Final Report: Evaluating prescribed fire effects in hurricane-influenced coastal habitats along the northern Gulf of Mexico. William J. Platt and Matthew G. Slocum, Principal Investigators. Submitted June 21, 2011.

INTRODUCTION & BACKGROUND. Fire is widely recognized as a natural ecological disturbance in coastal ecosystems of Mississippi and Louisiana. Observations regarding fires in coastal habitats over many decades (e.g., Viosca 1931) have resulted in descriptions of fires based on effects on marsh substrates (e.g., Penfound & Hathaway 1938, Lynch 1941, Smith 1942, Uhler 1944, O'Neil 1949, Penfound 1952). Yet, little is known about characteristics (behavior) and effects of natural fires in low-lying habitats or how fires interact with ecological disturbances, (e.g., floods or hurricanes; Hoffpauer 1968, Hackney and Cole 1981, Nyman & Chabreck 1995, Platt et al. 2006). As a result, there often is meager basis for management and restoration actions in coastal habitats (e.g., Schmalzer et al 1991, Frost 1995, Miller et al. 1998, Shirley and Battaglia 2006).

In this study, we investigated characteristics of fires and effects on vegetation in coastal marshes and savannas in Mississippi and Louisiana. This study incorporated some specific effects of anticipated global climate change (increased wrack associated with storm surges during landfall of intense hurricanes) that should affect fire regimes in coastal systems. We used a combination of experimental and observational approaches to conduct this study. We anticipated problems with burning of coastal refuge habitats, and these problems were pervasive throughout the two-year period of study. Nonetheless, we were able to conduct components of the study that enabled us to generate scientific concepts regarding fires and hurricane/fire interactions in coastal habitats along the Gulf of Mexico (e.g., Beckage et al. 2005, Slocum et al. 2003, 2007). We worked with land managers and refuge personnel to provide knowledge useful in making informed decisions regarding prescribed fires as an integral component of restoration and management practices in coastal habitats along the Gulf of Mexico.

Funds enabled an undergraduate at Grambling State University and Ph.D. graduate students at LSU to conduct research on coastal marsh and savanna ecosystems along the northern Gulf coast. Sites used for the study included the Grand Bay National Estuarine Research Reserve/National Wildlife Refuge/Coastal Preserves system of the Mississippi Department of Marine Resources (GBNERR/GBNWR/MDMR; Wieland et al. 1998) in Jackson County, Mississippi and Big Branch Marsh National Wildlife Refuge (BBMNWR) in St. Tammany Parish, Louisiana. Partners for this study included NOAA, GBNERR, and U.S.F.W.S.

OBJECTIVES OF RESEARCH. We had four primary objectives in our study of fire characteristics and effects in coastal marshes and savannas along the northern Gulf coast.

1. **To characterize inter- and intra-annual weather patterns along the Gulf coast to determine when weather/fuel conditions are conducive/not conducive for fire spread in coastal ecosystems.**

2. **To characterize fires (temperature profiles over time) and effects of fires on composition and dynamics of vegetation in Gulf coastal ecosystems.**

3. **To determine the characteristics and consequences of prescribed fires conducted at**

different seasons and in areas with/without fuels added by hurricane wrack.

4. **To provide managers of reserves along the northern Gulf coast with information and concepts regarding the characteristics and consequences of prescribed fires that can be expected in coastal ecosystems.**

Summary Report of Research Associated with Four Primary Objectives

1. Our first objective, climate modeling for the northern Gulf coast, was addressed by characterization of intra-annual weather patterns (Fig. 1). Analytical methods employed based on initial work of Camberlin and Diop (2003) and Slocum et al. (2010) are summarized in Appendix 1. We determined times during the year when weather/fuel conditions tend to be conducive/not conducive for fire spread in coastal ecosystems. Preliminary analyses revealed a general bimodal pattern of rainfall in the southeast, with dry periods in the spring and fall and wet periods in summer and winter. The transition from dry to wet seasons and vice versa was typically rapid, although some years showed a marked deviation from the typical pattern. Similar patterns were observed for three different north Gulf coastal regions distinguished by component analysis of rainfall data. These regions differed mainly in the intensity of winter wetting and spring drying seasons.

