GCE Annual Report Research Findings

September 2011

Context

The central paradigm of GCE-II is that variability in estuarine ecosystem processes is primarily mediated by the mixture of fresh and salt water flows across the coastal landscape. The program is focused on 5 main, inter-related questions:

Q1: What are the long-term patterns of environmental forcing to the coastal zone?

Q2: How do the spatial and temporal patterns of biogeochemical processes, primary production, community dynamics, decomposition, and disturbance vary across the estuarine landscape, and how do they relate to environmental gradients?

Q3: What are the underlying mechanisms by which the freshwater-saltwater gradient drives ecosystem change along the longitudinal axis of an estuary?

Q4: What are the underlying mechanisms by which proximity of marshes to upland habitat drives ecosystem change along lateral gradients in the intertidal zone?

Q5: What is the relative importance of larval transport versus the conditions of the adult environment in determining community and genetic structure across both the longitudinal and lateral gradients of the estuarine landscape?

Q1: What are the long-term patterns of environmental forcing to the coastal zone?

Coastal ecosystems are influenced by the characteristics of the upstream watershed (e.g., land use, slope), by those of the atmosphere (e.g., temperature, precipitation), and by those of the ocean (e.g., wave climate, sea level). The GCE LTER program collects data on local climate (temperature, precipitation, wind speed and direction) and on the water chemistry of the tributaries that discharge into the Altamaha River. We also obtain data from other organizations (NWS, USGS, NOAA, and other sources) on river discharge, watershed characteristics, human population demographics, sea level, oceanographic conditions, and climate.

Upstream forcing

The USGS gauge at Doctortown (Station 02226000) provides near real-time data on discharge into the Altamaha River estuary. We use data harvesting technology developed by GCE to automatically download and process data from USGS so that it is documented and standardized to compatible units and date formats for comparison with other GCE monitoring data, providing GCE investigators with high quality standardized data in various file formats to support synthetic research projects. River discharge over the course of the program shows a change from a wet period (2003-2005) to drought conditions (2006-2008) with a new drought starting in 2011.

S. Joye (UGA) continues to work with J. Sandow (Aquatic Research South) to monitor nutrients in the river water entering the GCE domain via the Altamaha River and its tributaries. The Joye lab (under the guidance of K. Hunter, UGA) analyzes samples to determine concentrations of dissolved inorganic nutrients (DIN, DIP, and DSi species), dissolved organic nutrients (DOC, DON, and DOP), and total suspended solids. This past year, the lab processed 54 river samples (about 4 samples per month on average). Since the drought began in the late spring of 2011, nitrate/nitrite concentrations in the river have decreased markedly.

As part of an effort to understand relationships between nutrient inputs to the watershed and in-stream water quality, S. Schaefer (UGA Ph.D. student, Alber) has combined calculations of the sources of N and P to the subwatersheds of the Altamaha with monthly measurements of in-stream nutrient concentrations. Average monthly loads of all forms of N (NO_2^-, NO_3^-, NH_4^+, DON, and PON) as well as PO_4^{3-}, were best related to those components of the N and P budgets that reflect livestock populations in the watershed (e.g., livestock consumption and excretion). This work will be presented at the 2011 meeting of the Coastal and Estuarine Research Federation.

The GCE program is also involved in several efforts to evaluate human use of the landscape. As part of this, we are participating in the cross-site initiative, Maps and Locals, led by R. Pontius (PIE), G. Kofinas (BNZ), and N. Sayles (JRN) to use spatial representations of land cover and land use to identify patterns of landscape change in regions in and around LTER sites. As part of this, GCE data were used by one Ph.D. student and three M.A. students at Clark University to illustrate their GIS and mathematical models and to examine the statistical principles that one should consider when sampling land cover and demographic information. This work was presented at the annual Association of American Geographers conference. In addition, J.P. Schmidt (UGA Post-doc, Alber) is working to evaluate ecosystems services in McIntosh County, GA, which is where the GCE site is located.

Atmospheric forcing

Meteorological stations, operated and maintained by various institutions affiliated with the GCE program, are used to characterize the weather and climate within the GCE domain. The station at Marsh Landing, which is operated in collaboration with SINERR, serves as our primary LTER meteorological station for inter-comparison studies and ClimDB. The station at Hudson Creek in Meridian is operated in cooperation with the USGS NWIS. Both near-real-time and historic data and plots from these and other relevant climate stations are publicly accessible on the GCE Data Portal website (http://gce-lter.marsci.uga.edu/portal/monitoring.htm).

This past year, A. Burd (UGA) and J. Sheldon (UGA) finalized their analysis of variability of precipitation to the Altamaha watershed in relation to various climate indices: the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO), and the Bermuda High Index (BHI). A manuscript of their findings concerning large-scale climate drivers, watershed precipitation, and Altamaha discharge is in preparation with planned submission in fall of 2011.

Oceanographic forcing

We obtain real-time monitoring data on oceanographic conditions from the National Data Buoy Center's station at Gray's Reef (Station 41008), which is in the Gray's Reef National Marine Sanctuary, approximately 39 km from the University of Georgia Marine Institute. We also obtain sea level data from the NOAA/NOS Center for Operational Oceanographic Products and Services web site (http://tidesandcurrents.noaa.gov/) for station ID 8670870 (Fort Pulaski, GA). Data are extracted from the CO-OPS web pages, standardized, and documented using GCE metadata templates.

Figure 1. Areas of eroding (red) and accreting (blue) shoreline on Sapelo Island and adjacent areas. Major channels are also shown (pink), (Imagery from USGS, 2006).

This past year, C. Alexander (SkIO) used GIS to quantify erosion rates in the major channels near Sapelo Island (Figure 1). In general, erosion rates along energetic shorelines are -1 to -2 m y^{-1}, whereas erosion is distinctly lower in smaller channels (-0.1 to -0.5 m y^{-1}). Similarly, energetic settings exhibit accretion rates from +1 to +3 m y^{-1}, whereas accretion in smaller creeks is only +0.1 to +0.3 m y^{-1}.

Q2: How do the spatial and temporal patterns of biogeochemical processes, primary production, community dynamics, decomposition, and disturbance vary across the estuarine landscape, and how do they relate to environmental gradients?

Variability in external forcing is manifest as environmental gradients (e.g., in salinity or nutrients) within the coastal landscape. We collect data on physical oceanographic conditions and nutrients in the water column, and on intertidal marsh soil, plant, animal, and microbial dynamics. Although data are collected throughout the domain, we primarily focus on conditions in the Duplin River, which is at the heart of our system. The variables of interest to us span all five of the LTER core research areas.

Water column

Moorings

Long-term measurements of conductivity, temperature, and sub-surface pressure are collected every 30 minutes at 8 moorings distributed across the GCE domain (see http://gce-lter.marsci.uga.edu/public/research/mon/sounds_creeks.htm). MicroCAT sondes are cleaned and inspected biweekly to minimize data loss due to fouling, and logged data are manually downloaded on a bimonthly to quarterly basis by GCE field technicians (J. Shalack, D. Saucedo, UGAMI). Data are processed by W. Sheldon (UGA) and D. Di Iorio (UGA).

This past year, Di Iorio and R. Castelao (UGA) continued their implementation of the Regional Ocean Modeling System (ROMS) to explore water circulation and exchange between interconnected estuaries. The model uses a highly idealized representation of the Altamaha-Doboy-Sapelo estuarine complex and the adjacent coastal ocean. River inflow is imposed at the head of the Altamaha River at 300 $m^3 s^{-1}$, increasing to 800 $m^3 s^{-1}$ during a 10-day discharge pulse event. The model is forced by tides and by winds that oscillate between downwelling and upwelling favorable every few days. The connectivity between the estuaries can be quantified by simulated dye releases in the model. In the example below (Figure 2), the initial normalized dye concentration was set to 1 in the idealized Altamaha Sound and to zero everywhere else in the domain. Results show that, in Doboy Sound, approximately 80-90% of the water that originated in the Altamaha Sound was first transported offshore into the coastal ocean, and then transported back into Doboy Sound via the estuary mouth. (The remaining 10-20% of the water was

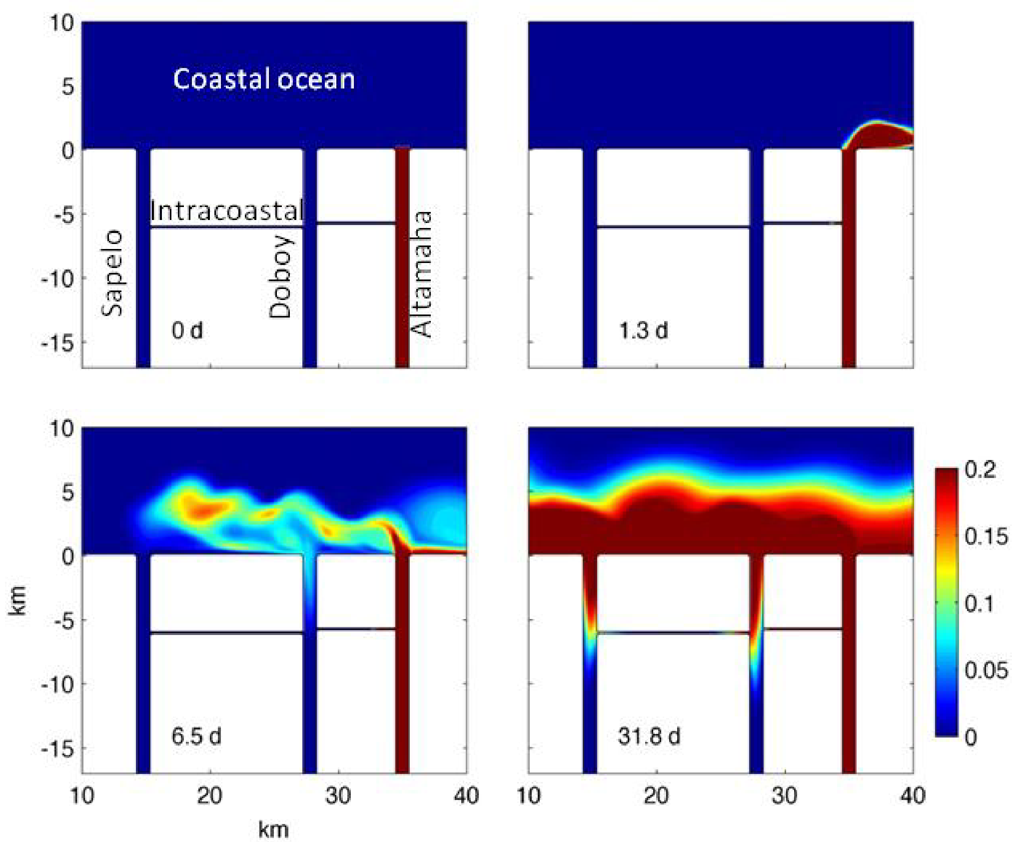


Figure 2. Model domain showing dye concentrations at 0, 1.3, 6.5, and 31.8 d after release.

