GCE Annual Report Research Findings
September 2009

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 project 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 ocean (e.g. wave climate, sea level), and by those of the atmosphere (e.g. temperature, precipitation). Each of these external forcing functions is expected to experience substantial changes over the coming decades due to factors such as climate change, sea level rise, and human alterations of the landscape. The GCE project collects data on local climate (temperature, precipitation, wind speed and direction), on watershed characteristics, and on the water chemistry of the tributaries that discharge into the Altamaha River.

Climate signals
We continue to collaborate with the Sapelo Island National Estuarine Research Reserve and USGS National Water Information System to maintain comprehensive climate and hydrographic monitoring stations on Sapelo Island (Marsh Landing) and the Georgia mainland (Hudson Creek at Meridian Landing), with near-real-time data telemetry. W. Sheldon (UGA) has developed programs to automatically harvest data on an hourly basis and display weekly weather plots and daily tide predictions for Sapelo on the GCE web site home page to provide current information about site conditions. Both near-real-time and historic data and plots from these and other relevant climate stations are also publicly accessible on the GCE Data Portal website (http://gce-lter.marsci.uga.edu/portal/monitoring.htm).

At the site level, A. Burd (UGA) and J. Sheldon (UGA) continue their work to evaluate variability in freshwater delivery to the GCE domain in relation to various climate indices: the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO) and the Bermuda High Index (BHI). This past year, they completed a project that compared monthly standardized...
anomalies of river discharge and climate indices to multi-decadal time series of Altamaha watershed precipitation. They used empirical orthogonal function (EOF) analysis to describe the precipitation patterns at 7-13 stations. The first EOF mode (65% of the variance) was spatially uniform with temporal variability at the monthly scale. The second mode (11% of the variance) showed a spatial gradient along the long axis of the watershed (NW-SE) whereas the third mode (6% of the variance) showed an onshore-offshore pattern with higher variability during June-September. There were no consistent relationships between NAO and precipitation. The SOI showed correlations with discharge and weak correlations with modes 1 and 2 of the precipitation. The BHI is correlated with May-January discharge with a 0-1 month lag, and is also strongly correlated with EOF mode 1 of precipitation. These results were presented at the 2009 LTER All Scientists Meeting and will be presented at the upcoming Coastal and Estuarine Research Federation (CERF) conference in November 2009.

At a broader scale, M. Alber (UGA) has been involved in a network-level effort to evaluate the effects of climate change on coastal systems. The LTER provides a network of coastal sites that differ in their biophysical vulnerability to various aspects of climate change, with some being more affected by sea level rise and storm surge (e.g. VCR, FCE) and others by acidification (e.g. MCR), loss of sea ice (e.g. PAL), changes in temperature (e.g. CCE), or changes in freshwater inflow (e.g. PIE, GCE). Coastal LTER sites also differ in their gradients of human vulnerability, with differences arising from coastal population densities and demographic compositions (e.g. FCE vs. VCR) and also from the location and resilience of their built infrastructure (e.g. BES vs. SBC). Alber and C. Hopkinson (UGA) led a working group at the 2009 Science Council meeting in May 2009 to discuss these issues, and have put together a prospectus describing our approach to the question of how human and natural templates interact to affect vulnerability to climate change. Alber also gave talks on coastal climate effects at both the NSF LTER mini-symposium in February 2009 and the Science Council meeting.

**Watershed inputs**

G. Kaufman (M.S. student, UGA) and Alber have completed an estimate of nitrogen inputs to the Altamaha River estuary using a combination of observations and literature values. Sources of nitrogen examined were atmospheric deposition, downstream advection of river water, flux from the marshes, flux from the subtidal sediments, and upstream tidal mixing of ocean water. Overall nitrogen input to the Altamaha River estuary is strongly dominated by riverine loading, which accounts for 95% of the input. Approximately 60% of the input is organic material, which is primarily dissolved. This work was done in preparation for a modeling study to link riverine input of nitrogen to estuarine nitrogen distributions.

