Chapter 9

Assessing the Potential Climate Change Impact on Salinity in the Northern Gulf of Mexico Estuaries: A Test Case in the Barataria Estuarine System

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Summary

Statistical models were developed which described 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 annual salinity pattern for each station using the data from 1990 through 2000 as an index period. The models were able to reproduce the annual signal at each of the stations. The potential salinity changes that could 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 ppt for the salt marsh, and ~1 ppt for the intermediate to brackish areas of the Barataria system. An analysis of literature data for twenty six estuaries around the northern Gulf of Mexico indicated that fairly small salinity changes are expected under most of the climate change scenarios for the northern Gulf of Mexico estuaries.

The potential impacts of these changes are difficult to assess since the present climate models give conflicting results on the expected changes in runoff (there is general agreement on precipitation changes). However, should the resulting changes in salinity be on the order of 3 ppt, then potential impacts would most likely be limited to small scale vegetation community changes at the boundaries of the major vegetation types. Larger salinity changes would be needed in order to see dramatic vegetation shifts in the coastal salt marshes.

9.1 Introduction

The purpose of this Case Study was to assess the potential changes that could occur in the salinity of northern Gulf of Mexico estuaries due to global climate changes. This was accomplished through a "Test Case" approach by analyzing the observed salinity patterns in the Barataria Bay Louisiana estuarine system in relation to known forcing functions. This present study has updated the work of Swenson and Turner (1995) to make predictions of probable salinity changes in the Barataria system resulting from global climate change. The analysis presented in this report quantifies the relationship between rainfall, Mississippi River discharge, coastal water levels, and salinity, using the available time series data. The results were then used (with the literature) to assess the likely changes that could occur in other Northern Gulf of Mexico estuaries.

Estuarine gravitational circulation is, in many cases, influenced by flows occurring as a result of other processes (e.g. wind forcing). Wind forcing causes the formation of buoyant effluent plumes, which influence shelf chemistry and biology as well as physics (Wisemann, 1986). These exchanges are bi-directional with significant transfers of mass, momentum, chemical, and geological constituents occurring between the shelf and the estuary (Wisemann, 1986). Meteorological forcing in estuaries along the northern Gulf of Mexico can be considered in terms of: (1) exchange between the estuarine waters and the waters in the coastal zone; and (2) local forcing occurring within the estuary proper. At time scales of a few days, the along-estuary wind stress drives an estuarine-shelf exchange; at longer time scales Ekman convergence/divergence driven by the alongshore wind stress drives the estuarine-shelf exchanges (Schroeder and Wiseman, 1986). Work by Kjerfve (1975) in Caminada Bay, Louisiana, demonstrated that the diurnal tidal influence, in addition to the wind forcing, can be important in controlling the internal dynamics of these systems. The most pronounced effect of wind forcing on the central Northern Gulf of Mexico systems is the difference between a northerly and a southerly wind. Strong winds from the south "push" water towards the coast forcing water into the estuaries, raising water levels about 0.3 – 0.5 m above normal. Conversely, winds from the north force water out of the estuaries depressing the water levels 0.3 – 0.5 m below normal. The "set up" of water usually occurs as a front approaches the area from the west and the

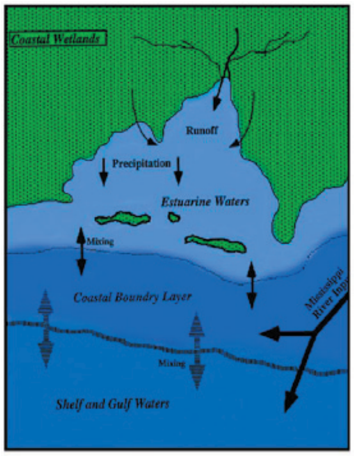

Figure 1. Schematic of an estuarine system illustrating the major pathways of fresh water and coastal ocean water inputs to the system.

Figure 2. Map of the Gulf of Mexico showing the estuaries characterized by Orlando, et. al. (1993).

southerly winds pile water along the coast, then after the front passes the winds shift to a more northerly direction. This situation results in a rapid drop in the estuarine water levels. Hart and Murray (1978) describe this type of situation occurring in Chandeleur-Breton Sound. These events result in substantial fluxes of water into, and out of, estuarine systems, and can have dramatic effects on the salinity distribution within the system. Thus, the salinity signal in these estuarine systems is fairly complex. A schematic detailing the major forcing functions discussed above is shown in Figure 1.

Orlando et. al. (1993) described the factors influencing salinity in 26 estuarine systems in the northern Gulf of Mexico (Figure 2). The distribution of freshwater input into these Northern Gulf of Mexico estuaries is presented in Figure 3. 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. The overall precipitation and evaporation pattern of the Gulf is presented in Figure 4. In general, the Gulf of Mexico is characterized by a decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. This results in an overall pattern in which there is a rainfall deficit (evaporation exceeds precipitation) in the western part of the Gulf (and southern Florida) and a rainfall surplus (precipitation exceeds evaporation) in the central portion of the Gulf. The overall result is that some of the estuaries in the northern Gulf have the highest freshwater input per unit estuarine volume (Ward, 1980). Orlando et. al., (1993) concluded that high Mississippi River flows reduced the salinities in the lower portion of the estuaries in the central gulf (Louisiana) due to advection of Mississippi River

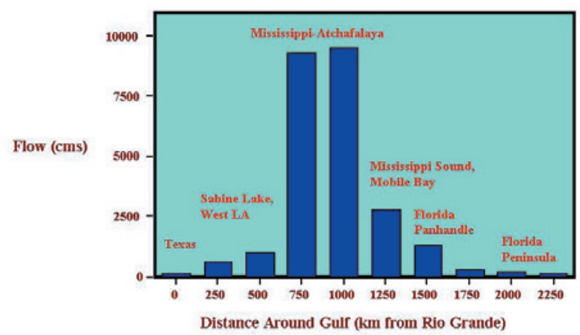

Figure 3. Distribution of river input into the Northern Gulf of Mexico. Modified from Orlando et. al. (1993).

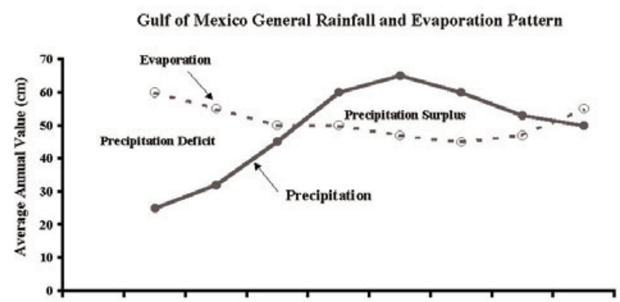

Figure 4. Distribution of annual average precipitation and evaporation around the Northern Gulf of Mexico. Modified from Orlando et. al. (1993).

water into the estuaries. During times of high river flow the local precipitation is unimportant. Conversely, at times of low Mississippi River flow, the salinities in the lower bays increase, and local precipitation becomes more important. The major freshwater sources for the 26 Gulf of Mexico estuaries described by Orlando et. al., (1993) are presented in Table 1.

