if they are trapped against the shore by a large anoxic water mass. Heavy mortalities occur in the benthic infauna and species diversity is drastically reduced when ambient oxygen concentrations decrease below 0.5 mg l^{-1} (Gaston, 1985; Boesch and Rabalais, 1991; Rabalais et al. 1993, 2001). There is some recovery of the benthic community after hypoxic events are over. However, the overall structure of the benthic community is shifted in species composition and age structure, to a smaller-sized, lower biomass, polychaete dominated fauna. An increase in areal extent and severity of hypoxia will decrease recovery rates and also reduce food resources (infauna) for recolonizing demersal groups, such as the commercially important penaeid shrimps. Further, alterations in benthic community structure will have implications for sedimentary processes, benthic pelagic coupling, and energy flow. Major alterations in benthic communities due to hypoxia stress, especially a reduction in diversity and biomass, will certainly alter the productivity base that leads to fishery stocks. Further, fishers have to travel farther to catch the migrating fisheries stocks that avoid hypoxic areas, thus reducing net economic returns.

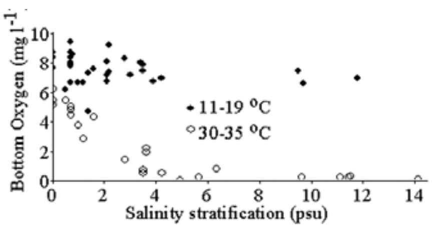

Figure 16. The relationship between salinity stratification between surface and bottom water (X axis) and bottom water oxygen concentration (X axis; (mg l^{-1}) in upper Charlotte Harbor, Florida. Data are for June-October from sampling by the South Florida Water Management District. Two portions of the data are included: where temperature in the surface water is 30°C or higher (open circles) and between 11 and 19°C (filled circles). From Turner et al., 2001.

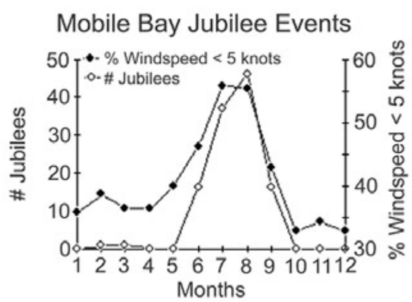

Figure 17. The percent monthly occurrence of low winds (< 5 knot wind speeds, 1974 – 1984) and the historical record of the total number of "jubilees" in Mobile Bay by month from 1946 – 1971. Adapted from Turner et al., 1987.

Climate Change and Hypoxia

Freshwater discharge and seasonal atmospheric warming control the strength of stratification necessary for the development and maintenance of hypoxia. The combined long-term average annual discharge for the Mississippi and Atchafalaya Rivers to the Gulf of Mexico is 19,920 $m^3 s^{-1}$ (1930 – 1997 period) (Bratkovich et al., 1994; Goolsby et al. ,1999). The long-term peak flow occurs in March, April and May, and the long-term low flow is in summer and early fall. Although flow is reduced in summer, large-scale circulation patterns facilitate the retention of the fresh water on the shelf (Rabalais et al. 1999). There is significant interannual variability in discharge, but the long-term average discharge for the lower Mississippi River is remarkably stable near 14,000 $m^3 s^{-1}$ (Turner and Rabalais, 1991; Bratkovich et al., 1994). Less obvious is a statistically significant and increasing trend in the Mississippi River discharge for 1900 – 1992 as measured at Tarbert Landing (Bratkovich et al. 1994). It appears to be due to a tendency for increasing discharge in September through December. This period, however, is much less important in the coastal ocean than spring and summer in the timing of important biological processes that lead to the development of hypoxia or the physical processes important in its maintenance. If a longer period of annual discharge were considered, e.g., for the early 1800s to present, the trends since the 1950s are obvious but are concealed within high interannual variability and no long-term change over a century and a half (Rabalais et al., 1999).

The projected global climate changes in the Gulf of Mexico includes higher temperatures, altered seasonal variations in river discharge and precipitation, and increased precipitation and (probably) Mississippi River discharge. Both increased temperature and freshwater discharge will affect the size and severity of hypoxic water masses in the Gulf of Mexico. Climate changes in the Gulf of Mexico will affect both of these factors, and often in a negative way. An example of the interrelationship between temperature (which is directly related to organic-decomposition rates), stratification and hypoxia is shown in Figure 16. Hypoxia in Charlotte Harbor is most likely to occur at higher temperatures and during periods of water column stratification. A lack of wind mixing of the water column may also encourage the likelihood of hypoxic events. Jubilees in Mobile Bay, for example, occur during the summer when wind speed is relatively low (Figure 17).