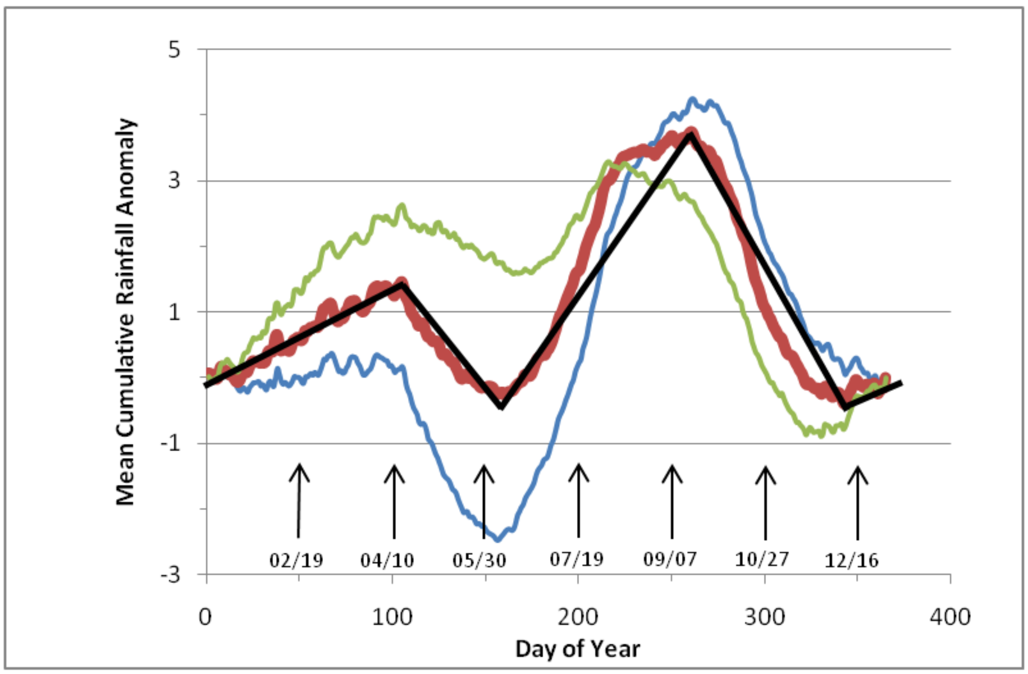


Figure 1. Daily mean cumulative rainfall anomaly (deviation from yearly average of natural log transformed data) for three north Gulf coastal regions (northwest-green, middle-red, southeast-blue) over a 60 year period. Increases in cumulative rainfall anomaly over time indicate a wetting trend; decreases over time indicate a drying trend. These data indicate four rainfall seasons, two wet and two dry, along the northern Gulf coast. Straight lines (black) fitted to the rainfall anomalies for the middle region (which includes BBMNWR & GBNERR) indicate the strength of mean wetting and drying trends during the different seasons.

We inferred expected fire regimes from our current climate analyses. Natural fires that burn large areas thus should be likely during the transition from spring dry to summer wet period, when fuels are dry enough to ignite, such dry fuels are contiguous over extensive areas, and storms provide lightning as an ignition source. Such fires appear historically to have maintained an open herbaceous-dominated landscape along north Gulf coastal transitions from marine to terrestrial habitats. Anthropogenic fires that burn large areas are less restricted by ignition sources to the spring/summer transition. Anthropogenic fires can be expected also during the fall dry season (if ignition sources are present) because dry fuels are contiguous over large areas. Such fall fires have been demonstrated to discourage herbaceous plants (often flowering or seeding at the time of fire) and to favor resprouting woody species, resulting in woody “walls of green” above the mean high tide line that impede upslope migration of plant species in a time of increasing sea levels. At other times of the year (summer, winter), small fires are expected, but occur at a frequency insufficient to maintain open marsh/savanna habitat along large areas of the Gulf coast.

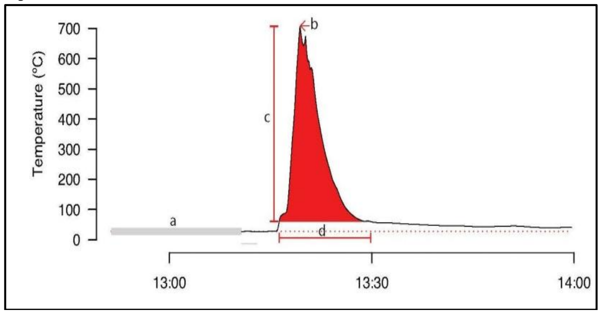
Our inferences suggest that effective restoration and management of coastal landscapes focus on frequent spring-summer transition fires, reducing fire frequency at other times of the year. We encourage land managers to track rainfall data annually to plan for prescribed fires once the drying trends have been established in the spring, but before extreme conditions are reached. We note that prescribed burning once summer wetting trends have begun is unlikely to achieve restoration/management goals because the rate of wetting is typically rapid enough that effective fires are unlikely to be achieved. Proactive fire management is essential for an ecologically effective fire program along the northern Gulf coast.

The frequency of spring-summer fires needed to restore and maintain coastal landscapes is likely to be dependent on year-to-year variation in rainfall patterns. Time constraints prevented us from exploring inter-annual variation in rainfall patterns during this study. More research and especially modeling should be conducted. Effects of global climate patterns (e.g., ENSO, NAO) on inter-annual variation in annual rainfall patterns are needed to understand year-to-year variation in rainfall, as well as develop concepts regarding how global climate change is likely to influence rainfall patterns along the northern Gulf coast.

2. Our second objective, to characterize fires and their effects on vegetation along the northern Gulf coast was partially successful. We were able to describe the physical characteristics of fires in some savanna systems in 2010 and 2011 based on thermocouple data on temperatures at replicated single points in fires (Fig. 2). Vagaries of weather in 2009 (El Niño conditions) and the BP oil spill in 2010 blocked repeated attempts to measure characteristics of prescribed fires experimentally in coastal transitions in both years because prescribed fires were postponed until conditions were no longer suitable for fires.

   Fire characteristics in coastal habitats were based on substantial measurements in a limited number of coastal habitats, primarily pine savannas in the spring of 2011. Methodology used for such data collection is described in Appendix 2. We focused on temperatures at ground level, those microhabitats important for herbaceous species in coastal habitats. Management of the data obtained from thermocouple records during fires requires extensive work to extract suitable parameters for analysis. These data are currently being used to obtain data for statistical analyses, and thus no analyzed data are yet available.

Figure 2. Diagram of a temperature-time series in a coastal pine savanna generated by a fire-logger located on the soil surface during passage of a head -fire. Ground-level temperatures pre-fire (a) increase rapidly to maximums (b) when a flame-front passes a point, resulting in maximum temperature increases (c). Rapid consumption of fine fuels results in short fire residence times (d) and total heat released (red-shaded area).



Prescribed fires in savannas are characterized by rapid onset of maximum temperatures at ground level as the flame front crosses a point. Temperatures typically are elevated several hundred to a thousand degrees Celsius above the background air temperatures. These temperatures decline rapidly as the flame front passes, producing fires that have short durations, often only several minutes. If dried wood or pine needles are present, however, maximum temperatures are enhanced as much as 1.5 to 3-fold. In addition, durations of temperatures at ground level above background, as well temperatures at ground level elevated above 60^{o}C, (lethal for bark cambium), are increased by the presence of wood or pine needles. Coastal pines, therefore, appear important for generating fires that maintain open coastal transitions along the northern Gulf coast. In addition, wood transported in wrack also tends to elevate temperatures and durations, resulting in the potential for killing shrubs and also buds of herbaceous plants at ground level.