Table 1 Summary of the major and secondary freshwater sources influencing salinities in the 26 northern Gulf of Mexico estuaries presented in Figure 2. 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 Christie 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/Vermillion	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

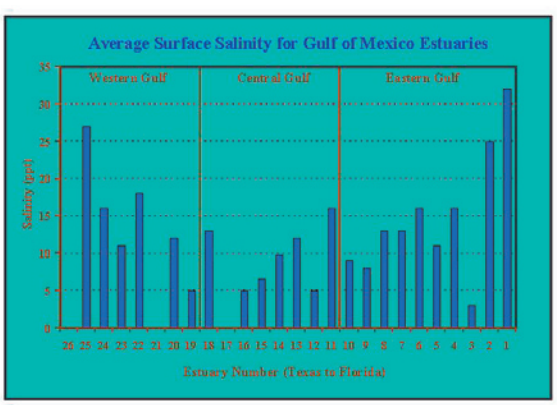

Figure 5. Distribution of surface salinity for 26 estuaries around the Gulf of Mexico. Data is from Orlando et. al. (1993), and updated as part of this study.

The salinity of the estuaries around the Gulf of Mexico shows a fairly large range of values as a result of the freshwater input distribution. The average surface salinity for the 26 Gulf of Mexico estuaries studied by Orlando et. al. (1993) is presented in Figure 5 (the data for Barataria and Terrebonne-Timbalier was updated as part of this study). In general the central Louisiana estuaries exhibit lower salinities due to the effect of the Mississippi River discharge. The south Texas estuaries and the south Florida estuaries exhibit the highest salinities due to the general pattern of rainfall deficits in these locations.

9.2 Methods

9.2.1 The Data base

The data used are from time series data sets that were readily available in a computer compatible format (usually an ASCII data file). The data came from the following sources:

1. Hourly salinity data from recording gages maintained by the Louisiana Department of Wildlife and Fisheries (LDWF). The gage locations are indicated in Figure 6.

2. Daily Mississippi River discharge data from the United States Army Corps of Engineers (USACE).

3. Climatic data (Palmer Drought Severity Index, Precipitation) from the Louisiana Office of Climatology at Louisiana State University and from the National Oceanic and Atmospheric Administration (NOAA). These data are available for various climatic regions in the Gulf of Mexico states. The climatic regions for each of the states are shown in Figure 7.

4. Water level data from the National Ocean Survey (NOS) of the National Oceanic and Atmospheric Administration). The gage location is indicated in Figure 6.

The data files were transferred to a desktop computer for analysis using Statistical Analysis System (SAS 1990 a, b, c, d, e). Because all the data were in time series format, the same basic techniques were used for all sites. The data sets were inventoried, checked for data quality, and put into the final form for analysis using the following general procedures:

A. Data Inventories
   Total Observations in data set
   Sampling Frequency

B. Descriptive Statistics
   Mean
   Standard Deviation
   Minimum
   Maximum

C. QA/QC checks
   Investigate potential outliers
   Raw data plots

D. Plots of monthly means for each station and variable

E. Data editing
   remove erroneous data points
   compute monthly means

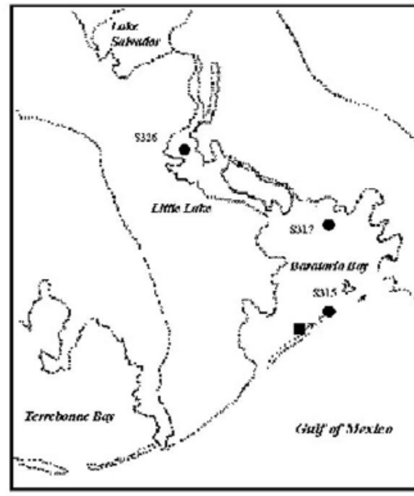

Figure 6. Map of the Barataria Estuarine system, Louisiana showing the locations of the gages used in the analysis. The Louisiana Department of Wildlife and Fisheries salinity gages located at the coast (S315 at Grand Terre), mid-estuary (S317 at St. Marys' Point), and upper estuary (S326 at Little Lake) are indicated by the filled circles. The National Ocean Survey water level gage at Grand Isle is indicated by the filled square.

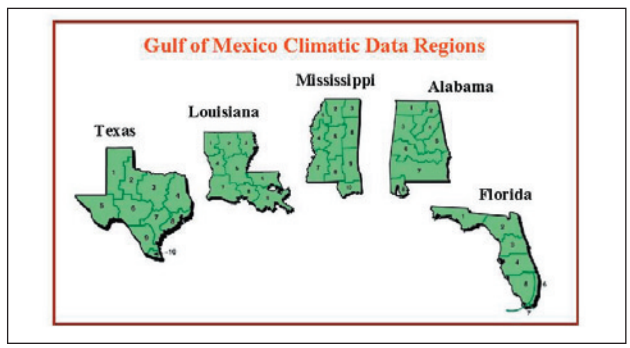

Figure 7. Map of the states around the Gulf of Mexico, indicating the Climate Division for which climate summaries (precipitation, Palmer Drought Severity Index, etc.) are available.

Any needed correction factors (for conversion to metric units, calculation of salinity from chloride or conductivity) were applied during these checks.

9.2.2 Barataria Bay Louisiana: A Test Case

Introduction

The Barataria Estuarine system just to the west of the Mississippi River consists of a series of lakes and bays surrounded by low lying marshes. These marsh systems are characterized hydrologically by numerous interconnecting lakes, channels, and bayous. The flows through these channels and bayous are coupled with extensive overland flooding, thus exchanging water between the marsh surface and the surrounding water bodies. The circulation patterns, and salinity structure within these estuaries is controlled internally by a combination of tidal dynamics, riverine input, and wind forcing. The Barataria Estuary system was used as a test case to develop statistical models which would explain the observed estuarine salinity as a function of the major forcing functions (Mississippi River flow, local precipitation, and coastal water levels).

In one of the first comprehensive studies of the hydrologic characteristics of the Barataria Estuarine system (Baumann 1987) the changes in the spatial and temporal salinity patterns in Barataria Estuary system were attributed to three basic factors:

1. The seasonal evapotranspiration and precipitation regime,
2. Mississippi River discharge,
3. Seasonal water level cycle.