6.3 Response/Coping/Adaptation Options Information and Research Needs in the future

The preceding discussion illustrated several ways in which the anticipated climate changes will affect coastal ecosystems. The physical structure of coastal systems may be changed through alterations in salinity and temperature, and by habitat changes resulting in the replacement of emergent vegetation with open water. These changes can affect fisheries. Further, nutrient reduction strategies meant to reduce the severity and frequency of hypoxic events can be compromised by increased riverflow.

The seemingly direct consequences of climate change, therefore, are not the only stressor on ecosystems. Anthropogenic stress from one factor (e.g., sea level rise) can be additive to existing stres-

Models of Climate Change Effects on Hypoxia

Because model projections for the Mississippi River runoff are highly variable, the assessments of future climate change scenarios for the northern Gulf of Mexico are complicated. The Canadian and the Hadley model projected a 30% decrease and a 40% increase, respectively, by the year 2099. Justić (Chapter 8) developed an eutrophication model to describe changes in surface and bottom oxygen concentrations within the core of the Gulf of Mexico hypoxic zone. A plot of the model results and the actual data are shown in Figure 18. A sensitivity analysis revealed that the model is highly sensitive to external forcing, yet sufficiently robust to withstand order of magnitude changes in the nitrate flux of the Mississippi River.

Model simulations suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity and global oxygen cycling in the northern Gulf of Mexico. A doubling of atmospheric carbon dioxide would lead to higher temperatures, increased runoff and longer, more severe and larger hypoxic zones in the northern Gulf of Mexico (Figure 19). Nominal model simulation for the period 1954-2000, for example, predicted 19 years with moderate hypoxia (< 2 mg O_2 l^{-1}) and 16 years with severe hypoxia (< 1 mg O_2 l^{-1}). A 30% decrease in the Mississippi River discharge for the same period would have significantly reduced the number of years with moderate and severe hypoxia to 8 and 4, respectively. For a scenario with 4°C increase in the average annual temperature and a 20% increase in the average Mississippi River discharge, the model predicts 31 year with moderate and 26 years with severe hypoxia. Importantly, model simulations suggest that pronounced hypoxia would not develop if the nitrate concentrations would had remained unchanged with respect to the period 1954 – 1967 (0.61 mg N l^{-1}). Thus, depending on future climate change scenarios and nutrient control strategies, hypoxia in the northern Gulf of Mexico may become more or less severe.

Model simulations indicated that bottom water hypoxia in the northern Gulf of Mexico has intensified in recent historical time, as a probable consequence of increased net productivity and an increase in the vertical flux of the organic carbon. Apparently, the long-term increase in riverine nutrient fluxes has been the primary factor controlling this historical decline in oxygen concentrations. Nevertheless, the influence of climatic factors on nitrate flux has been significant and may further increase as a result of global climate change (Figure 20).

In contrast to a relatively high degree of confidence associated with the projected temperature increases, the effects of global climate change on hydrological cycle are less certain, particularly on regional scales. The annual Mississippi River runoff, for example, was projected to decrease by 30% for the Canadian model, but increase by 40% for the Hadley model by the year 2099. Model simulations further suggest that altered freshwater and nutrient fluxes would have important implications for water column stability, net productivity and global oxygen cycling in the northern

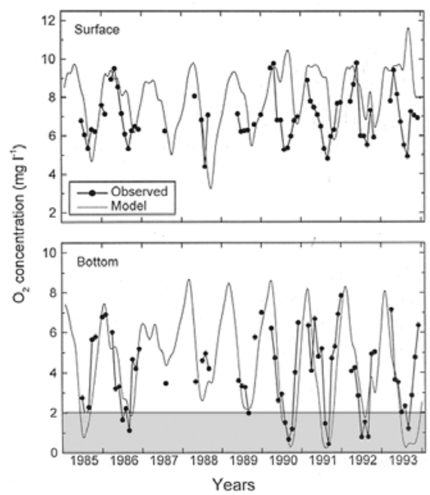

Figure 18. Observed and predicted monthly averages of surface (0-10 m) and bottom (10-20 m) oxygen concentrations at station C6 for the period June 1985 – November 1993. From Justić, Chapter 8.

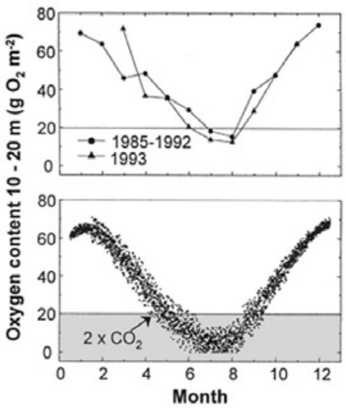

Figure 19. Seasonal changes in the integrated subpycnoclinal oxygen content (10-20m) at station C6 in the core of the hypoxic zone. Observed monthly averages for 1985 – 1992 and 1993 are compared to a Monte-Carlo simulation for a $2xCO_2$ climate. The $2xCO_2$ probability plot is comprised of 2880 points. From Justić et al. 1996.