We were able to describe coastal vegetation and the effects of fires on the coastal vegetation in areas that burned naturally or in prescribed fires conducted prior to the oil spill. The primary effects of prescribed fires included: 1) increases in the local biodiversity of plant species, 2) increases in the local invasibility by plant species from elsewhere (especially in areas affected by wrack deposits), and 3) increases in flowering and seed production by native marsh and savanna grasses, which resulted in upslope colonization in burned (but not unburned) areas. The prescribed fires enhanced local herbaceous vegetation and generated conditions favorable for upslope shifts in distributions with sea level rise.

3. The third objective, to characterize characteristics and effects of fires in areas with and without hurricane wrack present, also was partially successful. We designed experimental fires at GBNERR and BBMNWR. The former were not conducted during the period of funding, while the latter were partially conducted. Prescribed fires were conducted in spring of 2010 prior to the BP oil spill. As a result, we were able to study effects of prescribed fires on plant species biodiversity and abundance in areas with and without wrack in BBMNWR.

We established 60 m transects in coastal transitions along the north shore of Lake Pontchartrain in the Big Branch Marsh National Wildlife Refuge (St. Tammany Parish, LA). These transects occurred at similar elevations and spanned the transition from brackish marsh to pine savanna. We located transects in unburned and burned (spring, 2010) blocks so they crossed 20m wide bands of wrack that had been deposited in 2008 by Hurricane Gustav. These bands of wrack were located in the transition from brackish marsh to low wet pine savannas.

We established ten $10 m^2$ nested plots (containing subplots 0.01, 0.1, 1.0 m^2 in size) at 10 m intervals along the transect; plots in the wrack deposits occurred 15-35 m from the lowest point along the transect (in the brackish marsh outside the wrack zone).

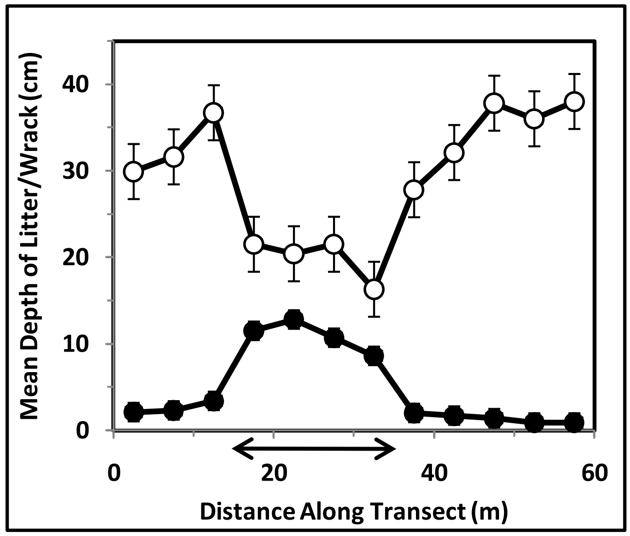


Figure 3. Mean depth of litter or wrack in $10 m^2$ plots along transects from brackish marsh to pine savanna along the north shore of Lake Pontchartrain at the Big Branch Marsh National Wildlife Refuge, St. Tammany Parish, LA. Closed circles: burned; Open circles: unburned. Ten plots were used to estimate means at each location. Wrack deposit from Hurricane Gustav was present 15-35m along each transect (arrow along abscissa). Wrack deposits were denser than litter in surrounding undisturbed marsh and savanna. Fires consumed most litter, as indicated by the only small amounts of litter along the burned transect. Fires reduced the depth of wrack, but did not remove the wrack; instead holes were opened in wrack.

We measured the depth of litter and hurricane wrack along each transect. The unburned transect, which had not been burned for about a decade, was characterized by 30-40 cm deep litter (Fig. 3). The depth decreased in the wrack deposit (Fig. 3), but the debris was dense and formed a thick mat that killed all vegetation buried beneath it. In contrast, in the burned transect, fire had removed almost all litter, leaving charred litter and bases of plants 2-4 cm deep (Fig. 3). The dense wrack deposits did not burn extensively because they contained moisture; on the average about 10-15 cm deep wrack remained after the fire (Fig. 3). We noted that the fire burned holes in the wrack, especially where dry wood was present.