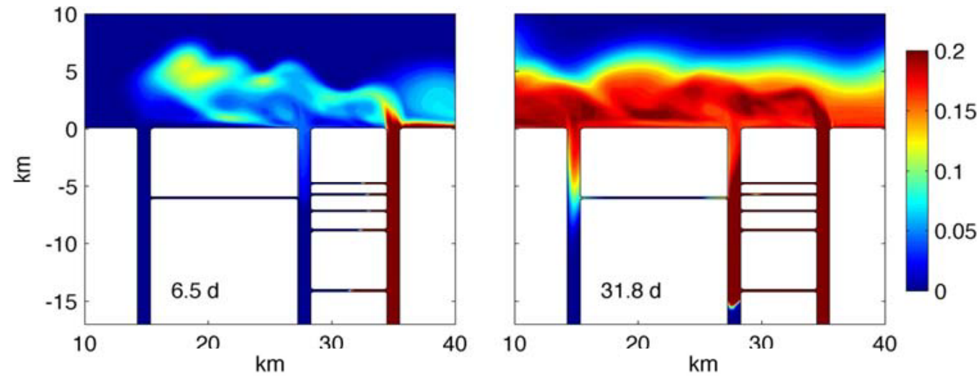


Figure 3. Model simulation for multiple cross channels, showing dye concentrations at 6.5 and 31.8 d after release.

transported through the Intracoastal Waterway). However, increasing the number of channels between the idealized Altamaha and Doboy sounds in order to better represent the observed network of channels and creeks resulted in substantially increased connectivity in the system (Figure 3). An EOF analysis of the modeled salinity reveals the dominant patterns of variability for these runs. The amplitude time series of the second mode (not shown) is correlated (r=0.74) with sea level at the coast, indicating that high water level at the coast leads to increased salinity in Altamaha Sound and freshening in Doboy and Sapelo sounds, which agrees closely with observations. Dynamical analyses are now underway to disentangle the mechanisms controlling water and salt exchange in this multi-inlet estuarine system.

Di Iorio is also collaborating with former Ph.D. student P. McKay (Naval Research Laboratory) to develop more realistic models of the GCE domain. This past year they have developed a preliminary unstructured finite element mesh of the GCE domain for use in modeling studies. The mesh extends from offshore to the 2 m inland contour and is based on the best available bathymetry and topography (Figure 4). The mesh has been tested with a 2D, depth integrated,

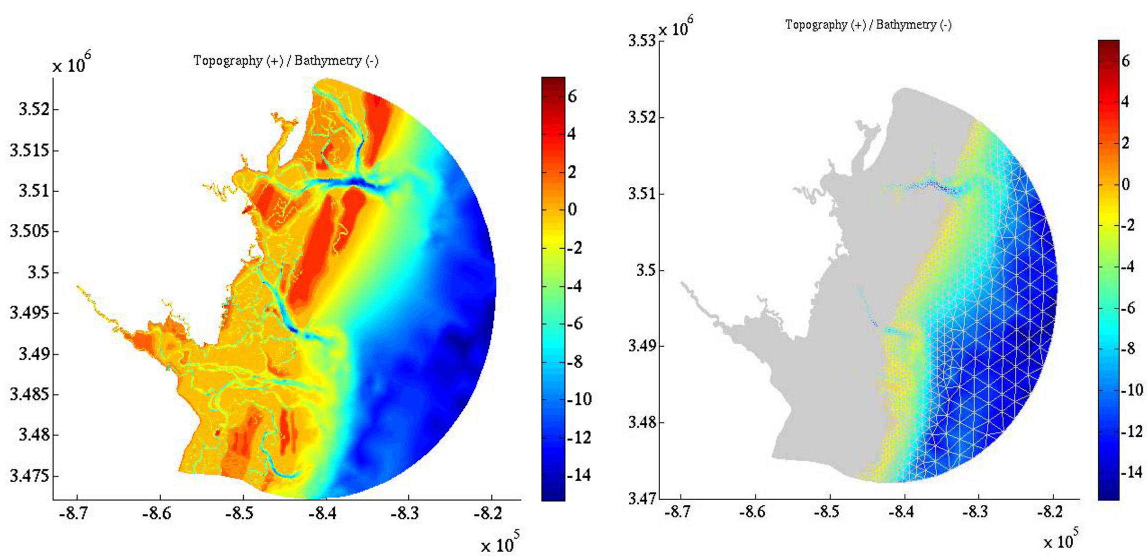


Figure 4. (left) Merged bathymetry and topography for the modeled GCE domain. (right) The initial GCE unstructured mesh with 492,947 nodes and 979,799 elements. Resolution varies from 500 m at the offshore boundary to 1 m in the marshes.

barotropic formulation of the ADvanced CIRCulation (ADCIRC) model with tidal forcing and wetting and drying of the marsh areas and has been shown to be stable. Further refinement of the grid is underway in order to fully resolve all areas of interest and to allow it to be run as a 3D, baroclinic model including river forcing.

Water column nutrients

We run regular cruises to measure the surface water concentrations of dissolved and particulate materials at core stations located across the GCE domain. Samples from the monitoring cruises are collected by the GCE field crew and analyzed by the Joye lab (S. Joye, K. Hunter). For the monthly cruises between Aug 2010 and Aug 2011, we processed 296 samples for determination of concentrations of dissolved inorganic nutrients (NO_2^-, NO_3^-, NH_4^+, HPO_4^{2-}, and $H_2SiO_4^{2-}$) and dissolved organics (DOC, TDN, DON, TDP, and DOP); 888 chlorophyll *a* samples; and 798 samples for total suspended sediment and particulate CN. These analyses are largely complete; the data will be submitted to the LTER database in mid-September. As observed in previous years, spatial and temporal variations among the study sites were apparent. The highest NO_x concentrations were present in Altamaha Sound at sites GCE 7 and 8. In Altamaha Sound, NO_x concentrations usually exceeded NH_4 concentrations whereas in Doboy and Sapelo sounds, concentrations of NH_4 usually exceeded NO_x. DOC concentrations were highest in Sapelo Sound, followed by Doboy and Altamaha sounds. DON concentrations were often equal to or higher than DIN concentrations. DOP concentrations have been markedly higher since June 2011.

G. Kaufman (UGA M.S. student, Alber, Meile) applied the EPA Water Quality Analysis Simulation Program (WASP v.7.4) model to the Altamaha River estuary. The model, which was calibrated and validated with GCE water quality observations (Figure 5), was used to simulate

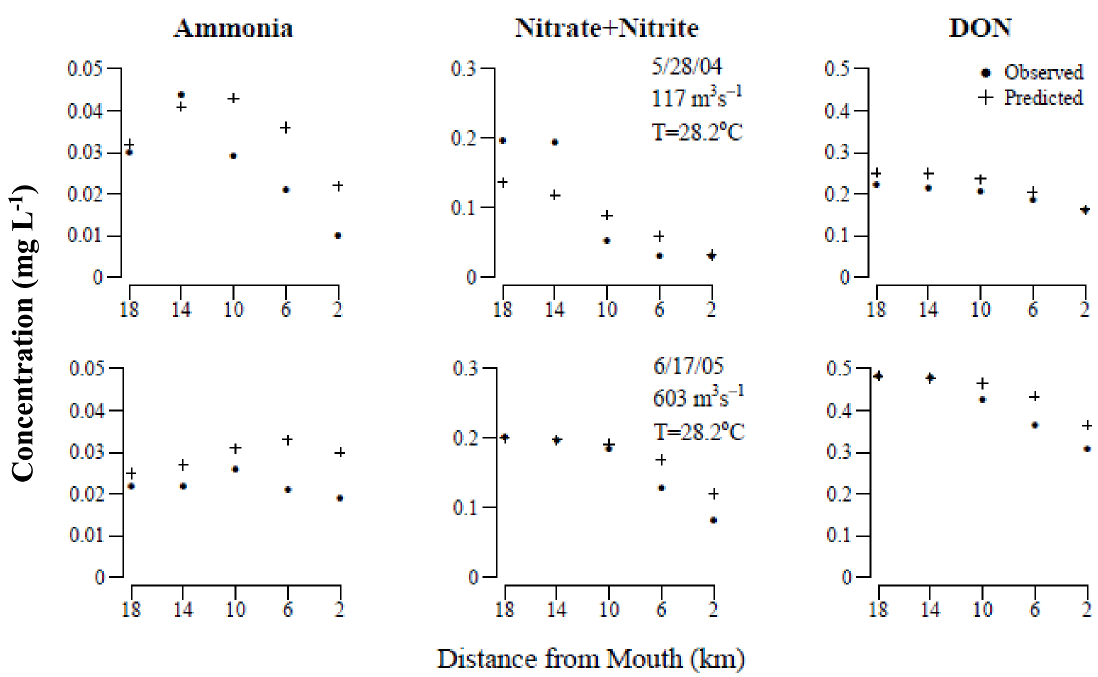


Figure 5. Nitrogen concentrations along the Altamaha River estuary (river mouth = km 0) for two different dates and flow conditions (top: lower flow; bottom: higher flow). Observed values (dots) are from GCE cruises; predicted values (plus signs) are from the EPA WASP model.

dissolved nitrogen concentrations in the estuary under different conditions. Results from the calibrated model showed that riverine DN input had an approximately 6-fold greater influence on predicted DN in the estuary than either river flow or temperature. Overall, predicted DN concentrations were highest for high DN input, high flows, and low and medium temperatures. Kaufman completed his M.S. degree in 2011.

Marshes

Soil processes

The ability of estuarine marshes to accrete is controlled by both physical and biological processes. Under the direction of C. Craft (IU), we measure vertical accretion and sedimentation using sedimentation-erosion tables (SETs) and feldspar marker layers to evaluate the effects of freshwater pulsing on long-term stability of tidal marshes. We also measure changes in marsh surface elevation and sediment deposition every six months at the ten GCE domain sites and at three sites of a directed study on Dean Creek.

In August 2010, Craft established a field experiment to evaluate organic matter decomposition in tidal freshwater forests. Bald cypress (*Taxodium distichum*) roots were harvested from a tidal freshwater forested area in the Altamaha River and transplanted to both levee and plain sites in the tidal freshwater forested area of the Altamaha River (control), a brackish area of the Altamaha Estuary, and a tidal freshwater forested area in the S. Newport River, which is experiencing altered hydrology and saltwater intrusion. After 340 days, decomposition rates at all of the levee sites as well as the plain site in the S. Newport River were similar, with 69-71% mass remaining. The two plain sites in the Altamaha (in the River and Estuary) had slower decomposition, with 78-79% mass remaining. Preliminary analysis suggests that decomposition of bald cypress belowground biomass is more dependent on soil moisture than on soil salinity.

Plant dynamics

S. Pennings (UH) and his lab monitor plant biomass with the goal of testing the hypothesis that end-of-year biomass varies as a function of freshwater discharge from the Altamaha River (especially in low-marsh plots), local rainfall (especially in high-marsh plots), and average sea level. Pennings and K. Wieski (UH Post-doc, Pennings) are currently analyzing plant production (end-of-year standing biomass) data collected over 11 years from both creekbank and mid-marsh zones of all ten GCE sites. Results vary among sites, but in general, plant production in the creekbanks is most strongly related to Altamaha River discharge (presumably because high discharge reduces the salinity of tidal waters), whereas plant production in the mid-marsh is most strongly related to local precipitation (presumably because local precipitation has a stronger effect on porewater salinity in the mid-marsh) (Figure 6). A rigorous analysis of the complete dataset using hierarchical modeling is underway, and we anticipate writing a manuscript based on these results during the 2011-2012 academic year.

Pennings also continues his ongoing monitoring of mid-summer plant composition at permanent plots located on 3 types of vegetation borders (*Spartina alterniflora*-*Juncus roemerianus*, *S. alterniflora*-meadow, meadow-*J. roemerianus*), to test the hypothesis that high marsh plant species composition is driven by variation in rainfall. He also continues to monitor recovery from disturbance and the role of competition in secondary succession in plots cleared since 2000. To date, succession has been fastest in plots on the *S. alterniflora*-meadow borders, which have already converged on control plot values, and slowest in the *J. roemerianus* plots, which are still early in the successional trajectory. Removal treatments indicate that competition plays a strong role in mediating the composition of the vegetation in each zone.