The GCE project is also involved in a cross-site initiative (Maps and Locals) led by R. Pontius (PIE), G. Kofinas and N. Sayles (JRN) to use spatial representation of land cover and land use to identify patterns of landscape change in regions in and around LTER sites. Specifically, we are comparing land cover within the GCE domain from 5 time points (1974, 1985, 1991, 2001, and 2005). This analysis will allow us to address several immediate questions: 1. Where and when did landscape changes occur, and at the expense of what type of land? 2. Has the process of land transformation been consistent across more than one time interval? 3. What are the differences in the landscape (and in landscape change) in the different watersheds? 4. Are there associations between landscape change and potential driving variables (e.g. slope, the location of roads and
protected areas)? 5. Can differences in the watersheds be linked to observations in response variables (e.g. estuary nutrient concentration, salt marsh primary production)?

We are particularly interested in the process of development and how that influences the receiving water. For example, an inspection of Figure 1 reveals build-out in the landscape, particularly in the towns of Doctortown and Darien. If we can find a relationship between impervious surface and water quality then we can use that to evaluate the effects of potential future development scenarios.

Figure 1. Landcover in the GCE domain in 1974 and 2005.
River delivery of dissolved and suspended material

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) receives approximately 8 samples per month and has analyzed about 600 samples to date. Samples are analyzed to determine concentrations of dissolved inorganic nutrients (DIN, DIP, and DSi species), dissolved organic nutrients (DOC, DON, and DOP) and total suspended solids. A paper describing temporal variations in concentration, nutrient and dissolved organic matter loading rates, and an evaluation of the watershed evolution over time was published this year (Weston et al. 2009) and another paper on nutrient delivery variability (Hunter and Joye) is in preparation.

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 (see Q1) is manifest as environmental gradients (e.g., in salinity or nutrients) within the coastal landscape. We collect data on physical oceanographic conditions, nutrients and organisms in the water column; groundwater hydrology and biogeochemistry; and intertidal marsh soil, plant, microbial and animal 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

Salinity structure

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, UGA Marine Institute). Data are processed by W. Sheldon and D. Di Iorio (UGA).

This past year, M. Ait Amrouche (undergraduate, U. Toulon, France) worked with Di Iorio on applying empirical orthogonal function (EOF) analysis to the sonde data in order to study salinity variability and the relative influences of freshwater and oceanic inputs across the GCE domain. (GCE 7 was excluded because it is almost always fresh water and GCE 1 was excluded because it responds primarily to rainfall). For the remaining 6 sites they found that the first EOF mode explains 85.6% of the variability and the second mode an additional 8.7%. The temporal variability for the first mode is negatively correlated with river discharge, with time lags increasing from 1-3 d to 6-8 d as one moves from Altamaha to Doboy and Sapelo Sounds, respectively (Figure 2). The coherence shows that variability over yearly time scales dominates. For the second mode there is a correlation with sea surface height (SSH) but there is a phase difference between the sounds: In the Altamaha River, salinity increases when SSH increases, whereas for Doboy and Sapelo Sounds, salinity decreases when the SSH increases. For this mode the coherence indicates a more seasonal time scale of variability. Over these seasonal time scales when SSH increases during Nor’easter storms, Altamaha River water may be forced...
through the Intracoastal Waterway or other channels moving freshwater north, or may recirculate back in through the Sounds from the ocean. Further investigation is needed to test this hypothesis.

**Patterns of dissolved and suspended material**

Monthly cruises to monitor surface water quality in the sounds continued during 2008 (Saucedo, Shalack). During the past year, the Joye lab processed 4800 samples from the monitoring
cruises: 496 samples for determination of concentrations of dissolved inorganic nutrients (NO$_2^-$, NO$_3^-$, NH$_4^+$, HPO$_4^{2-}$, and H$_2$SiO$_4^{2-}$) and dissolved organics (DOC, TDN, DON, TDP, and DOP); 1488 chlorophyll $a$ samples; and 1488 total suspended sediment and particulate CN samples. These analyses are in various phases of completion.