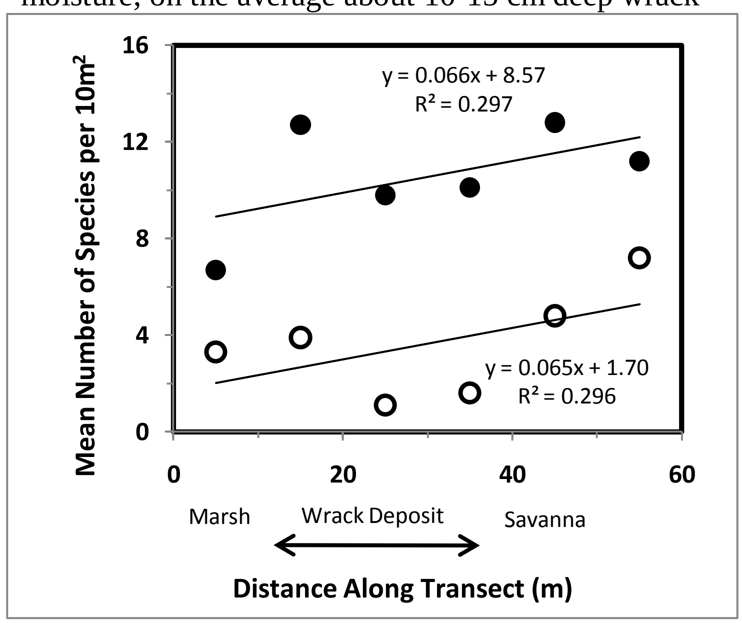


Figure 4. Mean number of species of plants in $10 m^2$ plots along transects from brackish marsh to pine savanna along the north shore of Lake Pontchartrain at the Big Branch Marsh National Wildlife Refuge, St. Tammany Parish, LA. Closed circles: burned; Open circles: unburned. Wrack deposit from Hurricane Gustav was present from 15-35m along each transect. Ten plots were used to estimate means at each location. More than four times as many plant species were present in $10 m^2$ plots in the burned compared to the unburned coastal transition. Wrack suppressed species abundances, especially in unburned coastal transitions.

Vegetation was sampled in the different subplots and plots in the summer and fall of 2010. Patterns of species richness along transects were affected by fire. Numbers of plant species in $10m^2$ plots showed a weak tendency to increase with elevation (expressed as distance from the lowest point along transects) in both burned and unburned coastal transitions (Fig. 4). The slopes of these relationships were almost identical. Nonetheless, there were more than four times as many plant species, on average in the burned transect (closed circles in Fig. 4) compared to the unburned transect(open circles in Fig. 4). Moreover, at the same elevations in the burned plots species differed among plots; numbers of species recorded in all burned plots containing wrack ($200m^2$ area) were about 50 times those of all similar plots with wrack in the unburned plots. Many new plant species appeared, including native annual and short-lived perennial herbaceous species indigenous to coastal plant communities. We propose that fire removes litter, stimulating germination of dormant seeds along coastal transitions, resulting in a very heterogeneous and species-rich flora, especially in areas where wrack suppressed the dominant graminoids (e.g., *Spartina patens, Juncus roemerianus).*

We also extended one ongoing field experiment exploring effects of wrack deposition (simulating hurricane deposition of wrack) and wrack removal (simulated fire) on coastal savanna vegetation at GBNERR (Hurricane Katrina wrack) and BBNWR (Hurricane Gustav). Results, summarized in Fig. 5, are presented in more detail in the attached draft manuscript.

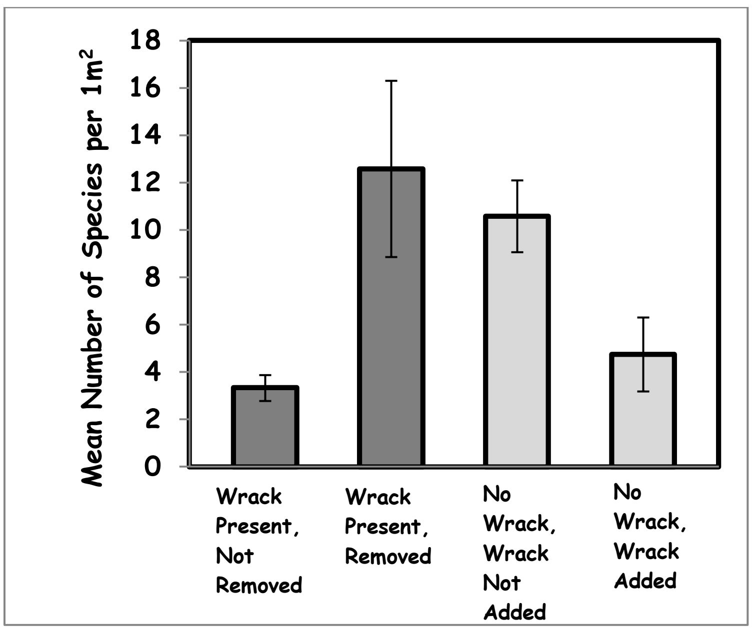


Figure 4. Mean numbers of plant species per m^2 in coastal pine savanna influenced by Hurricane Katrina storm surge. Mean numbers of plant species increased one year after wrack was removed from savanna groundcover (fire simulation) and decreased in surrounding groundcover where wrack was added (hurricane simulation). Vertical bars indicate standard errors. The mean overlap in species composition in the plots where wrack was present and removed and plots without wrack and to which wrack was not added was 26%.

We found that wrack has a large negative effect on plant species in coastal systems; areas where wrack was deposited contained about ½ the numbers of plant species found in areas without wrack. Moreover, effects of wrack burial were greatest on the dominant graminoid vegetation, opening space for other species, but delaying colonization until wrack was removed. Removal of the wrack (simulating fire) stimulated germination of seeds of plant species that tend not to occur in the surrounding undisturbed communities. The number of plant species increases greatly when wrack is removed; species include those that produce seeds with long-term dormancy in the soil, as well as species introduced with the wrack. The resulting communities are dominated by species that tend to respond to disturbance, producing seeds that are dispersed into the surrounding substrate and then remain dormant until the next disturbance (hurricane, fire, etc.). This aspect of the study revealed that coastal marshes and savannas contain many more plant species than normally are present in undisturbed habitat. This component of the overall biodiversity is only transiently present above ground and is dependent on recurrent disturbances (fires, hurricanes).

4. The fourth objective, providing managers with information and concepts regarding prescribed fires useful in restoration and management of coastal systems, has been accomplished through meetings with local groups, as well as presentations at regional and national meetings. During the course of this study, we have given presentations to land managers in eastern Louisiana (USFWS), Mississippi (NOAA, GBNERR), and Florida (DEP, NOAA). We have presented results of the study at symposia in the Natural Areas Association, American Society of Wetland Scientists, Society of Ecological Restoration, and Ecological Society of America. One manuscript is being prepared for submission for publication, and several others are in the process of analysis and writing at the current time.