Barrett (1971) and Gagliano et. al. (1973) described an inverse relationship between Mississippi River flow and coastal salinities in Louisiana. Their results were based upon linear statistics. Wiseman et. al., (1990) used Auto-Regressive Moving Average (ARMA) to analyze the relationship between weekly discharge of the Mississippi River and Louisiana coastal salinities based upon long term records, and time series modeling. This type of analysis assumes that the present state of a system is a function of the present and past values of its inputs. Thus, the model is able to account for lags in the system, with the larger lags having less effect than the more recent. The total models were able to account for 70 to 86% of the observed variance in the salinity signal. The river discharge portion of the model accounted for 30 to 50% of the variance of the observed salinity data. The remainder (the Auto-Regressive portion) described processes not directly related to the river flow (tidal dispersion, wind-driven estuarine-shelf exchange). Their analysis also indicated an increase in the lag between the Mississippi River flow and coastal salinity as one moved either into the estuary or downstream along the coast (westward). Although these are statistical models, the results were consistent with a conceptual model in which Mississippi River discharge alters coastal salinities, which in turn propagates up-estuary and westward along the coast (Wiseman et. al., 1990).

Assumptions

The approach in this study is a statistical approach (regression) to explaining the observed salinity in the Barataria estuary, there is no attempt to model the actual physical processes that control the salinity. This imposes some restrictions on what can be inferred (or predicted) using the results of the analysis:

1. The statistical model approach is useful for looking at possible changes in salinity under different forcing function scenarios (e.g. what if the river had been higher during the time period the data were collected). The statistical results will give a general idea of the range of values that can be expected with changes in the forcing functions under the present hydrological configuration of the Barataria estuary.
2. The predictions made in this report are to be used as a guide only since they do not take into account the impact of the Davis Pond diversion. This diversion, a structure that will divert up to 10,000 cubic feet per second (cfs) of freshwater into the upper portions of the Barataria system, (~ 50 km north of the Little Lake gage) will begin operation later this year. The operaton of this structure will significantly alter the hydrologic configuration of the Barataria system during the months that it operates. In order to account for the diversion a dynamic hydrologic (and salinity) model would be needed. That approach is beyond the scope of this present study.
3. The statistical approach in this study does not fully describe the dynamic nature of the system. Swenson and Turner (1995) presented data showing that the location of the 5 ppt isohaline is highly variable, moving ~20 km in response to changes in forcing functions from year to year. In addition frontal passages and tropical storms often result in large magnitude (5 ppt or greater) but relatively short duration (~3 days) salinity pulses in the system (Swenson and Swarzenski, 1995). The affect of these events is averaged out in the approach taken in this analysis.
4. This analysis is not able to address the overall spatial distribution of the salinity changes in the Barataria estuary, only the possible magnitude of the change at a few locations. This spatial distribution of the change is also an important component in assessing the overall impact of salinity change.

Table 2 Classification matrix for the BES based upon the Palmer Drought Severity Index (PDSI) and Mississippi River discharge. The matrix classifies the upper (north of Little Lake) and lower portions of the system as either a "high salinity year" a "low salinity year" or a "normal year". Values of river discharge greater than 1 standard deviation (S. D.) above the mean were considered high river discharge years, and values of river discharge less than 1 standard deviation (S. D.) below the mean were considered low river discharge years. The Palmer Drought Severity Index classifies the years into drought conditions. The index has a numeric value with 0 indicating normal conditions. Values equal to, or less than, -4 indicate extreme drought conditions. Values equal to, or greater than, +4 indicate extreme moist conditions. Very moist (>3) was used as an indicator of a high local runoff year, and moderate drought (<-3) as an indicator of a low local runoff year.

Palmer Drought Severity Index

	Moderate Drought Index		**Normal Drought Index**		**Very Moist Drought Index**	
	Lower Estuary	Upper Estuary	Lower Estuary	Upper Estuary	Lower Estuary	Upper Estuary
Mississippi River Discharge >1 S. D. Above Mean	Low Salinity or "Wet Year"	Low Salinity or "Wet Year"	Low Salinity or "Wet Year"	"Normal Year"	Low Salinity or "Wet Year"	High Salinity or "Dry Year"
Mississippi River Normal River Discharge	Low Salinity "Normal Year"	or "Wet Year"	"Normal Year"	"Normal Year"	"Normal Year"	High Salinity or "Dry Year"
Mississippi River Discharge <1 S. D. Below Mean	High Salinity or "Dry Year"	Low Salinity or "Wet Year"	High Salinity or "Dry Year"	"Normal Year"	High Salinity or "Dry Year"	High Salinity or "Dry Year"

Table 3 Climatic classification for the Barataria Estuarine System based upon the Palmer Drought Severity Index (PDSI) and Mississippi River discharge.

Year Classification					
Year	Season	Drought Severity	River Flow	Upper Estuary	Lower Estuary
1980	Jan. - Jun.	very moist	normal	wet	normal
1980	Jul. - Dec.	mild drought	-1 SD	normal	dry
1981	Jan. - Jun.	mild drought	normal	normal	normal
1981	Jul. - Dec.	moderate drought	normal	dry	normal
1982	Jan. - Jun.	normal	normal	normal	normal
1982	Jul. - Dec.	normal	-1 SD	normal	dry
1983	Jan. - Jun.	very moist	+1 SD	wet	wet
1983	Jul. - Dec.	unusual moist	normal	wet	normal
1984	Jan. - Jun.	moist	+1 SD	normal	wet
1984	Jul. - Dec.	normal	normal	normal	normal
1985	Jan. - Jun.	mild drought	normal	normal	normal
1985	Jul. - Dec.	normal	normal	normal	normal
1986	Jan. - Jun.	mild drought	normal	normal	normal
1986	Jul. - Dec.	moderate drought	normal	dry	normal
1987	Jan. - Jun.	moist	normal	normal	normal
1987	Jul. - Dec.	incipient drought	normal	normal	normal
1988	Jan. - Jun.	moist	normal	normal	normal
1988	Jul. - Dec.	moist	-1 SD	normal	dry
1989	Jan. - Jun.	mild drought	normal	normal	normal
1989	Jul. - Dec.	mild drought	normal	normal	normal
1990	Jan. - Jun.	normal	+1 SD	normal	wet
1990	Jul. - Dec.	moderate drought	normal	dry	normal
1991	Jan. - Jun.	very moist	normal	wet	normal
1991	Jul. - Dec.	extreme moist	-1 SD	wet	dry
1992	Jan. - Jun.	extreme moist	normal	wet	normal
1992	Jul. - Dec.	very moist	normal	wet	normal
1993	Jan. - Jun.	extreme moist	+1 SD	wet	wet
1993	Jul. - Dec.	incipient drought	normal	normal	normal
1994	Jan. - Jun.	normal	+1 SD	normal	wet
1994	Jul. - Dec.	moist	normal	normal	normal
1995	Jan. - Jun.	moist	normal	normal	normal
1995	Jul. - Dec.	mild drought	normal	normal	normal
1996	Jan. - Jun.	normal	normal	normal	normal
1996	Jul. - Dec.	normal	normal	normal	normal
1997	Jan. - Jun.	moist	+ 1 SD	normal	wet
1997	Jul. - Dec.	normal	normal	normal	normal
1998	Jan. - Jun.	normal	+1 SD	normal	wet
1998	Jul. - Dec.	normal	normal	normal	normal
1999	Jan. - Jun.	normal	normal	normal	normal
1999	Jul. - Dec.	incipient drought	-1 SD	dry	dry
2000	Jan. - Jun.	extreme drought	-1 SD	dry	dry

Climatic Characterization

Swenson and Turner (1995) used an overall climatic characterization to identify high freshwater inflow years and low freshwater inflow years. The salinity data from these time periods was then compared to determine the overall magnitude of the climatic drivers on the position of various salinity isohalines in the Barataria System.