This past year, M. Alber (UGA) initiated a wrack disturbance study with support from GA DNR. We established experimental plots in different plant zones that will be covered with wrack for varying amounts of time (from 2 weeks to 1 year). The experiment will allow us to determine how long it takes for wrack to affect marsh plants, whether the low marsh and high marsh respond differently, and how long it takes for affected areas to recover.

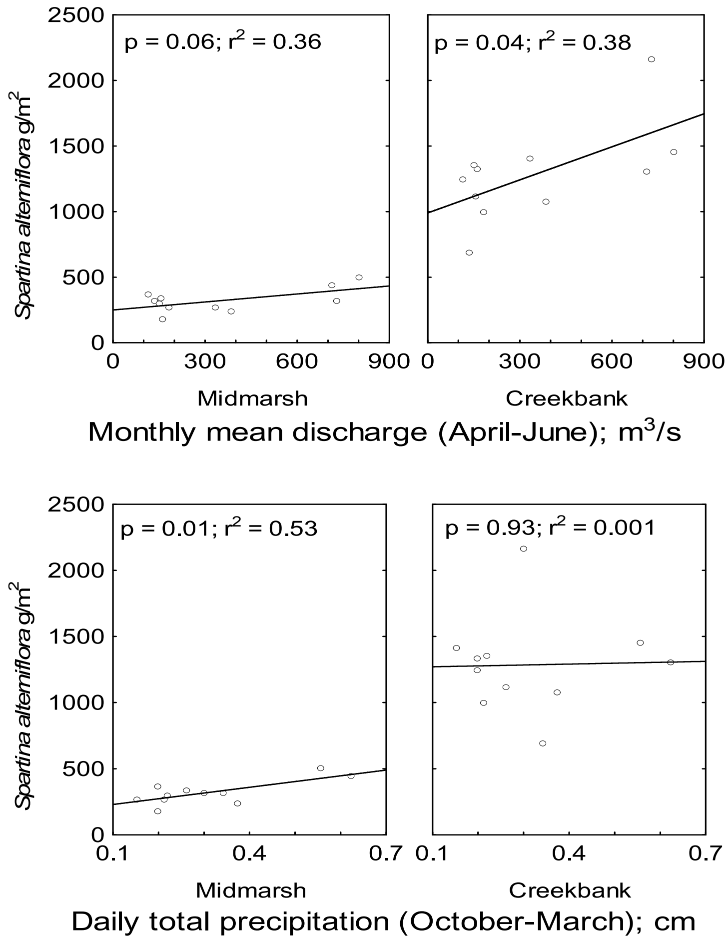


Figure 6. Relationship between standing crop biomass of *Spartina alterniflora* and Altamaha River spring mean discharge (Doctortown) (top) and total precipitation (Brunswick) (bottom) in two marsh elevation zones at GCE site 2 in 2000-2010. Although production is related to discharge in both mid-marsh (left) and creekbank (right) zones, the effect of discharge is stronger in the creekbanks. Biomass production is related to local precipitation only in the mid-marsh zones.

Additional plant studies

C. McFarlin (UGA Ph.D. student, Alber) is working to evaluate how *S. alterniflora* responds to disturbances and to determine how the loss of *S. alterniflora* affects marsh support of benthic and epifaunal invertebrate communities. Previous research has suggested that the secondary metabolite dimethyl-sulfoniopropionate (DMSP) is converted to dimethylsulfoxide (DMSO) when plants are stressed. McFarlin analyzed the concentrations of DMSP and DMSO in *Spartina* leaves collected from areas affected by wrack, increased snail densities, dieback, and horse disturbances. She found that the DMSO:DMSP ratio was elevated in all of the affected areas regardless of disturbance type, suggesting it is a potential indicator of plant stress in the field. This work will be presented at the 2011 meeting of the Coastal and Estuarine Research Federation.

Pennings received supplementary funding to develop a collaboration with Dr. Cendrine Mony at the University of Rennes (France) in the area of using mathematical tools to address problems in plant community ecology. He traveled to France in the summer of 2010 to meet with Mony, and they currently have a manuscript in preparation. C. Richards, a former Ph.D. student (USF), traveled with Pennings to discuss possible collaborations in the area of *Spartina* genomics with Dr. Malika Anouche at the University of Rennes.

Finally, Pennings is collaborating on a large-scale project to develop a synthetic understanding of plant zonation patterns in Georgia tidal marshes, evaluating 1) spatial associations between different plant species and abiotic conditions, 2) the results of experiments transplanting plants into new habitats and removing neighbors, 3) the results of experiments altering abiotic conditions, 4) variation among 55 sites in vegetation zonation patterns, and 5) temporal variation in plant community composition. This work is being written up for Ecological Monographs, with a submission planned during the 2011-2012 academic year.

Animal dynamics

Marine invertebrate population monitoring is conducted at the ten GCE monitoring sites each October in conjunction with vegetation sampling. Animal sampling areas are located several meters away from each permanent vegetation plot and are sampled for epifauna and macroinfauna. D. Bishop (No Bones Coastal Biology Consultants) and Alber are currently using this data set to evaluate temporal and spatial patterns in *Littoraria irrorata* density.

B. Silliman (UF) and his lab are continuing to document the patterns of macroorganisms across the GCE domain. In the falls of 2008, 2009, and 2010, they enumerated densities of the dominant marsh invertebrates in transects established across 8 barrier island marshes, 8 mid-estuary marshes, and 8 mainland marshes to test the hypothesis that barrier island systems support higher marsh animal densities.

Since 2000, S. Pennings and his lab have collected annual data on grasshopper abundance to test the hypothesis that it varies as a function of site characteristics and angiosperm production. An initial analysis of temporal variation in grasshopper densities (means and SE averaged over the three sites with highest densities) showed that densities have varied more than five-fold among years, with highest biomass following years of high creekbank *Spartina* biomass. We hypothesize that vigorous growth of creekbank *Spartina* in one year leads to high egg production by grasshoppers, leading to high grasshopper population densities the following year. A rigorous analysis of the complete dataset using hierarchical modeling is underway, and we anticipate writing a manuscript based on these data during the 2011-2012 academic year.

Additional animal studies

Pennings and former Ph.D. student C. Ho (Texas A&M) evaluated whether high-latitude plants are better food for herbivores than low-latitude plants by conducting growth experiments in the greenhouse. Preliminary results support this hypothesis, but suggest that the results may vary among feeding guilds. To the extent that superior foods lead to larger body sizes, high-quality plants at high latitudes could be one mechanism behind Bergmann’s rule (animals are larger at high latitudes). A manuscript discussing this idea was published in the American Naturalist (Ho et al. 2010) and attracted considerable media attention. An additional manuscript is in review.

The Pennings lab, with additional funding from NSF, has investigated the roles of top-down and bottom-up factors in producing geographic variation in salt marsh arthropod communities. In general, the work has found that geographic variation in plant quality is less important in determining herbivore population size than are local variation in plant quality and geographic variation in predation pressure. This work has produced a paper in Ecology (Marczak et al. 2011), a paper submitted to Ecography (McCall and Pennings in review) and a paper in the final stages of preparation for Ecosphere (Marczak et al. in prep). Data from a field enclosure experiment are being analyzed (Wieski et al.). Finally, Pennings and Silliman are conducting a synthesis comparing the importance of “marine” and “terrestrial” herbivores on *Spartina* productivity.

Microbes

Current microbial work in GCE-II includes our focus on biogeochemical processes in the water column as described above, our collaboration with SIMO (http://simo.marsci.uga.edu/), and studies of microbial food webs and decomposition processes. This past year, M. Booth (UGAMI) completed an analysis comparing microbial diversity in all three domains of life at four of the GCE sites from samples collected as part of the NSF-funded MIRADA I project led by L. Amaral-Zettler (MBL); a paper on these results is near completion. She is currently using supplemental funds to analyze a subset of archived DNA samples collected during GCE cruises over a 14 month period to evaluate temporal trends in bacterial diversity in the GCE domain. Pyrosequencing analysis has been completed and annotation of the sequences is currently underway using MBL's newly refurbished sequencing analysis computational pipeline.

J.T. Hollibaugh (UGA) also continues his collaboration with the SIMO project to evaluate the dynamics of ammonia-oxidizing organisms, predominantly ammonia-oxidizing archaea (AOA), in the GCE domain. He is currently conducting sampling to evaluate ammonia oxidizer abundance in the Duplin River/Doboy Sound. This study continues ongoing work on this topic by Hollibaugh and collaborator J. Caffrey (UWF) funded by the Chemical Oceanography program of NSF.

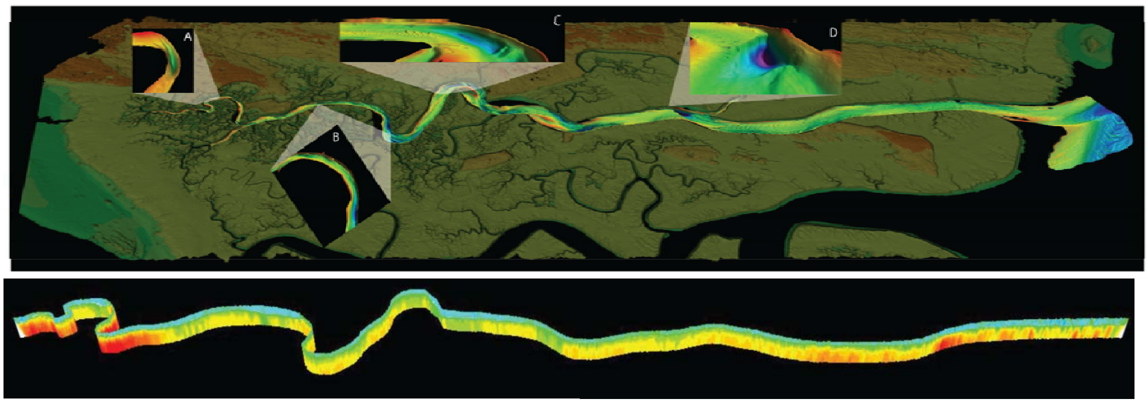
Duplin River estuary

The Duplin River estuary represents a core focus of our efforts to produce an integrated understanding of both water and marsh processes in estuaries. We are working to develop a detailed spatial understanding of the system that will allow us to address the interactions between the estuarine water and the extensive intertidal areas that surround it.

Hydrological studies

In 2009, ROA funding was used to support the collection of high-resolution multibeam bathymetry data throughout the Duplin River and a small area in Doboy Sound. This past year, a follow-up effort was conducted to expand the chart from the confluence of the Duplin River and Doboy Sound eastward to the Atlantic Ocean. In addition, an initial effort was made to characterize groundwater pathways and discharge magnitudes into the Duplin River and Intracoastal Waterway (within the GCE domain) from adjacent uplands. The groundwater characterization included continuous electrical resistivity profiling (CRP) to examine the electrical structure of the sub-bottom sediments and continuous radon-222 measurements to determine spatial and temporal variability in groundwater discharged to the Duplin River. The CRP method is sensitive to pore fluid salinity, thus providing insight into the distribution of relatively fresher and saltier saturation zones in the shallow aquifer system.

Results from the initial groundwater characterization are tantalizing and suggest unique geological controls on discharge hotspots (Figure 7, top and middle). Specifically, elevated radon values correspond spatially with bathymetric scours found along the eastern edge of the Duplin River. This spatial relationship suggests enhanced discharge occurs in areas of recently eroded marsh where sandier, sub-marsh aquifer is exposed along the edges of the river channel. Localized zones of enhanced discharge identified via the 222-radon method, however, do not necessarily imply freshwater discharge. Variability in pore fluid salinity is better detected with the CRP method. During this spring tide sampling, elevated resistivity values (possibly suggesting relatively fresher pore waters) were detected in the aquifer matrix at the head and mouth areas of the Duplin River, but not immediately in the vicinity of the high radon scours (Figure 7, bottom).