5. **Conclusions from Research.** Our study focused on interactive effects of fires and hurricanes on coastal transitions from marine to terrestrial habitats along the northern Gulf of Mexico coastline. Intra-annual weather patterns along the north Gulf coast based on 60 years of rainfall data revealed four rainfall seasons (two wet and two dry periods) and suggested that natural lightning fires during spring transitions from dry to wet seasons (when thunderstorms first occur) should be those that burn large areas. Such fires are most likely to favor dominant graminoids and maintain herbaceous –dominated groundcovers along coastal transitions. Our study further suggests that natural fires occur at high frequency in pine savannas along the upland ends of coastal transitions. Natural fire frequency at the lower end of coastal transitions should depend on the local ecosystems present, occurring at somewhat lower frequency in some (e.g., rush and sedge-dominated) ecosystems, but at high frequencies in graminoid (e.g., cordgrass-dominated) ecosystems. We recommend that prescribed fire efforts involved in management of coastal transitions focus on frequent fires during the spring dry period and involve management in which fires are allowed to burn from upland savannas downslope into lower elevation marshes when fuel conditions are suitable for fires.

OUTCOMES OF RESEARCH. This proposed study had outcomes in three areas: scientific data and information of interest to environmental scientists, concepts that can assist land managers in restoration and fire management of coastal reserves in Mississippi and Louisiana, and education of undergraduate and graduate students.

The proposed research provided information/concepts useful for scientists and managers. First, we developed analyses of local seasonal weather patterns. The resulting data should be of use for coastal fire management by identifying hazardous conditions under which fires are likely to be difficult to control, as well as those conditions under which large fires are unlikely to occur.. Second, we have obtained data on the characteristics of fires in coastal ecosystems, and we will link those data to measured ecological effects in which the consequences of fuels produced by hurricane wrack are considered in relation to the seasonal timing of fires. Third, by combining weather analyses, fire characteristics, and fire effects, we are now able to develop criteria useful in evaluating those fire conditions that are likely to facilitate ecological restoration of long fire-suppressed or altered habitats and fire management of coastal landscapes. The application of prescribed fires at times of drought when vegetation is likely to burn, the measurement of fire behavior, and the assessment of fire effects on vegetation are generating scientific concepts regarding the ecological role of fire in coastal marsh and savanna ecosystems, as well as potential effects of interactions between fires and hurricanes on these coastal systems.

This study has contributed to multidisciplinary training of undergraduate and graduate students in coastal fire ecology. Dr. Platt has mentored Dwayne Joseph, an undergraduate student at Grambling State University, over the three year period from 2008-2011. During this period of time, Mr. Joseph was involved in the HHMI Summer Research Program at LSU for two years, was awarded an undergraduate research grant through t he Louisiana Sea Grant College Program, and participated in research conducted under the auspices of this current study. His involvement in the research has resulted in a three year experimental study of the potential interactive effects of hurricane wrack and fires on coastal savanna vegetation. This study has produced a manuscript (Appendix 3, submitted separately) soon to be submitted for publication. Mr. Joseph has now graduated and is planning to enter graduate school at Clemson University in the fall of 2011.

Drs. Platt and Slocum are serving as primary advisors of Darin Ellair, a Ph.D. graduate student interested in fire ecology develop the expertise to become an independent researcher investigating the fire ecology of coastal transitions from marine to terrestrial habitats. The absence of scientific training in this area has resulted in concepts for coastal fire ecology that are outmoded and often decades behind the science of fire ecology as applied to adjacent mainland habitats (like longleaf pine savannas). Funding for this project has enabled Mr. Ellair to conduct research that should be publishable in major journals dealing with ecology and coastal systems. No manuscripts are yet available from his study.

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Appendix 1. Summarized Methods/Results of intra-annual patterns of rainfall along the northern Gulf Coast.

Daily surface rainfall data for the past 60 years (1950-2009) were downloaded from the National Climatic Data Center (http://cdo.ncdc.noaa.gov/CDO/dataproduct) for 8 climate divisions along the Gulf Coast from Louisiana to Florida. The number of stations included was limited to 56 based on number of recorded observations (>16,000 observations) and location (south of 32.33^{o} latitude, and between -90.52^{o} and -85.02^{0} longitudes). Any remaining gaps in a station's record were filled with multiple imputation procedure (MI procedure, SAS 9.1) based on Slocum *et al.* (2010). Data was imputed for stations based on proximity and correlation to neighboring stations. The natural log transformation of daily rainfall was taken for all 56 stations (Slocum *et al.* 2010). Natural log transformation emphasized steadier rainfall events, which may be more influential on wildfires. During frequent, steady rainfall, water is absorbed more readily rather than running off, as occurs with single, infrequent large storms (Camberlin and Diop 2003). The average log rainfall was calculated for each day-of-year to examine patterns of seasonality.

A principle components analysis (PCA) of the averaged daily rainfall for the 56 stations was performed with Proc Factor in SAS (SAS 9.1) using the rotate=varimax option. Factor 1 accounted for 57% of the variation. Stations were grouped into three subgroups using a contour map of factor 1. Factor 1 contours had higher values in the northwest and lower values in the southeast; the three subgroups are named Northwest (NW), Middle (MD), and Southeast (SE).