The climatic regime was classified into wet, dry and normal year classes for the upper and lower portions of the Barataria Estuary system using Mississippi River Discharge and the Palmer Drought Severity Index (PDSI) as classification variables. A value of +/- 1 standard deviation, was used for the cutoff point for Mississippi River flow for wet and dry years. The PDSI classifies the years into drought or moist conditions. The index has a numeric value, with zero indicating normal conditions, values equal to or less than -4 indicate extreme drought conditions, values equal to or greater than +4 indicate extreme moist conditions. The very moist (>3) condition was used as an indicator of a high local runoff year, and the moderate drought (<-3) category was used as an indicator of a low local runoff year. A classification matrix was developed (Table 2) which classified the upper and lower portions of the estuary into wet and dry years (based upon river discharge and the PDSI). The actual data were then used to classify the years from 1980 through 1995. Table 3 presents the yearly classification data from the Swenson and Turner (1995) study for the Barataria system. The Table has been updated through 2000 as part of the present study. The following discussion, however, is limited to the original Swenson and Turner (1995) time period (1980-1995). The data indicated that 1983 and 1993 were wet years. The first half (January - June) of each year was characterized by high river flow (>1 standard deviation above normal) with a PDSI indicating very moist (1983) or extremely moist (1993) local conditions. The latter half of the year (July - December) the river flow returned to normal for both years. It was more difficult to find a good example of a dry year during the 1980-1995 time period. There were no cases of low river flow and moderate drought conditions. The best candidate for a dry year was 1981 and this was used in a subsequent analysis. The salinity data from the Barataria Estuary for the wet and dry years determined above was then used by the Louisiana Department of Natural Resources to produce isohaline maps for the two contrasting conditions. The data indicated that a change from low rainfall to high rainfall shifts the 5 ppt isohaline ~15 km south, and the 15 ppt isohaline ~8 km south, and a change from low riverflow to high riverflow shifts the 5 ppt isohaline 20 km south, and the 15 ppt isohaline ~10 km south.

Forcing Function Salinity Relationships

The monthly mean Mississippi River stage and discharge and the de-trended monthly mean water levels at Grand Isle, from 1955 through 2000 are presented in Figure 8. The long term trend was removed from the water level data in order to more clearly show the seasonal pattern. The monthly Palmer Drought Severity Index (PDSI) for each of the three Louisiana Climate Regions from 1955 through 2000 are presented in Figure 9. The Mississippi River discharge exhibits a seasonal pattern in which the maximum discharge of ~22,000 $m^3 sec^{-1}$ occurs in April, and the minimum discharge of ~6,000 $m^3 sec^{-1}$ occurs in September. The mean monthly coastal water levels show a pattern in which there are two peaks. One is in May-June and the second (and larger) is in September-October. Although the standard deviation is large, a comparison of the monthly means using Duncans' multiple range test (SAS, 1988) indicated that all months are significantly different from each other with the exception of one grouping (August and November). September had the highest mean levels. The lowest water level values occurred in January. Linear regression was performed to investigate the temporal trends in each variable. The Mississippi River discharge shows a statistically significant increase of about 42 $m^3 sec^{-1} yr^{-1}$ over the time period from 1955 through 2000. The stage did not exhibit a statistically significant trend with time. The water level at Grand Isle exhibits a statistically significant trend (which is also a major portion of the signal) of ~1.17 $cm\ yr^{-1}$ over the time period from 1955 through 2000.

The Louisiana Department of Wildlife and Fisheries (LDWF) salinity stations used in this study (Figure 6) will be referred to as a coastal station (Station S315 - Grand Terre); a mid-estuary station (Station S317 - St. Mary's Point), and an upper estuary station (Station S326 - Little Lake). Although the upper estuary station is not at the upper limit of the system (which is the fresh marshes and swamps), it is located at a point where the system has changed from open bays to more restricted water bodies. Time series plots of the salinity at the coast (Grand Terre Island), mid-estuary (St. Mary's Point) and upper estuary (Little Lake) are presented in Figure 10. The most obvious feature of the forcing functions

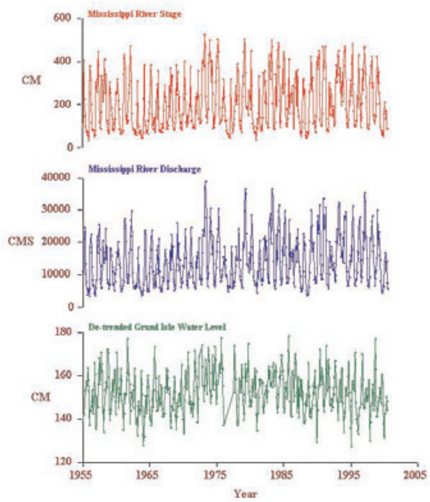

Figure 8. Plot of (top to bottom) monthly Mississippi River stage, monthly Mississippi River discharge, and de-trended monthly water levels at Grand Isle.

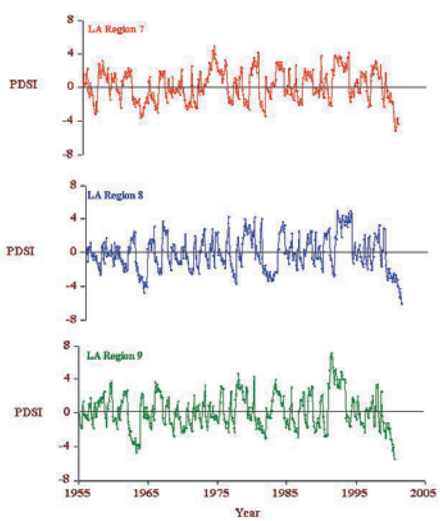

Figure 9. Plot of (top to bottom) monthly Palmer Drought Severity Index for (top to bottom) Louisiana climate division 7 (west Louisiana), climate division 8 (central Louisiana) and climate division 9 (east central Louisiana). Positive values indicate moist conditions and negative values indicate drought conditions.