Gulf of Mexico. Direct and indirect fisheries losses would likely be exacerbated if hypoxia expands in space or time as a result of global climate change.

The results of this model suggest that a large-scale reduction (~30%) in nitrogen concentration of the Mississippi River would eventually diminish the severity of hypoxia in the northern Gulf of Mexico. Nevertheless, the areal extent and the severity of hypoxia are very sensitive to climate-induced changes in freshwater and nutrient fluxes. If, for example, the Mississippi River discharge increases by 20%, as predicted in some climate change model scenarios, then a reduction in nitrate flux in excess of 20% would be required only to prevent the eutrophication from worsening. Consequently, nutrient control efforts for the Mississippi River watershed that are based solely on achieving a specific reduction in the non-point source loading, may have a limited success in controlling the eutrophication and hypoxia in the northern Gulf of Mexico.

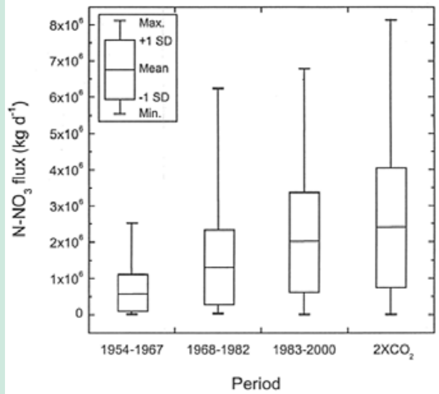

Figure 20. Box-plots showing nitrate flux ($N\text{-}NO_3$ flux) statistics for 1954 – 1967, 1968 – 1982, and 1983 – 2000, as well as projections for a $2xCO_2$ climate based on a 20% increase in the Mississippi River runoff (Miller and Russell 1992). From Justić, Chapter 8.

sors (e.g., eutrophication). In this context, managing the consequences of climate change become more complicated, not less complicated (Figure 21). Human activities cause some parts of the climate change "problem", but the resulting implications for ecosystems and climate change are also tied to each other, and then to new types or amounts of human uses.

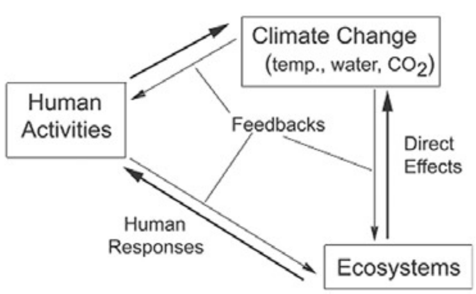

Figure 21. The effects and feedbacks in the interacting systems of climate, ecosystems and human societies. Adapted from Mulholland et al. 1997.

A long-term and integrated perspective is helpful, in this regards. It is widely understood that restoration of habitats is more difficult than sustaining them, at least from a non-political point of view. Climate change impacts are generally understood to add to, not subtract from, the total suite of coastal ecosystem stressors. Thus, preventing habitat change and loss is more cost-effective than rehabilitation and restoration.

However, it is also prudent to consider that some stressor impacts can be rolled back, but only reduced. Sea-level rise, for example, will probably continue, but at a lower rate than expected as a result of the anticipated from global climate changes. Under these circumstances, prevention is not enough, and future adjustments should be planned and anticipated. That type of planning and adjustment requires a substantial improvement in our knowledge and experience. The highlighted issues brought forth in this review suggest that this improvement should include long-term and comprehensive (integrated) programs that promote understanding of:

(1) wetland soil sustainability within the context of the entire organic and inorganic framework, and how the marsh ecosystem is affected by multi-year exposure to varying nutrients, altered food webs, and freshwater inflow management meant to provide single-problem solutions - e.g., oyster harvests or salinity management.

(2) the interactions between the social/political structure and function and the ecosystem attributes. The involvement of educators, social scientists, and natural scientists is required to find successfully-implement solutions to these complex problems.

(3) scenario testing approaches to strategically analyze the anticipated problems before their impact overwhelms abilities to react. Some approaches might involve computer modeling, others experimental field testing of contrasting methods, and still others comparative analyses of social and natural systems outside of the immediate region.

(4) control and management options for land use, harvest management, and water quality, with attention to the evaluation of unusual events (and subsequent management pressures) and competing resources claims.

(5) mechanisms and models of how build a better "tool kit" which has alternative options and support to try things, with the knowledge that, for some resources, we will only get one chance to fix the problem before it is unmanageable. We must be open to all kinds of solutions.

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