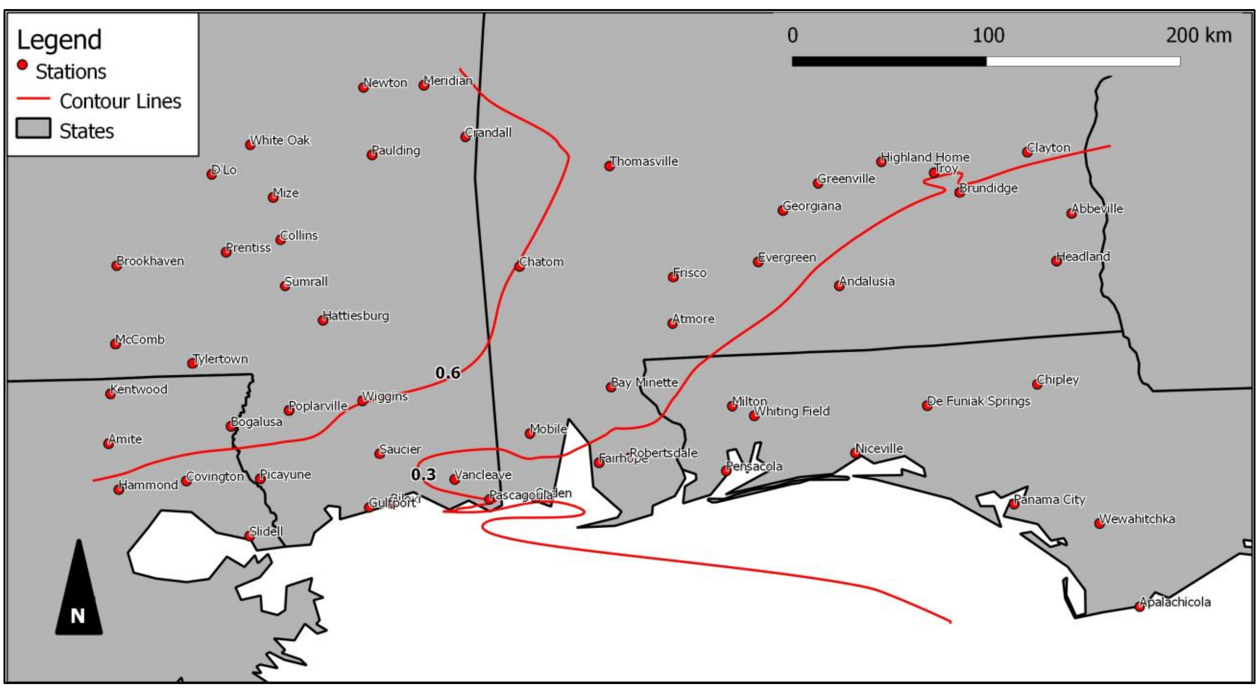


Figure 1: Map of the study region, showing locations of all 56 stations, and the 3 contour lines used to divide them into groups. The eastern Louisiana-Mississippi Gulf coast, the region of focus for this study is located in the mid region.

We used the cumulative rainfall anomaly method described by Slocum et al (2010) to examine seasonal patterns. Cumulative rainfall anomaly was determined by first computing average daily rainfall by averaging across all stations within a group to get a single mean value for each day-of-year. For example, there is one day-of-year value for January 1st across all stations within each subgroup for all 60 years. The daily average rainfall was next averaged over the entire time series to determine the mean rainfall for each group. A rainfall anomaly was obtained by subtracting each daily rainfall average from the mean of the daily rainfall over the entire time series. Rainfall anomalies were added consecutively for each group, starting with Day 1, to determine cumulative rainfall anomalies. Cumulative rainfall anomalies for each group were graphed in Microsoft Excel by day-of-year to observe seasonal patterns for wet and dry seasons. To capture the full bimodal dry/wet cycle, onset of the spring dry season was selected as the beginning of the cycle (Figure 2).