As observed in previous years, spatial and temporal variations in biogeochemical parameters among the study sites were significant. The highest NO$_x$ concentrations were present in Altamaha Sound at GCE 7 and 8. Surface and bottom NO$_x$ concentrations were comparable at all the stations. At all of the study sites, concentrations of dissolved organic nitrogen equaled (Altamaha stations) or exceeded (all others) concentrations of dissolved inorganic nitrogen. Ammonium concentrations were highest in Doboy Sound, followed by Sapelo and Altamaha Sounds. Concentrations of dissolved organic phosphorus were comparable to concentrations of dissolved inorganic phosphorus at all stations during all samplings; no depth variation in phosphorus availability was observed. As noted in previous years, DOC concentrations were highest in Sapelo Sound, followed by Doboy and Altamaha Sounds.

**Microbial Dynamics**

Starting in July 2008, M. Booth (UGAMI) has collected bacterioplankton samples during GCE cruises for analysis of bacterial cell numbers, leucine incorporation, and viral numbers. Samples for extraction of bacterial DNA and RNA were also collected and stored for later processing. We have also received supplement funds to conduct a survey of prokaryotic and small eukaryotic (<5 µm) diversity over 1-2 annual cycles to determine whether prokaryotic and/or eukaryotic diversity vary spatially and temporally within the GCE domain, and if they are related to one or more biotic or abiotic factors. Microbial prokaryotes and eukaryotes will be sampled at four sites concurrent with the GCE sampling routine over 12 months. The ribosomal RNA genes will be sequenced using high-throughput sequencing technology, e.g. 454 pyrosequencing.

**Groundwater inputs**

The groundwater wells within the GCE domain (Moses Hammock, Visitor Center) are sampled quarterly (April, July, October and January) by the Joye lab, but most of our efforts have concentrated on groundwater inputs to Moses Hammock, where wells are located across a

Figure 3. The Moses Hammock transect. Black rectangles represent approximate relative well locations and depths and are labeled with their respective well ID numbers. The black circles represent locations where sediment samples were collected.
gradient from the freshwater upland, across the upland-marsh transition, and into the ringing marsh (Figure 3). The well field captures the transition from freshwater to saltwater in the aquifer; the redox interface lies between these wells and physical exchange between the upland and marsh is modulated in this area by a strong gradient in hydraulic conductivity. A minimum in permeability is located in this area, which generates an amplification/focusing effect as the aquifer is forced by pressure variations resulting from tidal (diurnal and spring-neap) variations. Concentrations of many redox metabolites, including DOC, NH₄, H₂S, Fe, and DON, vary substantially across the well field (Figure 4). The degradation of dissolved organic nitrogen is enhanced during neap tides, and there is evidence for nitrification (accumulation of nitrate) during neap tide as well.

Marshes

Soil processes

We continue to 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. Under the direction of C. Craft (IU), we 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. Results from 6+ years of data collection indicate no clear trends in marsh surface elevation across the ten core sites of the GCE domain.

Figure 4. Comparison of redox metabolites in wells at Moses Hammock at spring and neap tides for April 2002 through April 2009. (left) DON, (center) NH₄, (right) NO₃.

Figure 5. Marsh surface elevation changes at GCE 6 since 2001. Timing of salt marsh dieback and recovery noted with arrows.
The SET at GCE 6, which was installed in 2001, is in an area that experienced marsh dieback. At the height of the dieback (2004), the plot was completely bare and the marsh surface elevation had decreased by 20 mm relative to the pre-dieback elevation (Figure 5). By 2006 vegetation began to re-colonize the site, and by 2008 the surface recovered to its pre-disturbance elevation.

**Plant dynamics**

S. Pennings (UH) and his lab continue to 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 (especially in low-marsh plots), local rainfall (especially in high-marsh plots), and average sea level. In 2000 they set up permanent plots at all 10 GCE monitoring sites. Plots were established at creekbank and mid-marsh zones (8 plots/zone/site). Most sites are dominated by *Spartina alterniflora*, but some zones at some sites are dominated by *Juncus roemerianus*, *Spartina cynosuroides*, or *Zizaniopsis miliacea*. An additional set of high marsh *Juncus* plots was established at site 10 in 2005 to increase replication of sites dominated by *Juncus*. Plants have been non-destructively monitored (stem counts, heights, flowering status) in October of every year since 2000.