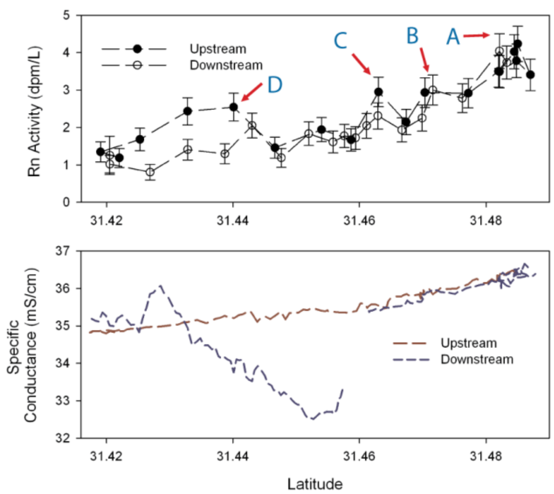


Figure 7. (top) Integrated multibeam bathymetry and Lidar data of the Duplin River and surrounding marsh, with inset showing detailed bathymetric views at locations A-D. (middle) Radon measurements along the Duplin River show hotspots in radon activity at locations A-D. (bottom) Electrical resistivity profile along the Duplin River shows relatively fresher pore fluids (red colors) at the headwaters and mouth.

The fact that such scours on the western (landward) edge of the Duplin River do not have higher radon levels has led us to speculate about the primary driving forces of groundwater inputs to this system. We hypothesize that relative water level differences resulting from a time lag in tidal propagation between the Atlantic Ocean and Duplin River set up a hydraulic scenario whereby ocean waters are driven through the aquifers of Sapelo Island toward the Duplin River. During certain stages in the tide, hydraulic forces allow this ‘groundwater’ to discharge into the Duplin through low points in the river where confining muds have been eroded by scouring.

R.Viso (CCU) attended the GCE annual meeting in January to present the initial results of this effort, along with R. Cash (CCU undergraduate), who presented a poster.

Groundwater

W. Porubsky (UGA Ph.D. student, Joye), C. Meile (UGA), and W. Moore (USC) used a combination of field measurements, laboratory experiments, and model simulations to characterize groundwater biogeochemical dynamics along a shallow monitoring well transect on Moses Hammock, on the Duplin River. They found that a switch in the redox status of the DIN pool in the well at the upland/saltmarsh interface occurred over the spring-neap tidal transition: the DIN pool was dominated by nitrate during spring tide and by ammonium during neap tide. A density-dependent reaction-transport model was used to investigate the relative importance of individual processes to the observed N redox switch. Modeling results suggest that the variation in inflow water chemistry was the dominant driver of DIN dynamics and highlight the importance of spring-neap tide variations in the high marsh, which influences groundwater biogeochemistry at the marsh-upland transition. This work was published in Biogeochemistry (Porubsky et al. 2010).

C. Schutte (UGA Ph.D. student, Joye) is using a combination of laboratory experiments and field observations to further investigate the biogeochemical dynamics of groundwater in this system. Sediment collected in the shallow mud layer near well 217, which is located in the marsh adjacent to the upland at Moses Hammock, showed measurable rates of denitrification only, whereas sediment from the deeper sand layer had positive rates of both nitrification and denitrification, indicating a possible coupling between the two processes that can result in the removal of fixed nitrogen from the aquifer. Shifting redox conditions are critical to this coupling, as denitrification is a facultatively anaerobic process while nitrification is an aerobic process. Dissolved oxygen concentrations in wells at Moses Hammock revealed substantial variation on the timescale of days to weeks (Figure 8). These shifts co-occur with changes in nutrient concentrations and likely affect the rates of subsurface biogeochemical processes. Work is continuing at both Moses Hammock and Cabretta Island to evaluate the influence of tides on aquifer biogeochemical processes across a range of coastal environments.

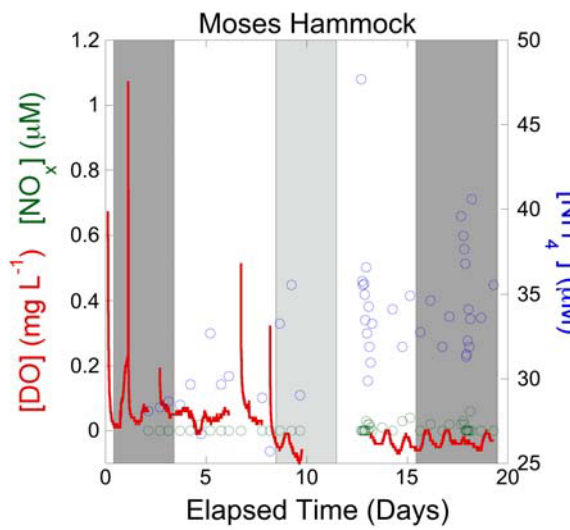


Figure 8. Time series of dissolved oxygen, oxidized DIN (NO_x), and reduced DIN (NH_4^+) at groundwater well 217 at Moses Hammock. Dark gray areas indicate spring tides and light gray indicates neap tides.

Water column observations

Extensive work has been done on understanding the physical processes within the Duplin River system and the spatial and temporal variability in the chemistry of the water. In an analysis of the nutrient concentrations measured in the Duplin River in comparison to those in Doboy Sound, Schutte and Meile found that spatial patterns are apparent and likely driven by the relative influences of marsh runoff and invading Doboy Sound waters. They found that concentrations of dissolved organic matter (carbon, nitrogen, and phosphorus) are consistently higher in the upper

Duplin than they are in Doboy Sound, potentially indicating a marsh source. Particulate materials have higher concentrations in Doboy Sound than in the upper Duplin, suggesting a stronger downstream rather than marsh influence. Some temporal patterns on the time scale of spring/neap and semidiurnal tidal cycles exist in the data, but they are complicated by seasonality and the strong influence of Altamaha River discharge. We are now working to synthesize these data in order to achieve a deeper understanding of how this saltmarsh/tidal creek system functions at a watershed scale.

This past year, J. Schalles (Creighton) and two students (J. Olley (M.S.) and J. O'Donnell (undergraduate)) collected high-resolution, spatially explicit measurements of chlorophyll and other algal pigments in the Duplin River. Initial analyses support earlier findings of the importance of algal exports from marsh surfaces into tributaries (Figure 9). This work was undertaken as a demonstration project, and was largely supported by leveraged funding to Schalles from the NOAA-Environmental Cooperative Science Center.

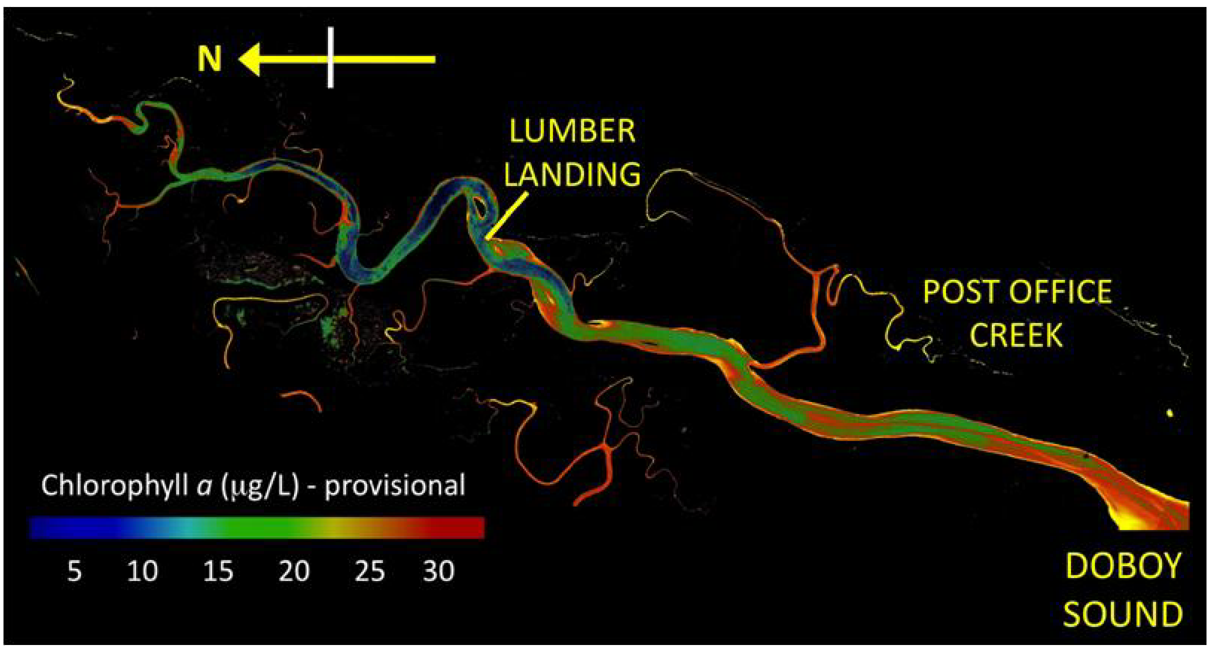


Figure 9. Surface chlorophyll *a* concentrations in the Duplin River, based on June 2006 AISA Eagle flightline. Provisional data from the Creighton Geospatial Laboratory.

Remote sensing

C. Hladik (UGA Ph.D. student, Alber) continued her work to characterize the patterns of marsh plant distribution in the salt marshes in relation to elevation based on a LIDAR-derived DEM for the salt marshes surrounding Sapelo Island. She found that LIDAR offsets for different cover classes ranged from 0.03 to 0.25 m in comparison to RTK GPS ground truth data, with the larger offsets for taller vegetation. Modification of the LIDAR-derived DEM to account for these differences greatly improved the accuracy of the LIDAR DEM (Figure 10). This work has been written up and submitted to Remote Sensing of the Environment. Now that this effort is complete, Hladik is working to combine these results with vegetation classification obtained from hyperspectral imagery to develop a corrected DEM for the entire watershed.

Schalles continued work with Hladik and Pennings to synthesize information collected from the June 2006 AISA hyperspectral flyover and ground truth survey, with an emphasis on comparing plant community composition and plant above-ground biomass in Duplin River sub-watersheds. They were able to extend this analysis to soil properties (percent organic matter, percent moisture, and salinity) within the sub-watershed units as well as the densities of three major marsh invertebrate populations (*Littoraria*, *Melampus*, and *Geukensia*). New sub-watershed mapping products of the above parameters will be included in a manuscript, which is now in preparation.