plots (Figures 8 and 9) and the salinity plots (Figure 10) is the uniqueness of the 1999 – 2000 data. The time period from the fall of 1999 through the end of 2000 was characterized by an extended and severe drought, low Mississippi River discharge, and low coastal water levels. This time period was also characterized by the highest salinities on record. The Grand Isle station exhibits a statistically significant trend of -0.05 ppt y^{-1}, the St. Mary's Point station did

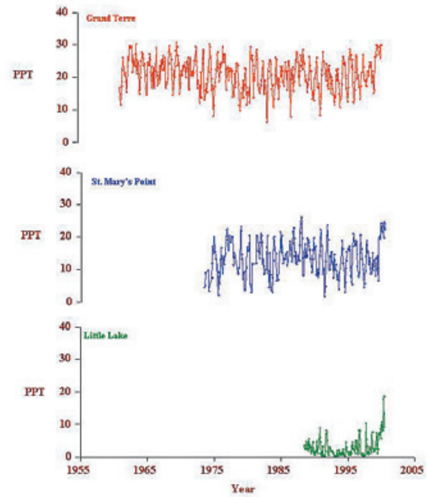

Figure 10. Plots of (top to bottom) monthly mean salinity for Grand Terre (a coastal station), St. Mary's Point (a mid-estuary station), and Little Lake (an upper estuary station) in the Barataria system. The monthly means were computed from hourly data.

not exhibit a statistically significant trend, and the Little Lake station exhibited a statistically significant trend of 0.29 ppt y^{-1}. The contribution of each of these forcing functions to the salinity will be discussed in the next section.

Statistical models for salinity prediction

Regression models (SAS, 1988) were used to look at the importance of Mississippi River discharge, the Palmer Drought Severity Index, rainfall, and coastal water levels. Coastal water levels (as defined by the water levels at Grand Terre) were included to account for the possibility of the "stacking up" of water at the coast which could influence the transport of water in and out of the Barataria system. Several models were run, using various lags for river flow, rainfall, and coastal water levels, in an approach that was similar to that of Gagliano et. al., (1973). Stepwise linear regression and Autoregressive models (SAS, 1988) were also used to produce a series of models using various combinations of variables (up to 9 variables). The results indicated that very little improvement in the model (5-7% improvement) was obtained by using more than three or four variables. In addition, any model used should be physically reasonable. A model using 1 month lag of the variables would be a physically reasonable model, whereas a model that used the 1 month lag and the 3 month lag, skipping the 2 month lag, would not be physically reasonable, although it might be statistically valid. Similar results were

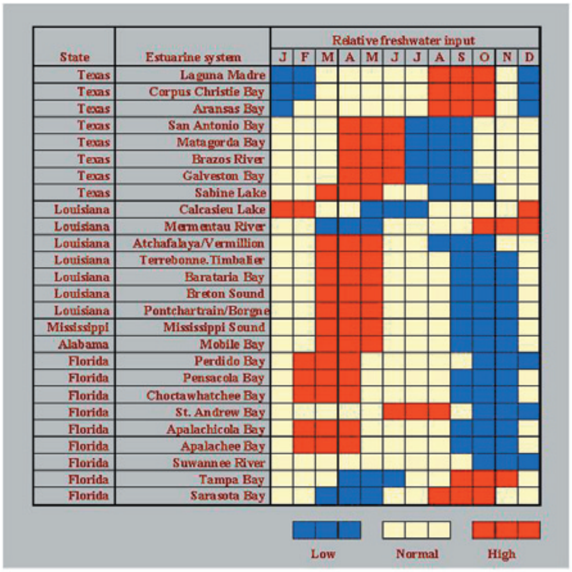

Figure 11. Monthly changes in relative freshwater input into estuaries around the Gulf of Mexico (Figure 2). Indicated, for each estuary, are the months during which high and low freshwater input occur. Adapted from Orlando et. al. (1993).

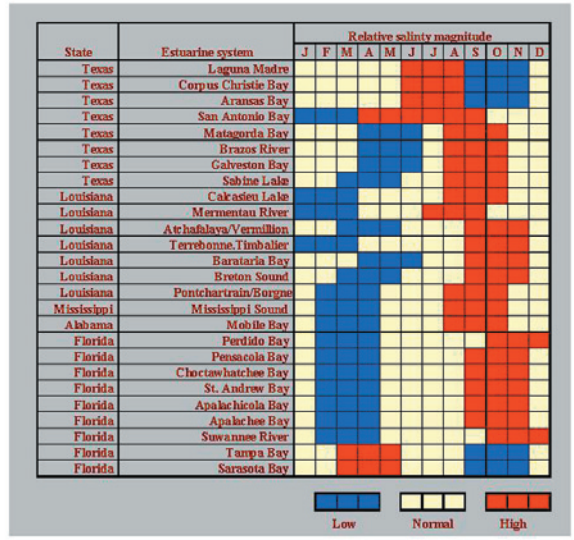

Figure 12. Monthly changes in relative salinity values for estuaries around the Gulf of Mexico (Figure 2). Indicated, for each estuary, are the months during which high and low salinity values occur. Adapted from Orlando et. al. (1993).

Table 4 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.

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	Temerature	4ºF increase	<3ºF increase	2ºF increase	2ºF increase	<3-4ºF increase
Spring	Temerature	3ºF increase	3ºF increase	3ºF increase	3ºF increase	3-4ºF increase
Summer	Temerature	4ºF increase	3ºF increase	2ºF increase	2ºF increase	3-4ºF increase
Fall	Temerature	4ºF increase	<3ºF increase	4ºF increase	4ºF increase	3-4ºF 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

obtained by Wiseman et. al. (1990) in their analysis of Mississippi River flow and salinity. Because the overall goal is to obtain a model that is both parsimonious and physically reasonable, it was decided to limit the models to three or four variables.

The changes in relative freshwater input and relative salinity magnitude for 26 estuaries around the Gulf of Mexico (Orlando et. al., 1993) are summarized, on a monthly basis, in Figures 11 and 12. The data indicate that there are strong seasonal differences throughout the Gulf. In order to assess potential impacts, the measured and predicted salinity from the last five years was used as an index period to develop a baseline yearly salinity pattern for each of the stations as discussed below.