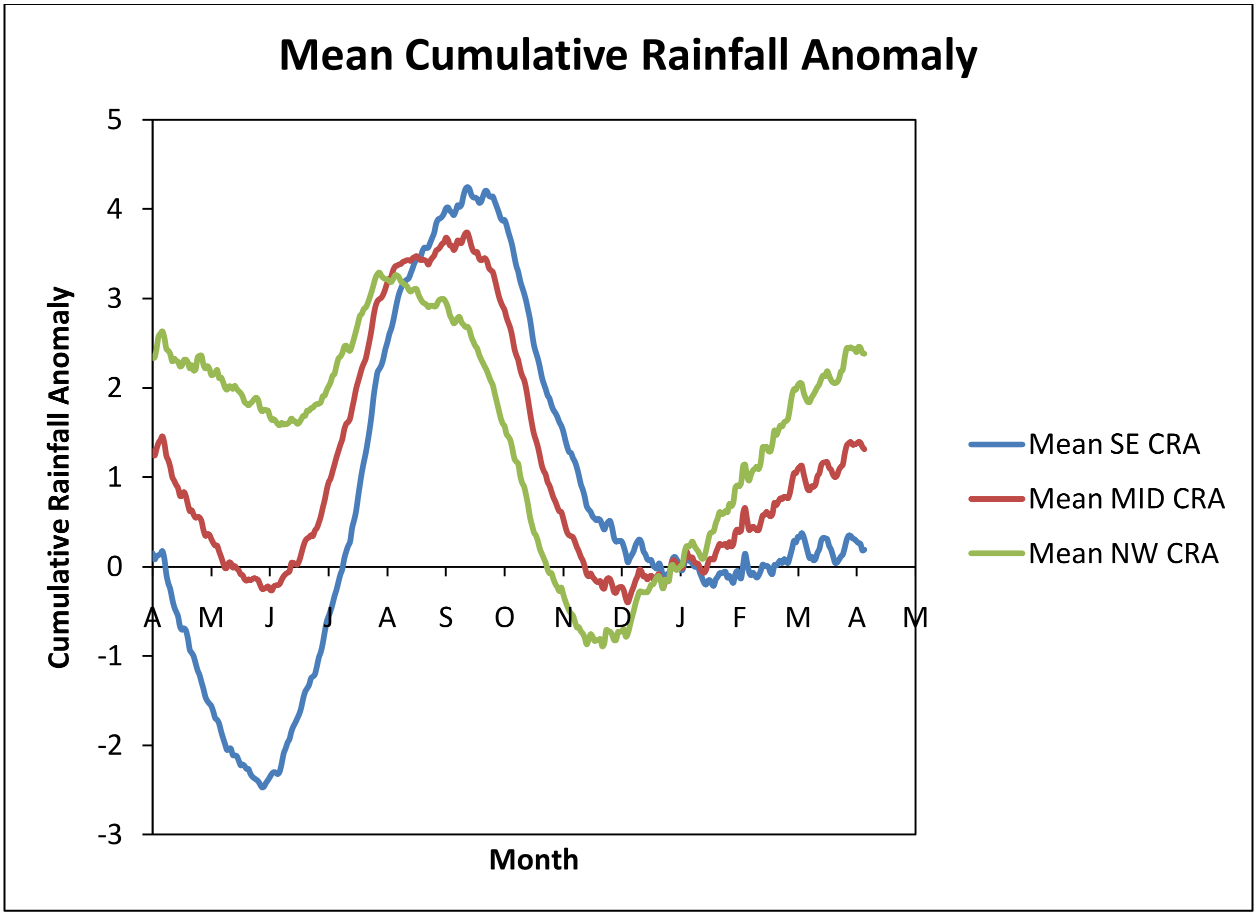


Figure 2: Cumulative rainfall for all 3 groups averaged over day-of-year, displaying bimodal pattern.

The mean dataset was useful to display the overall bimodal pattern in rainfall through the three groups, but in order to estimate variance it was necessary to examine individual years. Using the same subgroups from the mean dataset, the cumulative rainfall anomaly was determined by first computing average daily rainfall by averaging across all stations within a group to get a single mean value for each day. The daily average rainfall was next averaged over the entire time series to determine the mean rainfall for each group. A rainfall anomaly was obtained by subtracting each daily rainfall average from the mean of the daily rainfall over the entire time series. The rainfall anomalies were added consecutively for each group, starting with January 1, 1950, to determine the cumulative rainfall anomaly.

Then next step of the analysis was to assess characteristics of individual years. Specifically, we were interested in determining the onsets dates of each wet/dry season, the duration of each season, the total rainfall, accumulation rates, and trend consistency. These components would allow us to determine the length of a full bimodal cycle and how consistent these cycles occur among our three groups. By examining graphs of all 60 years for each of the three groups, we selected 20 years that most closely followed the bimodal pattern observed from the mean dataset. These 20 years best displayed a “normal” bimodal pattern that could be used to examine onset dates for wet and dry seasons. A wet season was noted to have a continuous increase in CRAs, while a dry season would have continuous decline. Points where these trends met were considered an onset, with a minimum being the onset of a wet season and the maximum the onset of a dry season.

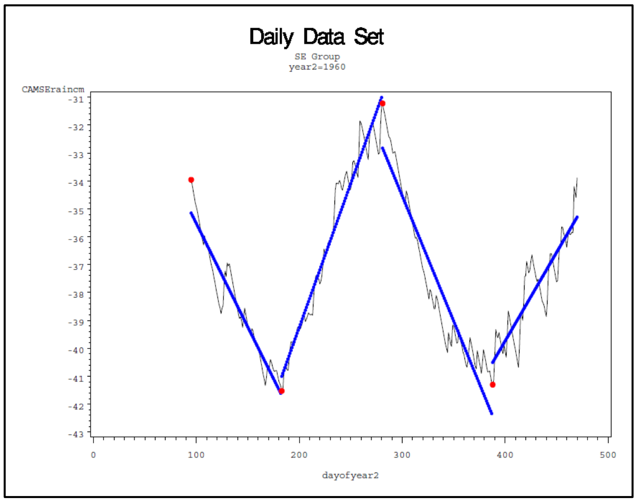
Seasonal cycles in the Gulf Coast do not always correspond to a calendar year. To capture the full trend of the wet/dry cycling water years were created. A water year starts with the beginning of the spring dry period and continues through to the onset of the following spring dry period. A typical year contained two onsets of dry seasons and two onsets of wet seasons.. Water years tended to include a portion of two calendar years, and were not always equal in length. For example, the water year for 2001, included both 2001 and 2002 calendar years. The water year was created by finding the first onset of the spring dry season, starting with 1950. A range of days was selected to capture the maximum CRA for the first onset of the dry season for every year within each group. The years immediately following each selected year were also examined for onset of first dry season so that complete water years could be calculated and graphed.

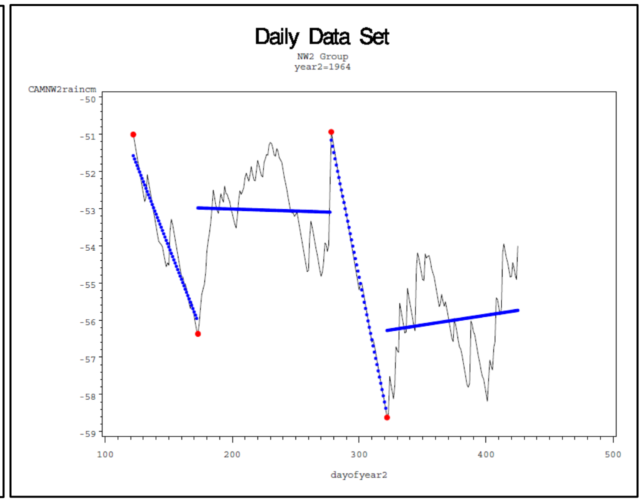
Onset dates for summer/winter wet period and fall dry period were located by determining the maximum or minimum date before a slope change. The onsets of the wet seasons were the lowest point (minimum) before an increase in slope. The onset of second dry season was determined as the highest point (maximum) before a decrease in slope. A data step in SAS was used to construct ranges around the maximum and minimum locations. Proc Means was used to locate and output onset dates for all onsets for all groups for a total of 16 individual data sets (four onset dates and four groups).