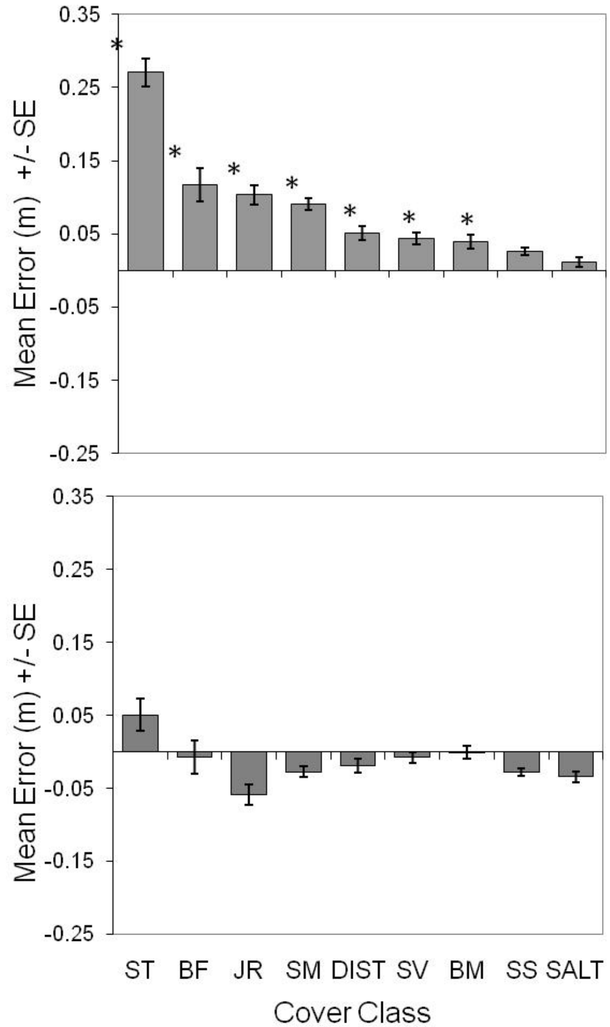


Figure 10. LIDAR-derived DEM elevations for each cover class before (top) and after (bottom) correction. Bars represent mean errors in meters (m) +/- standard error. Asterisks (*) above bars indicate significant differences ($p < 0.005$) from paired t-tests between the RTK GPS elevations and the predicted DEM elevations for each cover class. Cover class abbreviations are: ST: tall *S. alterniflora*; BF: *B. frutescens*; JR: *J. roemerianus*; SM: medium *S. alterniflora*; DIST: *D. spicata*; SV: *S. virginica*; BM: *B. maritima*; SS: short *S. alterniflora*; and SALT: salt pan.

Flux tower

We are in the process of setting up a flux tower that will be used to monitor CO_2, H_2O and heat fluxes between the intertidal marsh and the atmosphere based on eddy covariance methodology. The flux tower, along with other meteorological sensors, will be used to understand the processes that influence ecosystem-level carbon exchange between a *S. alterniflora*-dominated salt marsh and the atmosphere. The planned system is similar to that being used at other coastal LTER sites (including FCE, VCR, and PIE) and will enable us to collaborate and compare our results across the network of LTER sites. This past year, we identified a location for the micrometeorology station along the Duplin River and conducted surveys of the terrain using RTK GPS data for comparison to the DEM data (Figure 11). This site has some unique advantages in that it is relatively far to the upland forest (in dark red) and it has an isolated creek off the Duplin River where detailed studies of the carbon, water, and energy budgets can be made between the marsh and the creek itself. We plan to erect the tower at the lab in order to test the equipment this coming fall while we pursue the appropriate permits for construction at the site.

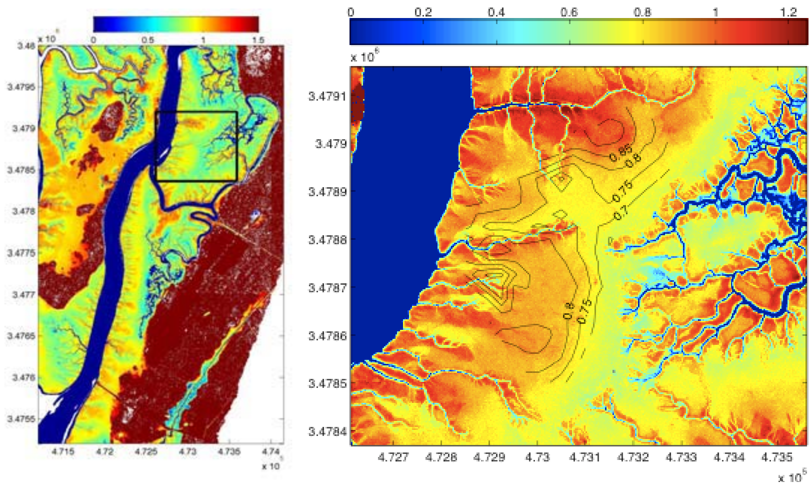


Figure11. (left) The lower Duplin River with box indicating the general location of the flux tower. (right) An expanded view of the flux tower location. Elevation contours (m) are from an RTK GPS survey of the marsh.

Q3: What are the underlying mechanisms by which the freshwater-saltwater gradient drives ecosystem change along the longitudinal axis of an estuary?

The data collected to answer GCE-II Question 1 (external forcing to the domain) and Question 2 (patterns within the domain) can be used to describe the longitudinal salinity gradient of the estuary over time and space, and to examine how well salinity correlates with observed patterns in ecosystem processes. Both sea level rise and the resultant saltwater intrusion, as well as the potential for altered precipitation regimes and increased human demand for freshwater, have the potential to alter the freshwater-saltwater gradient along estuaries. To predict how future changes in salinity distributions might affect the ecosystem, it is necessary to understand the mechanisms that drive these estuarine response to changes in salinity. In particular, we are interested in evaluating the effect of saltwater intrusion into tidal freshwater wetlands.

SALTEX

Previous laboratory and modeling studies by GCE researchers indicate that sea level rise will impact both the area and distribution of tidal freshwater wetlands on the Georgia coast and therefore the ecosystem services they provide (Weston et al. 2006; Craft et al. 2009; Jun and Craft in review; Marton and Craft in review). Although these studies provide baseline predictions of the impact of saltwater intrusion on tidal freshwater wetlands, they do not address the complex interactions of physical and biotic drivers observed in the field.

Craft and E. Herbert (IU Ph.D. student, Craft) are preparing to investigate the effects of saltwater intrusion on a tidal freshwater wetland on the Altamaha River in a field experiment, the Saltwater Addition Long Term Experiment (SALTEX), designed to mimic saltwater intrusion by artificially elevating pore water salinity. They have selected a study site at Champney Island in the Altamaha River Waterfowl Management Area and have secured permission from the DNR land manager and received the requisite Georgia Revocable License from the DNR Coastal Resources Division. A Preconstruction Notification under Nationwide Permit 5 is now under review by the US Army Corps of Engineers, Savannah District. GCE has also hired a full time technician (J. Manley) to oversee project management.

This past summer, the SALTEX team tested irrigation and shallow well delivery methods in small plots (0.1 m^2) at the field site and demonstrated that we can raise porewater salinity to 2-8 for several weeks The next phase of the project involves a pilot study to elevate pore water salinity and test saltwater delivery methods to 2x2 m plots. Seawater will be transported from Meridian, GA, diluted with Altamaha River water to a salinity of 10-15, and pumped into the experimental plots for a final soil pore water salinity of 6 throughout the top 40 cm of soil (rooting depth). When we have determined the most effective and least intrusive method for saltwater delivery via the pilot study, we will establish a long-term (4-6 y) fully replicated study. We will amend 6 large (3x3m) plots in the wetland with chronic (press) doses of low concentrations of saltwater to simulate long-term sea level rise and 6 plots with pulse doses of saltwater to simulate drought conditions. Six additional plots will receive equivalent amounts of freshwater as a control. The plan is to measure changes in vegetation, fauna, soil processes, greenhouse gas emissions, and nutrient and carbon cycling in these plots.

Additional studies

We have conducted several other projects that address the general issue of variation along the estuary. Craft, Pennings and Joye received leveraged funding from an EPA grant to examine how ecosystem services vary among tidal fresh, brackish and marine marshes. As part of this, Pennings, H. Guo (UH PhD student, Pennings) and Wieski examined factors creating plant community structure along the estuarine salinity gradient. They sampled plant biomass and diversity at replicate fresh, brackish and marine tidal marshes on the Satilla, Altamaha, and Ogeechee rivers. An overview of the results of this collaborative project were published in Frontiers in Ecology and the Environment (Craft et al. 2009), and a more detailed manuscript describing vegetation patterns was published in Estuaries and Coasts (Wieski et al. 2010).

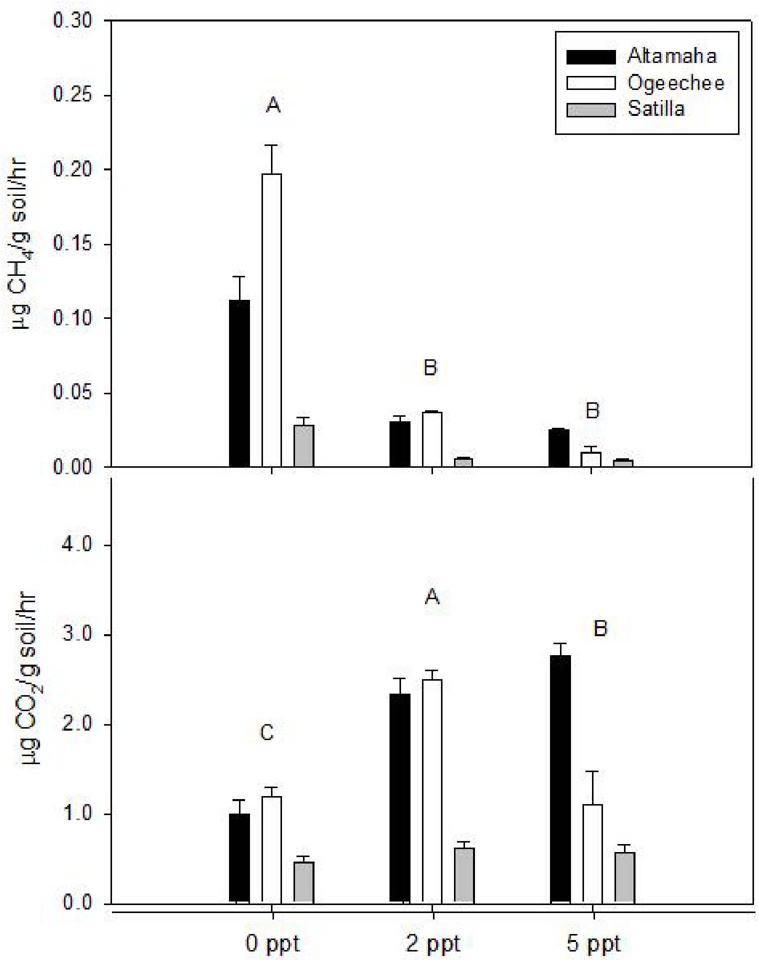


Figure 12. (top) CH_4 and (bottom) CO_2 production rates (mean ± standard error) in the three different salinity treatments. Different capital letters represent differences in production based on the Ryan-Einot-Gabriel-Welsch test ($\alpha = 0.05$). (Marton and Craft submitted)

Craft also received funding from the US DOE (National Institute for Climatic Change Research Program) to evaluate how saltwater intrusion might affect N and P cycling in tidal forests. In one experiment, the salinities of soils collected from the tidal freshwater floodplain forests in the upstream portions of three Georgia estuaries were incubated at salinities of 0, 2, and 5. Increasing salinity led to a decrease in CH_4 emissions but a concurrent increase in CO_2 emissions (Figure 12). The increase in CO_2 emissions was attributed, in part, to increased sulfate reduction based on increased production of acid volatile sulfate (AVS) in incubated cores; AVS was highly correlated with increased CO_2 production in the Altamaha and Satilla rivers ($R^2 = 0.89$, $p < 0.0001$). There was no consistent effect of increased salinity on N_2O emissions, which were two to three times lower than CO_2 and CH_4. The study concluded that the overall net effect of increasing salinity is to reduce the global warming potential of tidal freshwater forested soils due to the decline in CH_4 emissions (Marton and Craft submitted).

Q4: What are the underlying mechanisms by which proximity of marshes to upland habitat drives ecosystem change along lateral gradients in the intertidal zone?