The potential changes in the salinity forcing functions for the Gulf of Mexico, by season, are summarized in Table 4 (based on Ning and Abdollahi (1999). The model predictions are for 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, uncertain (Boesch et. al., 2000). The effect of climate change on Mississippi River discharge is the most important consideration for the Louisiana estuaries. 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 over the time period 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 over the time period from 2090 through 2099. Data presented by Boesch et. al., (2000) project changes in sea level on the order of 30 centimeters by 2100. The actual forcing functions during the index period (1995-2000) were then altered to reflect these projected changes in precipitation and Mississippi River discharge. The statistical model was re-run and a new mean yearly pattern was produced for each station. These yearly patterns present what the salinity would have been during the 1990-1995 period if the forcing functions were at the levels predicted by the climate change models. The yearly salinity patterns were calculated for the following scenarios:

1. An increase of 30 % in Mississippi River dis charge.
2. A decrease of 30 % in Mississippi River discharge.
3. An increase of 10 % in local precipitation.
4. A decrease of 10% in local precipitation.
5. An increase of 30 cm in water levels.
6. Conditions 1, 3, and 5 combined.
7. Conditions 2, 4, and 5 combined.

The yearly salinity pattern from each of the above scenarios was then compared to the baseline conditions. The baseline conditions used were those generated by the best fit statistical model to the forcing function and salinity data. These conditions will yield a broad range of the possible salinity changes that may result from global climate change impacts on salinity forcing functions.

9.3 Results

9.3.1 Statistical Model Results

In all cases the most successful models were those that contained an autoregressive term. The models were run for the entire data record for each station (1961 – 2000 for Station 315, 1973 – 2000 for Station 317, and 1988 – 2000 for Station 326). The results of the final statistical models are presented in Table 5. The results of the model predictions for the time period from 1995-2000 are presented in Figure 13. The measured values are shown by the solid line and the predicted results from the statistical model are shown as a dashed line (with solid dots). The model for station 315 (coastal station at Grand Terre) explained a total of 72 percent of the observed signal, with the linear portion of the model explaining 48 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, Grand Isle water levels, and the previous month's salinity. The model for station 317 (mid-estuary station at St. Marys' Point) explained a total of 74 percent of the observed signal, with the linear portion of the model explaining 41 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, Grand Isle water levels, and the previous month's salinity. The model for station 326 (upper-estuary station in Little Lake) explained a total of 63 percent of the observed signal, with the linear portion of the model explaining 16 percent, using Mississippi River discharge, precipitation from Louisiana climate division 9, and the previous 3 month’s salinity. The results show a decrease in the magnitude of the effect of the Mississippi River discharge and coastal water levels from the coast inland. The effect of precipitation is maximum mid-estuary (St. Mary’s Point) and minimum at the upper station (Little Lake). This

Table 5 Summary of regression results to predict salinity in the Barataria system using Mississippi River discharge, precipitation at Louisiana climate region 9, and de-trended coastal water levels.

LDWF S315 Coastal Station at Grand Terre

Overall Model R-square = 0.72
Linear portion R-square = 0.48

Variable	Estimate	F-value	Probability > F
Intercept	19.99		
Mississippi Discharge	-0.00029	544.38	0.0001
Region 9 Precipitation	-0.2761	99.56	0.0001
Grand Isle Water Level	-0.0329	83.50	0.0001
1 month previous salinity	+0.5466	354.00	0.0001

LDWF S317 Mid-estuary station at St. Mary's Point

Overall Model R-square = 0.74
Linear portion R-square = 0.41

Variable	Estimate	F-value	Probability > F
Intercept	9.66		
Mississippi Discharge	-0.00024	277.17	0.0001
Region 9 Precipitation	-0.3806	88.96	0.0001
Grand Isle Water Level	-0.0065	22.74	0.0001
1 month previous salinity	+0.6297	330.94	0.0001

LDWF S326 Upper estuary station in Little Lake

Overall Model R-square = 0.63
Linear portion R-square = 0.16

Variable	Estimate	F-value	Probability > F
Intercept	2.916		
Mississippi Discharge	-0.00007	47.25	0.0001
Region 9 Precipitation	-0.1522	11.55	0.0009
Previous month salinity	+0.8728	145.63	0.0001
2 months previous salinity	-0.4220	7.37	0.0075
3 months previous salinity	+0.2511	6.96	0.0094

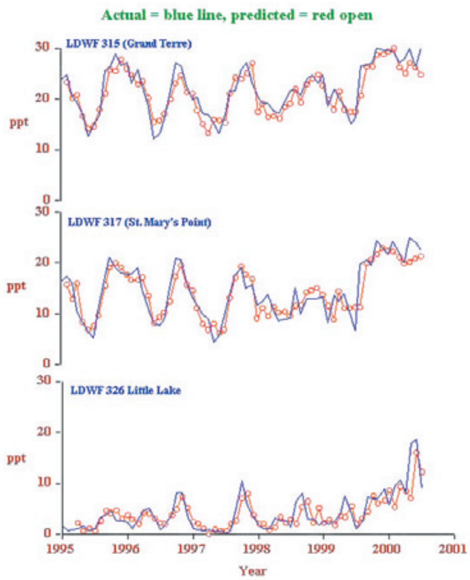

Figure 13. Plots of measured monthly mean salinity (blue line) and predicted monthly salinity (dashed red line with circles) for LDWF Station 315 (Top), LDWF Station 317 (middle) and LDWF Station 326 (bottom) in the Barataria system. The following models were used: Station 315: Salinity = 19.99 - 0.00029 Q - 2761 P - 0.0329 WL - 0.5466 S^{-1}; Station 317: Salinity = 9.66 - 0.00024 Q - 0.3806 P - 0.00655 WL +0.6297 S^{-1}, and Station 326: Salinity = 2.92- 0.00007 Q - 0.1522 P + 0.8728 S^{-1}, - 0.4220 S^{-2}, + 0.2511 S^{-3} where Q = total monthly Mississippi River Discharge (m^3s^{-1}), P = total monthly precipitation (cm), WL = de-trended water level at Grand Isle (cm), S^{-1} = salinity (ppt) of previous month, S^{-2} = salinity (ppt) two months previous, S^{-3} = salinity (ppt) three months previous.

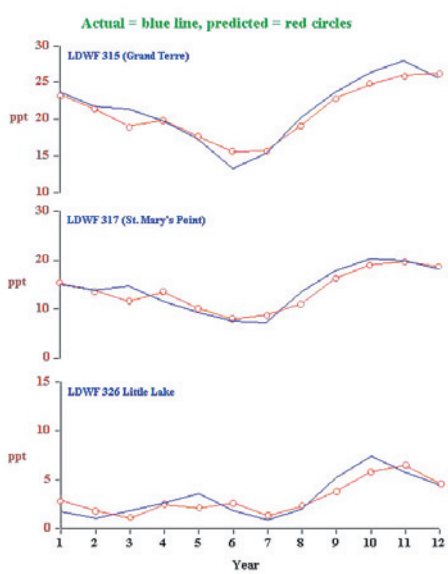

Figure 14. Measures (blue line) and predicted (dashed red line with circles) mean monthly salinity pattern for the LDWF Grand Terre station (top), the LDWF St. Mary's Point (middle) and the LDWF Littlt Lake station (bottom) in the Barataria estuary system in Louisiana. The values are the mean monthly values of data from 1995 through 2000.

is not what would be expected but may be a result of the shorter data record at the Little Lake station. The autoregressive parameter seems to indicate a faster flushing in the lower portion of the system (one month lag at the coast and mid-estuary compared to three month lag at Little Lake).