Duration of water year, season duration, total rainfall, rainfall accumulation rate, and trend consistency were used to examine patterns in seasonality. Total rainfall was calculated as the difference between the value of the CRA at the end of the season and the value of the CRA at the beginning of the season. For dry seasons this yielded a negative value, and for wet seasons a positive value. Slopes from linear regressions for each season of each year were used to determine the accumulation rate for each season. The rates were negative for dry seasons and usually positive for wet seasons. The R-squared values from linear regressions for each season of each year were used to determine trend consistency. In general, the bimodal pattern was most consistent in the SE group, and most variable in the NW group (Figures 3 & 4).

Figure 3 (left): Water year for 1960, from the SE group, showing a strong bimodal pattern. The black line is raw CRA, red dots indicate onsets, and the series of blue dots show regression fit to the raw data for each season.

Figure 4 (right): Water year for 1964, from the NW group, showing a weaker bimodal pattern. The black line is raw CRA, red dots indicate onsets, and the series of blue dots show regression fit to the raw data for each season.





Future Directions: From this study we were able to describe seasonal patterns of the Gulf Coast region within the last sixty years. Our next step is to correlate the seasonal data with El Nino Southern Oscillatin (ENSO) and recorded natural wildfires within our study area. We have started a comparative analysis between our seasonal characteristics and the Nino 3.4 index. We have obtained wildfire records for Louisiana and Florida, and are waiting for records from Mississippi and Alabama. Future research will utilize this information for identifying times when potential wildfires are likely to occur. This will be especially useful in prescribed fire management

Final analysis of extracted variables is preliminary. Future research will utilize the datasets created to analyze differences between the three regions examined. Of the 60 years in the original dataset, we selected the 20 clearest to examine rainfall patterns; future analysis will incorporate additional years that may have occurred during extreme El Nino/La Nina events, which may help further clarify seasonal patterns.

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Appendix 2. Field measurements of fire characteristics.

Measurements of fire characteristics focused on effects of fuel manipulations on characteristics and intensity of fires. Fires in any habitat involve combustion of plant materials, producing heat. We propose to measure characteristics of this combustion process in two ways. We plan to measure total fuel combustion using samples of vegetation adjacent to subplots; samples taken before and after fires will be dried and weighed. The total fuel and percent combustion of that fuel provide estimates of total potential and realized heat production (Whelan 1995). Because heat rises, its effects are spread upward and away from the soil, and so percent combustion may not measure ecological effects. Thus we also propose to measure a vertical profile of the combustion process using thermocouples to record temperature profiles over time at different heights and depths in the substrate. These profiles will be useful in characterizing changes in temperature at different heights/depths in subplots, especially at locations of roots and seeds. By conducting the fires under different seasonal conditions, we should be able to explore how fuels influence characteristics of fires.

We use thermocouple sensors attached to data loggers inside buried waterproof containers. These "fireloggers", initially developed by Dr. Jim Grace at the USGS National Wetlands Research Center, Lafayette, LA for studies of tallow invasion of coastal prairies (Grace et al. 2005), have been adapted successfully to obtain continual temperature measurements in subplots during prescribed fires in pine savannas and marshes. To withstand temperatures > 1000^{o} C, type K thermocouples are used (20 gauge, solid conductor wires with Nextel® braided ceramic fiber insulation enclosed within Inconel 600® high nickel content alloy overbraid; Omega Corporation, Stamford, CT). HOBO type K data loggers are capable of recording temperatures up to 1250^{o} C (with a resolution of 5-10^{o} C) and can record temperatures from the thermocouple wire (via microconnectors) for 4.5 hours at recording intervals of every 0.5 seconds (Onset Computer Corporation, Bourne, MS). Thermocouple tips are placed at designated heights/depths; small-diameter holes in the soil are made using a stiff wire and each hole is filled with soil after inserting the thermocouple wires to the appropriate depth.

The compact (48 x 68 x 19 mm) datalogger is sealed within a cylindrical container with caps that contain ports for the thermocouple cable and a mini-jack coupler (connected to the datalogger by an in-line 3 mm-diameter stereo audio cable). The mini-jack coupler enables electronic interface with the data logger without opening the shell, which is made waterproof using a silicon sealant. Fireloggers are buried 20-25 cm deep using a 10-cm diameter auger; a length of wire attached to one end facilitates removal of units after fires. Internal logging of temperatures provides ground temperatures, which should not change at the depths of burial during fires. Fires in pine savannas and marshes burn quickly and fire residence times are relatively short, but fireloggers are removed in about 3 hrs after fires to be sure that post-fire temperatures have equilibrated with air/soil temperatures.

Fireloggers interface with a hand-held palmtop via interface cables. Data management software (for launching the recording process and downloading data) from Onset Corporation at LSU is used with the HOBO data loggers.

Three fire metrics are readily calculated from thermocouple data (Figure 1). These include: 1) maximum temperature increase, calculated as the difference between the ambient temperature pre-fire (mean temperature for the 30 minutes prior to fire) and the highest temperature recorded during fire; 2) fire residence time, calculated as the time in minutes between fire onset (first time at which temperature increased more than 0.3°C per second) and fire end time (first time at which temperature falls below 50°C [in most plots], or to within 5°C of pre-fire ambient temperature following maximum temperature [for those loggers whose temperatures never exceed 50°C]); and 3) total heat, measured as the time-integrated difference between measured and pre-fire temperature from fire onset to fire end time. We calculate these variables using a custom R script (R Development Core Team 2005) and analyze data using SAS(SAS 2005).

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