A preliminary analysis of data for *S. alterniflora* (means and SE averaged over sites dominated by *S. alterniflora*) from 2000-2006 shows that end-of-year biomass in creekbank plots varied more than two-fold among years (Figure 6). The two years with highest biomass (2003 and 2005) were years with high discharge from the Altamaha River during the spring months, which reduced water column salinities and provided superior growing conditions. End-of-year biomass in the mid-marsh plots varied slightly less than two-fold among years and did not vary in synchrony with biomass in the creekbank plots (in particular, mid-marsh plots showed no peak in biomass in 2003, Figure 6). Variation in biomass in mid-marsh plots is likely driven by variation in sea level and local precipitation, rather than Altamaha River discharge. A rigorous analysis of these data leading to a publication will be conducted once several more years of data have been collected.

These plots are also proving useful in documenting spatial and temporal variation in disturbance from physical (floating dead plant material called wrack) and biotic sources. Wrack disturbance is high in creekbank plots at some sites and low in mid-marsh plots. Biotic damage from snail grazing and pig digging is high in some mid-marsh plots at some sites. (Disturbed plots were omitted from above analyses of annual variation in biomass).

In a separate set of plots, Pennings is testing the hypothesis that annual variation in high-marsh plant species composition is driven by variation in rainfall. Salt marsh vegetation often consists of discrete stands with abrupt borders between different species or associations. Pennings has monitored mid-summer plant composition at permanent plots located on 3 types of vegetation borders (*Spartina alterniflora-Juncus roemerianus*, *S. alterniflora*-meadow, meadow-*Juncus*...
roemerianus), at two sites each, since 1996. Vegetation composition in these plots is dynamic and appears to be related to variation in rainfall, although more years of data will be needed to test this hypothesis rigorously.

Finally, Pennings is conducting parallel experiments in GA and AL to examine 1) how rapidly marsh vegetation can recover from disturbance, and 2) the role of competition in secondary succession. In 3 vegetation zones (Spartina alterniflora-meadow border, meadow-Juncus roemerianus border, J. roemerianus zone) at each of 2 marshes in each state, replicate 3 x 3 m plots were cleared using herbicide and clipping and maintained free of vegetation for 2 years. Control plots were marked but unmanipulated. In 2000, individual plots were divided into halves or quadrants, depending on the diversity of the vegetation in each zone, with one section allowed to recover without further manipulation and the other section(s) treated by periodically removing 1 or 2 dominant plant species occurring in each zone. To date, succession has been fastest in plots on the Spartina alterniflora-meadow border, 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.

**Animal Dynamics**

Fall annual monitoring of animal populations in the salt marsh continued this year. One of the striking patterns since monitoring began in 2000 is that densities of the periwinkle snail, Littoraria irrorata, are lower in the Altamaha than in the other sounds. This may be a result of the inability of larvae to recruit upstream, or else reduced survival of the new recruits. Another striking pattern is that snail densities are higher at barrier island sites (GCE 3, 6, 9) than at mainland sites on the same estuaries (GCE 1, 4 and 7). We are currently investigating mechanisms creating these patterns (see Q5).

In addition, Pennings and his lab collect 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) from 2000 through 2006 shows that densities have varied more than five-fold among years (Figure 7, top). The two years with highest biomass (2004 and 2006)
followed years (2003 and 2005) of high creekbank Spartina biomass. More generally, there is a strong trend (P=0.07) for grasshopper densities to be correlated with the previous year’s biomass of creekbank Spartina (Figure 7, middle); this trend is driven by two “bumper years” in plant biomass followed by years with high grasshopper populations. 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 these data leading to a publication will be conducted once several more years of data have been collected.