Our approach to this question involves taking advantage of marsh hammocks as natural laboratories for evaluating the influences of landscape structure and freshwater input on marsh processes. This portion of the program is under the direction of Alber and Alexander, with involvement from co-PIs Pennings, Joye, Burd, Meile, Moore, and V. Thompson (OSU).

Hammock survey

In 2007 we surveyed 55 hammocks representing a range of sizes and origins. Wieski is using structural equation modeling (SEM) to evaluate the relationships among upland characteristics (e.g., area, age, grain size, maximum elevation) and the high marsh (e.g., area, plot height, slope, plant composition). His initial analyses suggest that hammock area and maximum elevation are well-related to the area and slope of the high marsh, which in turn relates to pore water salinity and plant composition. He is currently working with Alexander and Alber to refine these analyses.

Intensive hammock research

In 2008 two hammocks were selected for detailed study: HNi1 is west of and adjacent to Blackbeard Island to the north of Sapelo Island, and PCi29 is adjacent to the south end of Sapelo Island. These hammocks are of similar size, with similar vegetation zones in the high marsh. This past year, Alexander collected samples for optically stimulated luminescence (OSL) dating from HNi1 and Blackbeard Island to complement the OSL dates that have already been obtained for PCi29.

The two study hammocks each have a series of groundwater wells that run in a transect from the nearby upland (Blackbeard and Sapelo Islands, respectively), through the marsh, and up and over each hammock to the marsh adjacent to the sound (Sapelo and Doboy, respectively). We have been measuring pressure, salinity, and temperature with loggers in these wells since 2008. The data from all of these loggers are now available through the GCE catalog. J. LeDoux (UGA Ph.D. student, Meile) is in the process of using this information to evaluate groundwater flow underneath the hammocks. This past July, Alexander also installed a rainfall/temperature/soil moisture logger system that will record data at three soil depths (25, 50 and 75 cm) to start to examine the water retention and migration of rainfall within hammock environments.

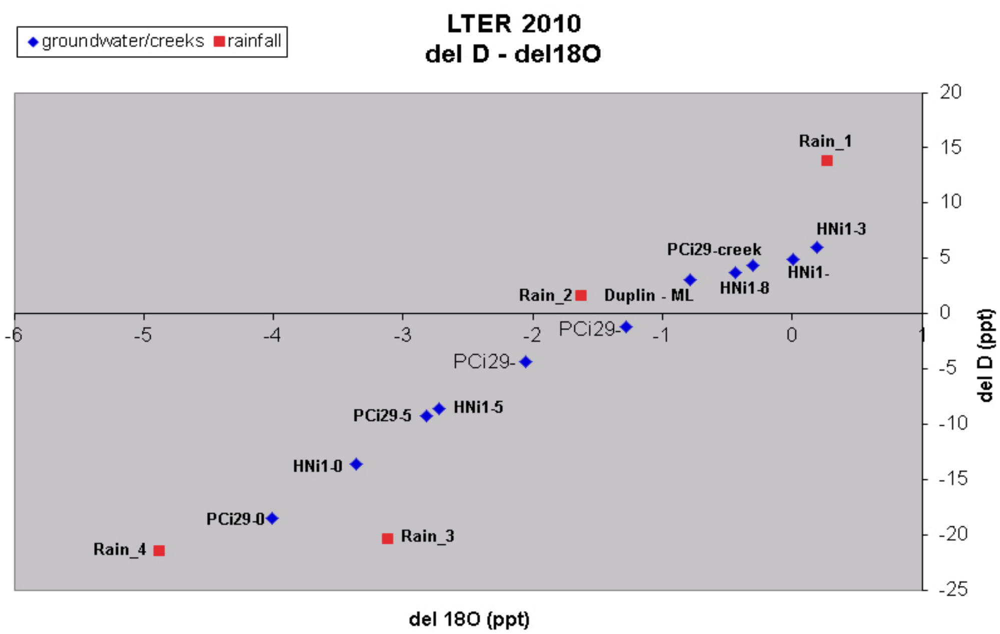


Figure13. ^{18}O and deuterium concentrations in groundwater samples taken from well transects on hammocks HNi1 and PCi29 (blue), along with values measured in rainfall (red).

Alexander is collaborating with J. Brandes (SkIO) to measure oxygen and hydrogen isotopes of water samples collected from wells, creeks, and rainfall near the two study hammocks to determine if these tracers can help us separate the major sources of water to the upland and marsh plants. A plot of these data (Figure 13) indicates that there is good separation among the various wells. We plan to collect water from the root zone and vascular tissues to continue this study in the coming year.

Plant modeling

To investigate how changes in the relative amounts of groundwater and sub-surface flow affect plant species growth and competition, Y. Jung (UGA PhD student, Burd) is developing a plant model to evaluate primary production and growth of salt marsh plants. The model will involve explicit descriptions of plant below- and above-ground biomass of *Spartina*, *Juncus* and *Borrichia*, with particular attention to rooting depth (since that will affect pore water availability and quality). The biomass models will be driven primarily by irradiance within the canopy, salinity, and sediment nutrient availability. Competition between the species will be based upon salt tolerance and light competition.

Groundwater modeling

Meile and M. Hagens (Utrecht University Ph.D. student) used a reactive transport model to describe tidally driven flow and solute dynamics across a marsh cross-section. As part of this effort, porewater residence times were computed to identify zones of rapid fluid exchange. Model simulations suggest the presence of circulation hotspots at the creek bank and the upland-marsh transition zone, with intensity varying over a tidal cycle. The location of these regions and magnitude of rapid fluid exchange depend on the tidal amplitude and on the presence or absence of terrestrial groundwater input from the upland. The introduction of oxygenated creek water to the marsh subsurface also promotes biogeochemical reactions and hence may be important for regulating the marsh's filter function. Reaction hotspots are located at the interfaces between chemically distinct water bodies such as upland-derived groundwater and the intruding tidal creek water. As a result, reaction hotspots can develop at the fringes of circulation hotspots, but are not identical to the locations of highest infiltration. This work was presented at the 2011 Georgia Water Resources Conference.

In a related project (supported by GA Sea Grant), Meile and Joye used a transport model to evaluate the role of septic systems as potential nitrogen (N) sources to coastal open water bodies in McIntosh County, GA and examined factors governing the mitigation of septic N loading in coastal groundwater. They found that the removal of bioavailable nitrogen via denitrification may be increased by increasing the septic system setback distance, in particular in brackish and saline coastal settings where sulfide produced in sulfate reduction can limit N_2 production.

Archeological studies

Thompson continues to explore coupled human-environmental dynamics of the Georgia coast in relation to resources and the health of past populations. This has involved using stable isotopes to assess the exploitation of shellfish resources. Thompson has also begun tracking health of populations via the development of a new bioarchaeological database of skeletal remains from the Georgia coast, which includes information on trauma, pathologies, and changing subsistence. These data sets will be articulated with our ongoing research regarding human settlement and use of the barrier and back-barrier islands in the context of large-scale environmental changes, such as sea level rise. Thompson also works with J. Turck (UGA PhD student) and Alexander to carry out collaborative studies of human use of the landscape in relation to geologic development. A paper that used vibracore analysis to evaluate the unique stratigraphy under Pleistocene hammocks (stiff Pleistocene clays that form the platform on which the hammocks developed) and the rapid colonization of landforms as they developed over the past 2000 years is now in review.

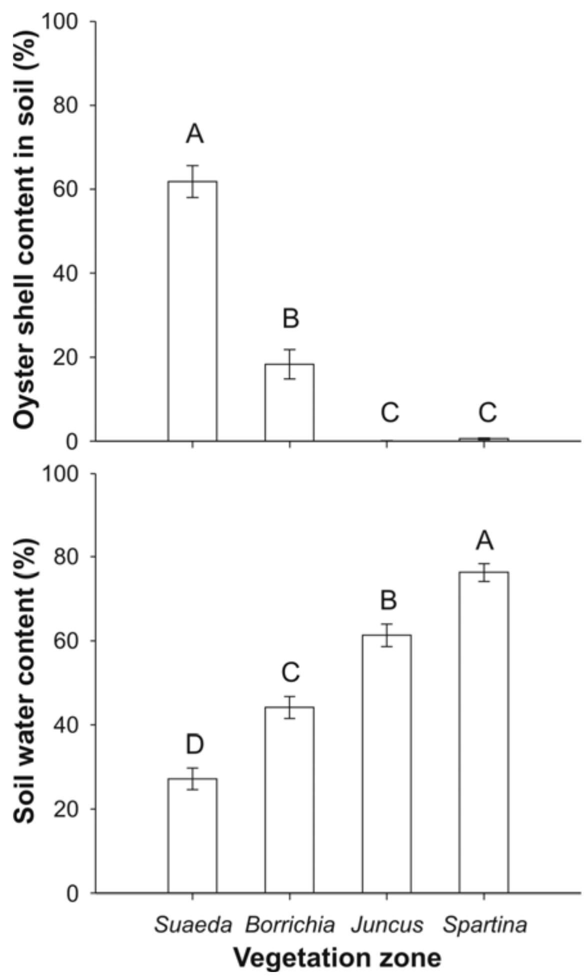


Figure 14. Percentage of oyster shells (top) and water (bottom) of soils found in areas dominated by different marsh plants.

One of the consequences of the shellfish middens left by Native Americans is that they can affect soil chemistry and, potentially, plant distribution. This past year, Guo and Pennings completed a study on the distribution of the saltmarsh annual *Suaeda maritima* (Figure 14), which is strongly associated with oyster deposits in the soil. Oyster shell habitat is physically stressful and provides a refuge for *Suaeda* from competition from other marsh plants. A manuscript based on this work is in review at Oecologia.

Q5: What is the relative importance of larval transport versus the conditions of the adult environment in determining community and genetic structure across both the longitudinal and lateral gradients of the estuarine landscape?

We have documented a variety of distribution patterns of different plant and invertebrate species across the GCE domain. Some of the variation in population densities is likely driven by longitudinal and lateral gradients in the estuarine environment (Questions 3 and 4). However, population density may also be affected by transport mechanisms and larval shadows that affect larval delivery, habitat suitability for adults, and competition. We are using a combination of recruitment studies, transplant studies, and genetic approaches to begin to understand these patterns. This portion of the program is led by Pennings in conjunction with Silliman, J. Wares (UGA), and Bishop.

Mechanisms explaining plant distributions

Guo and Pennings have conducted a series of transplant experiments to explain patterns of vegetation composition in the GCE domain (see above, Q3). Their results indicate that the freshwater plants were excluded from saltier sites by physical stress (they died with or without neighbors), and that the intensity of competition increased at less saline sites, excluding salt marsh species. There were hints of facilitation of some plant species by background vegetation at the saltiest sites. Their results suggest that salinity and plant-plant interactions are the primary drivers of vegetation pattern along the estuarine salinity gradient. A number of differences between these results and similar previous studies suggest that previous studies have been too simple in design (too few sites or too few study species) to fully explain the vegetation patterns. A manuscript based on this work is in press at Ecology.

Mechanisms explaining animal distributions

The Silliman lab continued their studies of the relative effects of habitat quality, larval transport, and predation in governing invertebrate densities across the GCE domain. They did this by: 1) assessing recruitment rates using integrative methods and assessing adult densities using quadrats of all major marsh invertebrates at all sites (2008-2010); 2) transplanting low densities of tethered periwinkle snails, ribbed mussels, and mud snails (n=4 cages per site with 5 animals of each species in each paired uncaged and caged area) across this gradient both with and without predator/competitor access (2009-2010); and 3) employing a multiple regression study design to compare separate and combined effects of recruitment rates and predation rates as assessed by tethering all invertebrates at all sites (n= 40 animals/ site/ zone) (2009-2010) . This work will be written up and submitted for publication to Ecology in spring of 2012.