The measured and predicted yearly salinity patterns for the statistical models are presented in Figure 14. The model reproduces the observed annual pattern at all stations with a fairly high degree of accuracy. The model is useful for looking at possible changes in salinity under different forcing function scenarios (e.g., what if the river had been higher during 1995 – 2000).

9.3.2 Potential Salinity Changes in Barataria Bay, Louisiana

The model results are presented in Figures 15 through 17. These figures only present the results for changes in Mississippi discharge and changes in precipitation. The changes due to coastal water level changes were very small in all cases. The results were similar at all three stations, with changes in Mississippi River discharge resulting in the majority of the salinity changes. The greatest change occurs from January through July. Taking the worst case scenario (30 percent change in the Mississippi occurring with a 10 percent change in precipitation), the analysis predicts changes of ~3 ppt at Grand Terre, and St. Marys' Point, and ~1 ppt at Little Lake.

Orlando et. al., (1993), classified estuaries around the gulf into 5 major categories ranging from stable to highly variable depending upon whether or not the salinity is controlled by one dominant forcing function or multiple forcing functions (Table 6). The stable systems are characterized by two extreme cases: (1) Type 5 systems such as Atchafalaya Bay, Louisina that have an extremely large freshwater source which prevents significant saltwater intrusion, thus maintaining relatively low salinity variability, and (2) Type 1 systems such as Laguna Madre, Texas where the salinity is always close to the Gulf level and also exhibits relatively low salinity variability. The variable systems (Types 2 – 4) range between these two extreme cases depending upon the relative contribution of freshwater inflow and tidal forcing. The systems exhibiting the highest level of variability (Type 3) are those where the salinity is controlled by multiple factors with freshwater inflow and tidal forcing being of equal dominance (e.g. Apalachicola Bay, Florida). The Type 2 systems are those where the salinity is controlled by multiple forces, but the

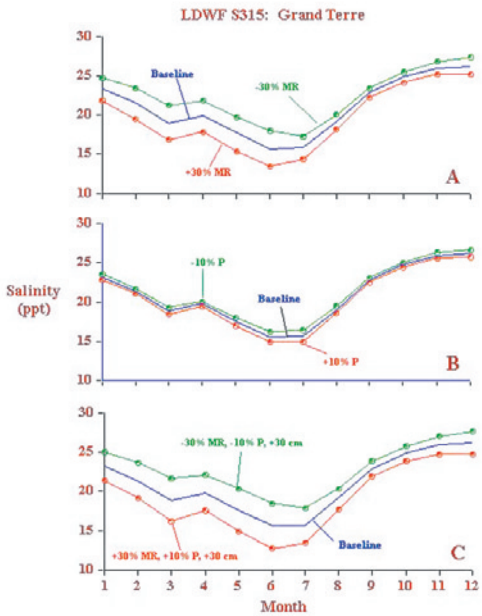

Figure 15. Grand Terre (LDWF S315) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

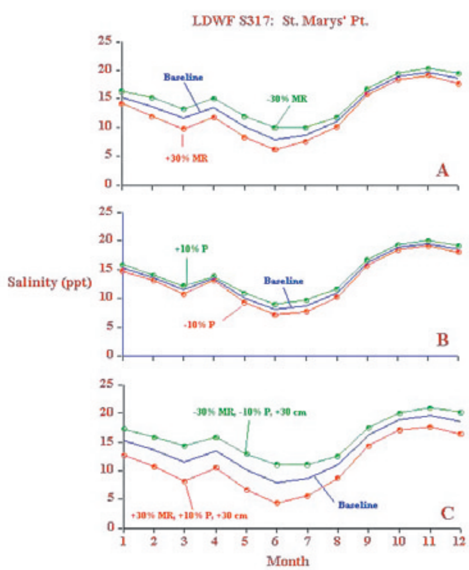

Figure 16. St. Marys' Point(LDWF S317) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

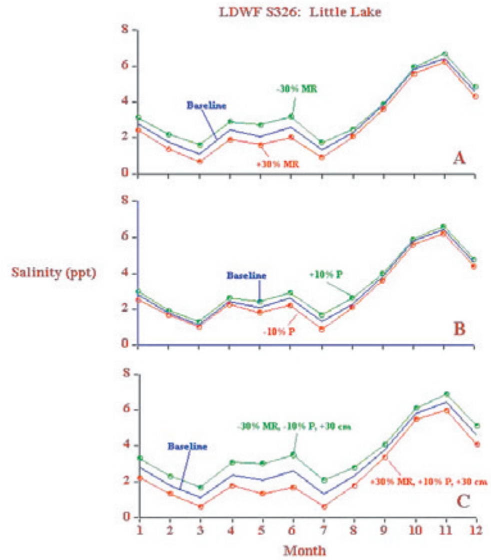

Figure 17. Little Lake (LDWF S326) baseline salinity conditions, as defined by the autoregressive model (blue line) and predicted salinity changes due to: **(A)** a 30 percent increase (red circle) or a 30 percent decrease (green circle) in Mississippi discharge; **(B)** a 10 percent increase (red circle) or a 10 percent decrease (green circle) in precipitation; **(C)** a 30 percent increase in Mississippi discharge and a 10 percent increase in precipitation (red circle) or a 30 percent decrease in Mississippi discharge and a 10 percent decrease in precipitation (green circle).

tidal forcing predominates (e. g. San Antonio Bay, Texas).). The Type 4 systems are those where the salinity is controlled by multiple forces, but the riverflow predominates (e. g. Mobile Bay, Alabama).

The data from Orlando et. al. (1993) were analyzed to look at salinity changes that occur in the Gulf of Mexico estuaries with current changes in freshwater for high and low freshwater input years. The overall data are shown in Figure 18 that pres-

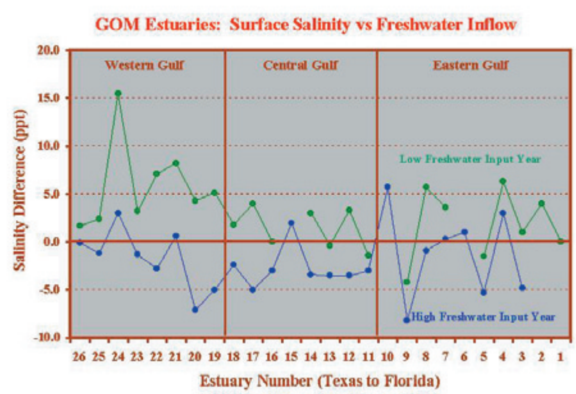

Figure 18. Changes in surface salinity (in ppt) for 26 estuaries around the Gulf of Mexico resulting from either a high freshwater input year (blue circles) or a low freshwater input year (green circles). Data are from Orlando et. al. (1993), and updated as part of this study.