An analysis of spatial variation in grasshopper densities (means and SE averaged over years) from 2001-2008 found that densities (all species combined) differed more than ten-fold among sites (Figure 7, bottom). Grasshoppers were common on barrier island sites, moderately abundant at mainland sites, and almost absent at mid-estuary sites. Several mechanisms might explain these spatial patterns in grasshopper population density, and experiments to address these hypotheses are planned (see Q5).

This past year, B. Silliman (UF) and his lab conducted a one-time survey of densities of mud snails and ribbed mussels at all GCE sites. (Our routine monitoring protocol does not include mud snails and samples ribbed mussels poorly.) Densities of these two species roughly mirrored each other: Both were rare at some sites (7, 8, 9), present at others (2, 3, 4, 5, 6) and most abundant at site 10. Both species also displayed a highly patchy distribution. These data provided a good baseline for long-term monitoring and shed insight into the patchy nature of the animals, but lacked sufficient replication to rigorously test whether there was a pattern in densities across the barrier island – mid-estuary – mainland gradient. To assess this possibility, we will enumerate densities of these species and the other dominant marsh invertebrates in a highly replicated transect with 8 barrier island marshes, 8 mid-estuary marshes, and 8 mainland marshes. Sampling is planned for fall 2009.

We are also conducting short-term studies of animal dynamics. Graduate students C. Ho and J. Jimenez (both Ph.D. students at UH), in collaboration with Pennings, are investigating top-down and bottom-up control of arthropod food webs. It is generally believed that the diverse and reticulate interactions promoted by omnivory will tend to reduce strong trophic cascades. In both laboratory and field experiments, however, Ho found that an omnivorous crab suppressed both predator and herbivore populations on the shrub Iva frutescens, releasing plants from herbivore pressure and promoting plant performance. Ho graduated in 2008, and a manuscript based on this work was published in Ecology in 2008. A similar experiment, but focusing on the arthropod food web of Spartina alterniflora, was conducted by Jimenez, who graduated in 2009. A publication based on Jimenez’s work is planned in the near future.

At a larger spatial scale, Pennings is also working with Ho to evaluate 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 is in press at the American Naturalist.
J. Nifong (MS student, UF) and Silliman are working on a project to assess population densities of the American alligator on Sapelo Island. They have found that alligators spend significant time feeding and moving in marine waters and can be abundant in marsh creeks with full strength salt water (Table 1). T-tests (P<0.05) revealed three categories of alligator density: high (Oakdale), low (Factory, Blackbeard to Cabretta, Duplin), and medium (all others). They hypothesize that alligators cope with osmotic stress by moving every week or two into freshwater to drink and rest, and then move back into marine waters to feed. Nifong and Silliman plan to sample alligator density across the entire domain and use isotopic data to better understand their feeding habits and role in the marsh food web.

**Duplin River estuary**

The Duplin River estuary continues to be a core focus of our efforts to produce an integrated understanding of both water and marsh processes in estuaries. The 12.5 km tidal inlet is part of the Sapelo Island National Estuarine Research Reserve and at the geographic center of the GCE domain. It represents a defined “tidal-shed” in which we can couple water column and marsh processes at a spatial scale that is more manageable than our entire study system. Our efforts this past year have focused on obtaining and analyzing remote sensing data collected for the area.

**Remote sensing**

We obtained aerial, hyperspectral AISA imagery ([http://calmit.unl.edu/champ/](http://calmit.unl.edu/champ/)) for the Duplin River watershed in June 2006. This past year, C. Hladik (Ph.D. student, UGA) worked with J. Schalles (Creighton) to classify two of the flight lines using both the Maximum Likelihood Classification (MLC) and Spectral Angle Mapper (SAM) supervised classification algorithms in Environment for Visualization Images (ENVI). The following salt marsh plant classes were used in the classification based on ground data obtained in 2006 and 2007: *Batis maritima*, *Borrichia frutescens*, *Salicornia virginica*, *Spartina alterniflora* (short, medium and tall forms) and *Juncus roemerianus*. Nonvegetated cover classes (mud, creek bank, salt pan) were also included. The best overall classification accuracies for the two flight lines were 75% and 66% and were obtained using the MLC algorithm after a land and water mask had been applied. The classes most often confused were short and medium *Spartina*, short *Spartina* and *Salicornia*, and short *Spartina* and mud. Continued improvement of the classification is planned using advanced hyperspectral procedures and analysis of training data. A paper on this effort is currently in preparation. Hladik will also present this work at the CERF conference in Fall 2009.