In addition, the Pennings laboratory is investigating the distribution of grasshoppers across the estuarine landscape. Marsh grasshoppers tend to be abundant at marsh sites near upland habitats, but rare at marsh sites far away from uplands. A growth experiment in the summer of 2010 ruled out the possibility that this pattern was caused by variation in plant quality that affected grasshopper growth or survival. We plan to conduct future research to test additional hypotheses that could explain this distribution pattern.

Program Management

GCE administration

Day-to-day program administration is shared by Alber and Pennings, with support from the GCE Executive Committee. Program management involves submitting supplementary proposals, overseeing the core budget (including setting up subcontracts, approving purchase orders, travel, etc.), taking care of routine reporting, supervising core program personnel, and writing letters of support for collaborative projects. Pennings also continued his administrative duties related to field efforts, including supervising field technicians at Sapelo Island and overseeing repair and maintenance of boats and field instruments.

The GCE bylaws call for an election of the PI and Executive Committee for year 5 of the funding cycle, in order to make a smooth transition to the next phase of the program. At this year's annual meeting, which was held January 2011 at UGA, we elected Alber to remain as Lead PI for GCE-III, and we elected Pennings, Di Iorio, Craft, and Burd to serve on the Executive Committee W. Sheldon also serves on the committee, as a function of his role as IM for the program. The annual meeting was attended by the following members of our scientific advisory committee: Jane Caffrey (UWF), Iris Anderson (VIMS/VCR), and Cathy Pringle (UGA). George Jackson (TAMU), Wim Kimmerer (SFSU) and Mark Hay (Georgia Tech) were unable to attend the meeting but continue to serve on the committee.

LTER network activities

As detailed below, GCE scientists are actively collaborating on cross-site comparisons and are involved in network planning and governance.

- GCE hosted the LTER Science Council Meeting at Jekyll Island in May 2011. Many GCE scientists participated in the field trip as well as a poster reception held as part of the program. Alber and Pennings represented GCE at the meeting.
- Pennings is a member of an LTER cross-site synthesis group examining whether the traits of plant species can predict different responses by different taxa in fertilization experiments. This work will enhance our ability to predict the impacts of anthropogenic inputs of nitrogen into natural systems. The group has published five manuscripts based on this work, one in PNAS, one in Ecology Letters, two in Ecology and one in Oikos. They have another manuscript in review and several more in preparation.
- Alber hosted Katherine Ewel at the GCE field site on a site visit conducted as part of the LTER 30-year review. W. Sheldon and Silliman also met with committee members.
- Schmidt represented GCE at a network-wide meeting of the LTER "Maps and Locals" initiative in Fairbanks, AK in October 2010 and is helping the group put together a manuscript.
- Alber was an invited participant at the LTER Children's Book workshop at Univ. of Colorado and gave a talk about the upcoming GCE book, "And the Tide Comes In."
- Hollibaugh participated in a PAL-LTER cruise this past year and actively participates in their activities.

- Alexander is working with D. Rachal, a student at the Jornada LTER, by analyzing sediment samples for short- and long-lived radionuclide activities (^{7}Be, ^{234}Th, ^{228}Th, ^{210}Pb, ^{137}Cs, ^{40}K and ^{238}U). The distribution of these radionuclides will be used to determine erosion, accumulation, and sediment sources in various desert environments.
- Craft collaborated with R. Jaffe and M. Zwilling (FCE) to collect samples to characterize DOC along the salinity gradient of the Altamaha River.

We also have a strong network presence in terms of information management, through the activities of W. Sheldon and T. Douce (UGA). Over the past year, GCE IM staff served the network in the following capacities:

- Sheldon concluded his term as co-chair of the LTER Network Information System Advisory Committee in 2011 after 4.5 years of service.
- Sheldon co-chairs a web services working group to define standards and best practices for deploying this technology in LTER. This group met at LNO in 2011 to develop a new database, XML exchange schema, and web services to upgrade the LTER personnel database.
- Sheldon served on an LTER NIS Tiger Team, helping LNO software developers design and test web services for running analytical workflows using data stored in the PASTA framework; a workshop to develop best practice guidelines for writing PASTA workflows is planned for winter 2012.
- Sheldon provided database design and programming support to SBC and MCR sites, which are adopting GCE technology for their data management programs.
- Douce participates in the LTERMapS working group, which is developing GIS standards and tools for the LTER network and sites.
- Sheldon and Douce are working closely with the IM program at CWT, providing GCE bibliography, metadata, and research project databases and helping to modify them for CWT use; providing web application hosting to leverage GCE-developed web applications and web services for the new CWT web site; and providing near-real-time USGS streamflow data harvesting, including automated plots and metadata generation for 8 stations.
- GCE continues to host the USGS Data Harvesting Service for HydroDB (see http://gce-lter.marsci.uga.edu/public/im/tools/usgs_harvester.htm). Data from 85 USGS stream flow gauging stations are automatically harvested on a weekly basis for 12 LTER sites (AND, BES, CAP, CWT, FCE, GCE, KBS, KNZ, LUQ, NTL, PIE, SBC) and one USFS site.

Information Management

Overview

Information Management for the GCE program is led by W. Sheldon; Douce assists Sheldon and also serves as our GIS specialist. A major focus of Information Management effort during the past year has been redesigning our core information system to support broader classes of research data as well as new LTER network initiatives (e.g., controlled keyword vocabulary, NIS workflow execution, EML congruency checks). Notably, these changes were done in close collaboration with IM teams at three other LTER sites (CWT, SBC, MCR) that are currently leveraging or adapting GCE database designs and applications. To facilitate broader sharing of technology developed at GCE, we also began releasing all data management software developed by the GCE program under a GPL open source license and established software distribution web sites linked to our Subversion code repository for downloading code and submitting bug reports. We also developed a comprehensive research registration, permitting, and tracking system for Sapelo Island, which we expect will be leveraged by our research partners on the island (Sapelo Island NERR, Georgia DNR and the UGA Marine Institute) over the coming year.

IT infrastructure

We currently operate three production servers to support GCE research and operations, including a general database server, a web application server, and an enterprise geodatabase server. We also operate an additional server to support GCE software development and provide web-based access to software source code and XML data. All servers are equipped with RAID-5 hard drive configurations and uninterruptible power supplies to provide fault tolerance; utilize secure transport protocols for off-site access; and are backed up daily to disk and weekly to tape to protect against data loss. We currently have approximately 6 TB of secure disk storage available for GCE use at UGA, in addition to 2 TB of hard disk storage on Sapelo Island. We purchased a 14-slot LTO-3 tape autoloader this year to improve our backup efficiency, which increases our near-line storage capacity by approximately 10 TB.

We also manage five high performance workstations to support core GCE information management activities as well as several field computers. We provide database client software and ArcGIS software and licenses to GCE investigators, staff, students, and affiliates in the Dept. of Marine Sciences at UGA and the UGA Marine Institute on Sapelo Island to support working with data in relational and GIS databases and general GIS analyses.

Spatial data management and GIS

The primary focus of spatial data management activities during 2010 was automating routine GIS operations and improving ties between tabular environmental data and geospatial information managed in our information system. We used supplemental NSF funding received in 2010 to develop a Python-based geospatial software library that bridges between ESRI GIS tools (e.g., ArcGIS and ArcSDE), relational databases (e.g., SQL Server), and file-based data (e.g., CSV text files). This software allows us to generate distributable GIS products on demand, such as shapefiles and Google Earth KML files, for all GCE data sets and to provide links to these resources through the GCE Data Catalog (http://gce-lter.marsci.uga.edu/public/app/data_catalog.asp) and in EML metadata. GIS feature classes can also be registered in the ArcSDE geodatabase by parsing information from tabular data files (e.g., CSV text) and Google Earth KML files, which greatly simplifies registering new data in ArcSDE for GIS analysis. We are currently developing code for bi-directional synchronization of metadata content between ESRI GIS files and the GCE metadata database to further improve our capacity to distribute EML-described GIS products.

We continue to provide mapping and geo-analytical support for all GCE projects, maintain the ArcSDE server, edit content for GIS-based web pages, manage spatial data for GCE personnel use, post-process all GPS data, and create reference maps of study sites for GCE publications and presentations. General GIS files are distributed in various formats through the GCE file archive (http://gce-lter.marsci.uga.edu/public/app/resource_search.asp).

Website development

This year we added new web pages to the public website describing major GCE research findings (http://gce-lter.marsci.uga.edu/public/research/research_bullets.htm), with prominent links on both the home page and research overview page (Figure 15). These vignettes were developed in concert with other LTER sites to help showcase major research findings resulting from long-term ecological research. These pages will be updated as new high-impact findings and publications are identified, and replicated on new web pages being developed for the LTER Network web site.

We also developed a comprehensive web-based application for permitting and tracking research activities on Sapelo Island. Research guidelines and application forms were created in collaboration with the Sapelo Island National Estuarine Research Reserve (SINERR) and UGA Marine Institute (UGAMI) (http://gce-lter.marsci.uga.edu/public/site/research_requests.htm). To support this activity, we designed a relational database and dynamic web forms for submitting, reviewing, and approving research applications and generating printable field tags for display at the research site (Figure 16). Supporting information can be uploaded and attached to applications, including GPS data, maps, documents, reports, and photographs. GIS maps describing all research activities, organized by PI and study characteristics, are being developed to provide site managers from GCE, SINERR, and UGAMI information they need to manage sites, mitigate research conflicts and prevent unnecessary environmental damage. This database will also be a critical resource for investigators as they plan their field research and seek

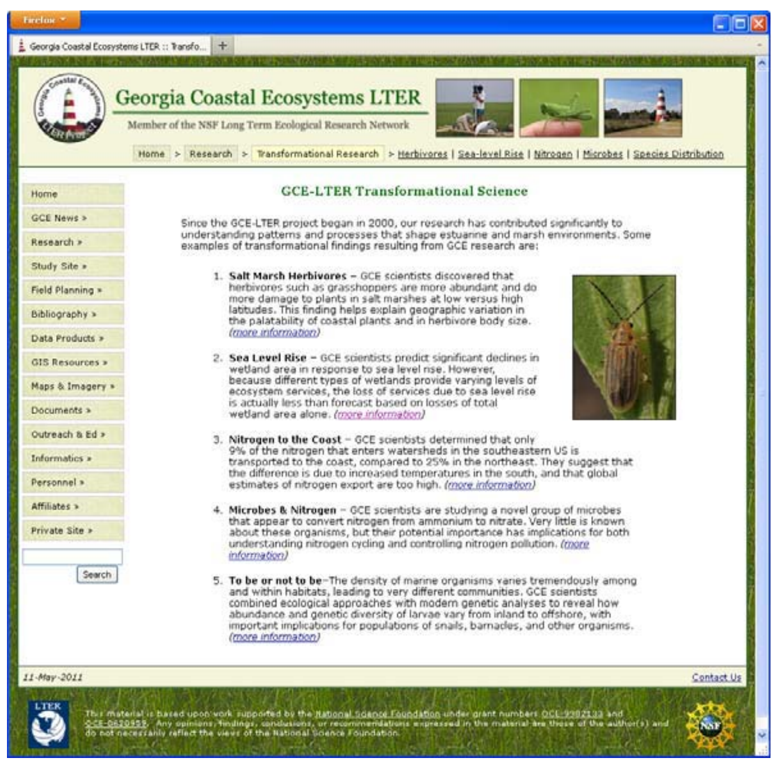


Figure 15. GCE-LTER Transformational Science web page, with links to research vignettes.