Table 6 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. This Table was adapted from data found in Orlando et. al. (1993).

Type	Description	Characteristics	Examples
1	Stable	1. Salinity controlled by one factor. 2. Lack of dominant and continuous freshwater source 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. 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	1. Salinity controlled by multiple factors. 2. Riverflow and tidal flow are equal. 3. Medium variability at day-week time scales. 4. High variability at day-week time scales. 5. Medium salinity variability at yearly time scales.	Suwanne River, FL Perdido Bay, FL Pensacola Bay, FL Apalachicola Bay, FL Mermantau River, LA
4	Variable	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, LA 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 4. Low salinity variability at all times scales	Atchafalaya Bay, LA Lakes Pontchartrain, LA Clealeleur Sound, LA Mississippi Sound, LA

ents the changes in surface salinity (from normal) for high and low freshwater input years. The data show a general trend of salinity decreases of 2 to 5 ppt for high freshwater input years and increases of 5 to 7 ppt for low freshwater input years. There are a few exceptions to the overall pattern which is to be expected since this is a very limited data set. In general, however, these changes are the types of changes that might be expected.

9.4 Discussion

9.4.1 Impacts of Predicted Salinity Changes in Barataria Bay, Louisiana

In general, the predicted salinity changes are fairly small (3 ppt or less). Boesch et. al., (2000) state that major changes in salinity would be required before shifts in the saline marsh communities would occur. In the brackish-intermediate sections of the Barataria system however, these predicted changes, although small, could result in some minor species shifts along the vegetative community boundaries. Sasser, et. al., (2001) documented increases in polyhaline and mesohaline vegetation and decreases in oligohaline and fresh vegetation types in the Barataria Bay system as a result of the recent (1999-200) high salinity event in that system.

9.4.2 Implications for Other Gulf of Mexico Estuaries

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, D. B. and P. H. 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. The stable systems such as Lagiuna 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 Bay, Louisiana estuary (1 – 3 ppt). 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 salinity increase.

9.5 Conclusions

This case study has yielded some insight on the potential changes in estuarine salinity that may occur as a result of global climate change. This was accomplished through the development of statistical models to explain the observed salinity signal, in relation to forcing functions, at one (Barataria Bay, Louisiana) of the many estuaries around the northern Gulf of Mexico. In order to more adequately address the issue around the Gulf, this type of detailed analysis should be conducted on several representative estuaries in order to cover the wide range of salinity variability observed in the Gulf of Mexico estuaries. The major findings of this case study are summarized below:

- Estuaries in the northern Gulf of Mexico are influenced by (1) exchange between the estuarine waters and the waters in the coastal zone; and (2) local forcing (river discharge, precipitation) occurring 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.

- The northern gulf of Mexico precipitation-evaporation exhibits a general characterized by a decrease in precipitation from east (Florida) to west (Texas), while surface evaporation rates generally increase from east to west across the Gulf. This results in an overall pattern in which there is a precipitation deficit in the western part of the Gulf (and southern Florida) and a precipitation surplus in the central portion of the Gulf.

- Isohaline data from the Barataria estuary in Louisiana indicated that a change from low rainfall to high rainfall shifts the 5 ppt isohaline ~15 km south, and the 15 ppt isohaline ~8 km south, and a change from low Mississippi River discharge to high Mississippi River discharge shifts the 5 ppt isohaline 20 km south, and the 15 ppt isohaline ~10 km south.

- The Mississippi River discharge exhibits a seasonal pattern in which the maximum discharge of ~22,000 m^3sec^{-1} occurs in April, and the minimum discharge of ~6,000 m^3sec^{-1} occurs in September.

- The mean monthly coastal water levels (at Grand Isle, Louisiana) show a pattern in which there are two peaks. One is in May-June and the second (and larger) is in September-October. The water level at Grand Isle also exhibits a statistically significant trend (which is also a major portion of the signal) of ~1.17 cm yr^{-1} over the time period from 1955 through 2000.

- The time period from the fall of 1999 through the end of 2000 was characterized by an extended and severe drought, low Mississippi River discharge, and low coastal water levels. This time period was also characterized by the highest salinities on record.

- Regression models (SAS, 1988) were used to look at the importance of Mississippi River discharge, the Palmer Drought Severity Index, rainfall, and coastal water levels on salinity in the Barataria estuary, Louisiana.

- Climate model predictions are for 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. 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 over the time period 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 over the time period from 2090 through 2099, and sea level is predicted to increase on the order of 30 centimeters by 2100.

The most successful models were those that contained an autoregressive term. The model for station 315 (coastal station at Grand Terre) explained a total of 72 percent of the observed signal, with the linear portion of the model explaining 48 percent, using Mississippi River discharge, precipitation, Grand Isle water levels, and the previous months salinity. The model for station 317 (mid-estuary station at St. Marys' Point) explained a total of 74 percent of the observed signal, with the linear portion of the model explaining 41 percent, using Mississippi River discharge, precipitation, Grand Isle water levels, and the previous months salinity. The model for station 326 (upper-estuary station in Little Lake) explained a total of 63 percent of the observed signal, with the linear portion of the model explaining 16 percent, using Mississippi River discharge, precipitation, and the previous 3 month's salinity.

The yearly salinity patterns were calculated for the following scenarios, and compared to baseline conditions, using the models developed for the prediction of salinity from the forcing functions: (1). An increase (or decrease) of 30 % in Mississippi River discharge; (2) An increase (or decrease) of 10 % in local precipitation; (3) An increase (or decrease) of 10% in local precipitation; (4) An increase of 30 cm in water levels; (5) Combinations of (1) through (4).

The results were similar at all three stations, with changes in Mississippi River discharge resulting in the majority of the salinity changes. Taking the worst case scenario (30 percent change in the Mississippi occurring with a 10 percent change in precipitation), the analysis predicts changes of ~3 ppt.

Literature data for Gulf of Mexico estuaries (Orlando et. al., 1993) show salinity decreases of 2 to 5 ppt for high freshwater input years and increases of 5 to 7 ppt for low freshwater input years. These are the magnitude of the salinty changes that might be expected with global climate changes.

The predicted salinity changes for the Barataria estuary would likely have little impact in the salt marsh. In the intermediate sections of the system, these predicted changes, could result in minor species shifts along the vegetative community boundaries.

For estuaries around the Gulf, assuming the impacts to be on the order of the Barataria system (~ 3ppt), large scale negative impacts would not be expected. A majority of these systems are influenced by multiple forcing functions, thus a negative change in one forcing function may be offset by a positive change in another forcing function.

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