The GCE project contracted with the National Center for Airborne Laser Swath Mapping (NCALM) to acquire LIDAR data for both the Duplin River and Blackbeard Island in March 2009 (Figure 8). NCALM processed and filtered the data to produce a Digital Elevation Model (DEM) with vegetation removed (bare earth interpolated from the last return) and a canopy DEM (from the first return). Approximate vertical and horizontal accuracies of the geolocated laser

<table>
<thead>
<tr>
<th>Creek Name</th>
<th>Alligators km⁻¹</th>
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<tr>
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</tr>
<tr>
<td>Southend Creek</td>
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<tr>
<td>Oakdale Creek</td>
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<tr>
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<td>Post Office Creek</td>
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<tr>
<td>Factory Creek</td>
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<tr>
<td>Cabretta Creek</td>
<td>1.19</td>
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<tr>
<td>Blackbeard Creek NW END</td>
<td>1.36</td>
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<tr>
<td>Blackbeard Creek S to Cabretta</td>
<td>0.25</td>
</tr>
<tr>
<td>Duplin River</td>
<td>0.43</td>
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return points are 7-10 cm and 20-30 cm, respectively. In order to enhance this data set, C. Alexander (SKIO) is working to classify the LIDAR intensity data, which is part of the data return that is not used to obtain elevation, and to evaluate the correlations between intensity and the physical and biological characteristics of the study area (e.g. LIDAR elevation data, National Wetland Inventory plant classifications, observations that can be obtained from aerial imagery, such as the presence of manmade structures). This work will advance the field as the interpretation of LIDAR intensity data in these types of applications is currently the subject of on-going research by scientific users of LIDAR data.

Hladik is currently in the process of performing an accuracy assessment of the LIDAR and DEM models. In summer and fall 2009, she worked with C. Connor (undergraduate, UGA) and K. Anstead (UGAMI technician) to do a field survey of marsh platform elevation using a Real Time Kinematic (RTK) GPS. At least 100 ground LIDAR points were selected and surveyed for each of the major vegetation classes found in these marshes (S. alterniflora, J. roemerianus, S. patens, Batis maritima, Salicornia virginica, and Borrichia frutescens) as well as nonvegetated classes (mud, creekbank, salt pan). In addition to the RTK data, a preliminary sampling of vegetation characteristics (plant composition, height, percent cover and density) were done to groundtruth the imagery, with more planned for the upcoming year. LIDAR and RTK data will be analyzed using ArcGIS (version 9.3, ESRI) and ENVI (version 4.5, ITT Visual Information Solutions) software packages. Once this is complete, Hladik will be in a position to use the LIDAR information on elevation in conjunction with the hyperspectral information on plant species to model the relationship between observed salt marsh species distributions and potential controlling factors, including elevation, proximity to tidal creeks, and proximity to uplands.

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

To predict how future changes in salinity distributions might affect the ecosystem, it is necessary to understand the mechanisms that drive these patterns. In particular, we are interested in separating the effects of salt from that of sulfate on ecosystem processes, given that these factors
are correlated across the estuarine gradient. This portion of the project is under the direction of Joye, with involvement from co-PIs Pennings, Craft, C. Meile (UGA), and Alber.

In 2009 we hired a technician to manage this portion of the project. In summer 2010 we will set up a field experiment at a freshwater site along the Altamaha River about 30 km from the ocean (in the vicinity of GCE 7). The experiment will consist of four treatments (control, salinity-amended, sulfate-amended and salinity+sulfate-amended) in which freshwater sediments will be amended with increasing salinity (from 0 to 10) and/or sulfate (proportional increases, from 0 to 9 mM) in an orthogonal design over 12 months. In addition to the field experiment, the effect of short-term variations in substrate concentrations, ionic strength, pH, and H$_2$S on potential rates of nitrification, denitrification, methane oxidation, methanogenesis and sulfate reduction will be evaluated in slurry experiments in the laboratory.