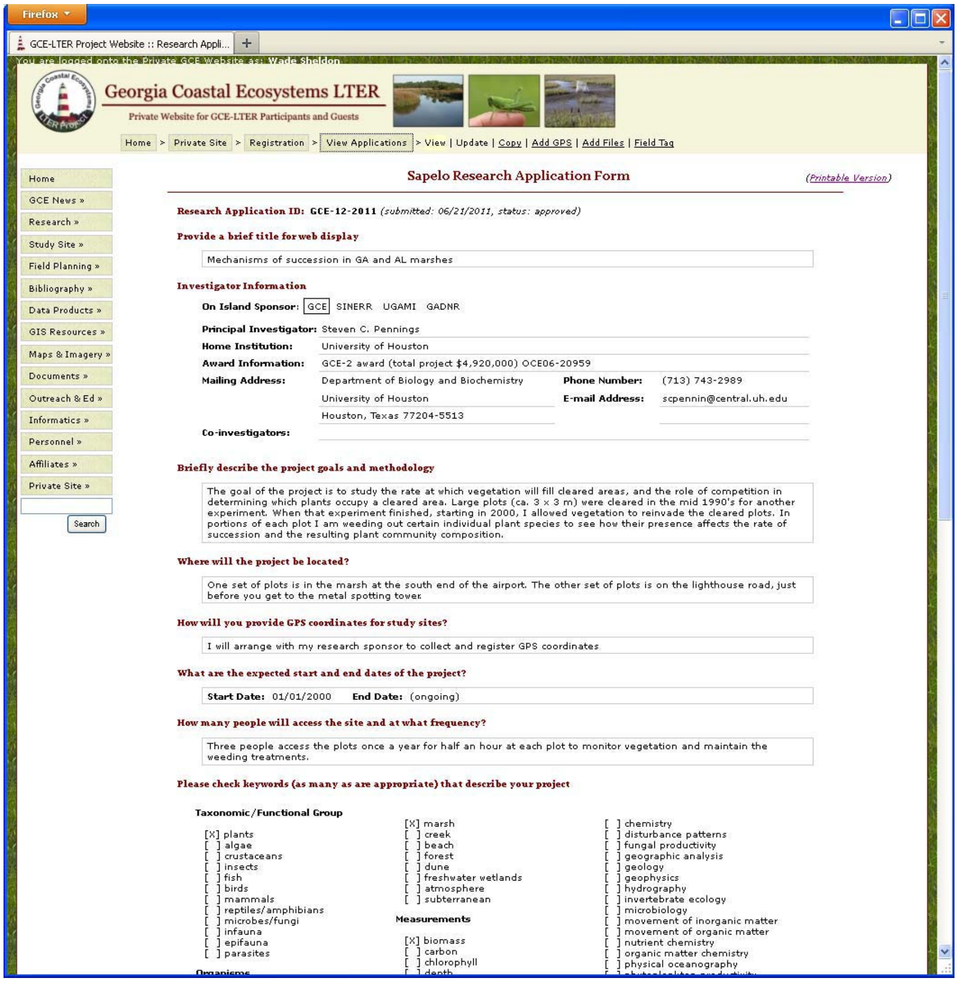


Figure 16. Web page view of an approved Sapelo research application, with links to download a printable version and generate field tags for display at the research site.

data for synthesis projects in the future, and for program leaders and IM staff as they track research progress and data submissions. Applications are currently limited to GCE-affiliated investigators, but work will begin in fall 2011 to open up the application to SINERR- and UGAMI-sponsored investigators as well.

Web site and data access statistics

Public downloads of GCE data sets from Fall 2001 to Fall 2011 are summarized in Table 1. Since January 2001, nearly 2 million GCE web pages have been viewed by more than 580,000 visitors from 227 distinct countries and territories (based on web log analysis and DNS resolution). Over the past year, approximately 5000 visitors viewed 15-35,000 web pages each month (excluding malicious requests and hits from web indexing spiders). Following the home page, the file archive, species list, personnel directory, bibliography, and EML metadata pages were the most popular pages requested in 2010-2011. Table 1 shows website activity broken down by data set theme and user affiliation. We observed a substantial increase in overall data requests in 2011 (1048 total), particularly requests originating from the LTER Data Catalog and Metacat. Downloads by GCE participants are not currently tracked, due to open data access policies within the program.

Table 1. GCE data downloads summarized annually by data set theme and by user affiliation.

Annual Data Downloads by Theme												
Theme	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**All**
Algal Productivity	0	0	0	0	1	13	9	13	1	6	12	55
Bacterial Productivity	0	0	4	15	36	16	39	115	12	24	41	302
Chemistry	0	0	0	0	6	2	8	5	2	6	8	37
Fungal Productivity	0	2	1	1	13	1	3	4	3	9	7	44
Geology	0	0	0	0	0	2	18	6	5	8	7	46
GIS Analysis	0	0	0	0	0	0	0	0	0	0	8	8
Hydrography	0	0	0	0	4	6	5	11	1	4	9	40
Invertebrate Ecology	0	0	12	137	110	94	101	122	20	102	109	807
Meteorology	12	27	8	20	22	13	31	47	37	16	17	250
Multi-Disciplinary Study	0	0	0	0	0	0	0	0	2	1	4	7
Nutrient Chemistry	0	7	5	8	31	11	8	20	20	42	27	179
Organic Matter	0	5	1	13	17	12	27	66	17	22	23	203
Physical Oceanography	0	2	2	54	322	128	83	244	94	235	437	1601
Phytoplankton Productivity	0	0	1	17	42	20	8	57	3	29	21	198
Plant Ecology	0	13	9	19	97	28	29	65	48	40	42	390
Pore-water Chemistry	0	0	0	2	8	4	5	3	3	1	4	30
Real-time Climate	0	0	0	4	78	29	64	55	59	82	56	427
Terrestrial Insect Ecology	4	7	3	12	15	27	29	40	22	54	215	428
Various (custom file)	0	0	0	0	1	5	12	7	15	6	1	47
All Themes	**16**	**63**	**46**	**302**	**803**	**411**	**479**	**880**	**364**	**687**	**1048**	**5099**

Annual Data Downloads by Affiliation												
Affiliation	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**All**
Academic Research	5	26	19	46	168	118	206	230	126	215	104	1263
Educational (College)	4	12	1	50	129	65	114	66	30	30	91	592
Educational (K-12)	0	7	2	0	36	5	3	15	9	15	0	92
Environmental Advocacy	0	1	0	0	0	3	2	0	1	0	0	7
Government Agency	6	1	0	19	210	26	10	3	70	13	14	372
International LTER Site	0	0	0	2	1	1	4	0	0	0	2	10
Metacat Network	0	0	2	148	166	131	115	421	87	371	762	2203
Other LTER Site	1	12	16	10	29	29	5	41	17	11	9	180
Other/Unspecified	0	4	6	27	64	33	20	104	24	32	66	380
All Affiliations	**16**	**63**	**46**	**302**	**803**	**411**	**479**	**880**	**364**	**687**	**1048**	**5099**

Software development

We have continued to enhance the GCE Data Toolbox for MATLAB software and offer this toolbox for public download on our web site (http://gce-lter.marsci.uga.edu/public/im/tools/data_toolbox.htm) and on the LTER Information Management web site (http://intranet.lternet.edu/im/project/gce_toolbox). In 2010 we established a dedicated software development web site for this toolbox (https://gce-svn.marsci.uga.edu/trac/GCE_Toolbox) to provide web-based SVN access, project tracking, support tickets, and a Wiki for producing documentation. Beginning in October 2010, we began releasing the source code for this toolbox to the scientific community under a GPLv3 open source license and added additional documentation and tutorials on the web site. Approximately 3000 web visitors have registered and downloaded this software to date.

The GCE Data Toolbox software can now be used to mine data from the NOAA National Climatic Data Center directly over the Internet, in addition to data from the USGS National Water Information System, LTER ClimDB/HydroDB, and NOAA Hydro-meteorological Automated Data System, then resample and integrate data to produce derived data products with structured metadata. This software is therefore useful for a broad range of data synthesis tasks beyond primary data processing. The GCE Data Toolbox has been adopted by the CWT-LTER program for processing data from their new synoptic monitoring program. Other LTER sites (e.g., MCR, NTL, NWT, PIE, SBC, SEV and VCR) have also expressed interest in using this software for managing sensor data, and W. Sheldon is scheduled to provide demonstrations of its use at both the Environmental Information Management Conference in September 2011 and an LTER sensor data workshop at HBR in October 2011.

Database Development

This year we collaborated with information managers from CWT, SBC, and MCR to revise the GCE metadata database model (GCE_Metabase) to support multi-table data sets, non-tabular data (e.g., GIS, remote sensing, and genomics data), and LTER controlled keyword and attribute name vocabularies that are under development. The new database model (GCE_Metabase2) is now fully implemented at GCE, and NSF supplement funding was used to update the GCE Data Toolbox software and EML implementation to support this new model. These upgrades allowed us to add new geospatial data sets to the GCE Data Catalog, which are also accessible through the LTER data catalog, KNB Metacat, and NBII metadata clearinghouse.

Support for LTER network science and synthesis

We fully participate in all LTER Network Information System modules, including the all-site bibliography, Data Catalog (Metacat), personnel directory, and SiteDB, as well as new initiatives such as ProjectDB (for archiving information about LTER research projects) and EcoTrends. The GCE Information System natively supports all LTER standards and protocols, and we have implemented automatic harvesting and synchronization where supported by the LTER Network Office (e.g., EML metadata and bibliographic information). We have contributed all available data from 7 long-term climate stations and 6 streamflow stations to ClimDB/HydroDB. Additionally, we used GCE data processing technology to develop an automated USGS data harvesting service, allowing 12 LTER sites and 1 USFS site to contribute streamflow data to HydroDB on a weekly basis without additional effort (http://gce-lter.marsci.uga.edu/public/im/tools/usgs_harvester.htm).

This past year, W. Sheldon co-chaired an LTER IM Committee working group to design web services to improve interoperability of LTER network databases and site information systems. He participated in a workshop in February 2011 to develop a new database and web services for managing personnel information in LTER to replace the outmoded database currently used by LNO. A new database structure, XML schema for data exchange, and prototype web services are currently being tested. In addition to modernizing the design of this critical network database, the new system will allow LTER sites to programmatically synchronize personnel updates to the

LTER personnel database and manage personnel information at LNO while still providing a searchable roster on their own local web sites, which are long-standing needs identified by LTER sites.

As mentioned above, we collaborated with information managers from CWT, SBC, MCR, and other sites to revise the GCE metadata database model (GCE_Metabase) to support multi-table data sets, GIS data, and LTER controlled keyword and attribute name vocabularies. CWT has now implemented the GCE_Metabase as well as the GCE bibliographic database (GCE_Biblio), and we are providing web application hosting and web services to support web-based access to their database on their newly redesigned web site (http://coweeta.uga.edu/news/2011_04_19_new_site). SBC, MRC, and several other LTER sites are interested in using the GCE_Metabase as a starting point for a network-wide metadata model, and we continue to support these efforts. W. Sheldon also provided remote training for SEV scientists and IM staff on using the GCE Data Toolbox software to process and provide quality control for eddy flux tower data, and provided support to NTL IM staff writing a proposal to leverage this toolbox for analyzing streaming buoy data managed using DataTurbine. In addition, IMs from seven LTER sites have requested training on getting started with this software for managing sensor data, and a workshop at UGA is tentatively scheduled for 2012 to meet this need.

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