In addition to the core experiment, we are also addressing this question with leveraged funding from an EPA grant (PD: Craft, co-PIs: Pennings and Joye). Pennings, H. Guo (PhD student, UH) and K. Wieski

![Figure 9. Plant species richness in three salinity zones for sites (top) and plots (bottom).](image1)

![Figure 10. Plant height, standing biomass, carbon, nitrogen, and phosphorus in three salinity zones.](image2)
(UH) are examining 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. A total of 109 plant species were found, but 11 species dominated the plant communities. Site-level species richness decreased across the salinity gradient and did not differ among rivers (Sa=11.3, A=13.0, O= 12.2). Plot-level richness showed a similar pattern (Figure 9).

Standing biomass was greatest at brackish sites (Figure 10) and in both brackish and fresh sites tended to decrease away from the creekbank, whereas in the salt marsh sites biomass was greatest in the mid-marsh zones dominated by *Juncus roemerianus* (data not shown). Standing stocks of C, N and P were estimated based on total biomass, the relative abundance of different plant species, and the elemental composition of each plant species. Total carbon stocks paralleled patterns of biomass in that they were greatest at the brackish sites and lowest at the salt marsh sites. Nitrogen stocks decreased across sites as salinity increased and were greatest in the creekbank zone. Phosphorus stocks did not differ between fresh and brackish sites, but were lower at salty sites (Figure 10). An overview of the results of this collaborative project were published in Frontiers in Ecology and the Environment in 2009, and a more detailed manuscript describing vegetation patterns is in review.

In collaboration with Pennings, Guo is also conducting a series of transplant experiments to explain these patterns. This work is described in detail below (Question 5).

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

The GCE project is investigating 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 a natural laboratory for evaluating the influence of landscape structure and freshwater input on marsh processes. The hammock research includes basic characterization of groundwater flow as well as physical and biological characteristics at selected sites, experiments designed to understand the effects of manipulating water flow on marsh processes, and modeling. In 2007 we did a survey of 55 hammocks representing a range of sizes and origin, and these data are still being analyzed. Our activities this past year included processing geological samples; collecting data from instrumented hammocks; and continuing archeological studies. We also continued our analysis of the plant community associated with hammocks and initiated field and greenhouse studies to support our modeling efforts. This portion of the project is under the direction of Alber and Alexander, with involvement from co-PIs Pennings, Joye, Burd, Meile, B. Moore (USC), and V. Thompson (Ohio State).

**Geology**

Geologic characterization of marsh hammocks within the GCE domain, under the direction of Alexander, continued along several fronts in the past year. The Alexander lab completed textural analyses of the hammocks sampled in summer 2007 and showed that there are distinct textural differences between hammocks based on origin. Holocene hammocks contain the greatest amount of sand, followed by Pleistocene hammocks and GCE monitoring sites (as would be
expected from their locations on Pleistocene upland bodies), followed by ballast stone hammocks, which accumulate a wide range of materials from the water column, and lastly, dredge spoil hammocks, which are created from an indiscriminant mixture of flocculant muds and sands rapidly deposited in channels over time. During the last year, we also assessed the textural preferences of the focus salt marsh plants in our study. Results indicate that *Borrichia* prefers sandy sediments (75-95\% sand) with little mud (4-30\%), as is expected from its tendency to grow on the eroding flanks of sandy hammocks and in environments where the texture does not change dramatically with depth. *Juncus* is found in zones of somewhat greater mud content (7-40\%) and in a wider range of sand contents (60-95\%). *Spartina* grows in more variable settings, with a wide range of sand (5-90\%) and mud (7-90\%), suggesting that other factors are more important than sediment type for constraining this species.

Coring throughout the region behind Sapelo Island has revealed that stiff, Pleistocene-aged marsh mud discontinuously underlies many of the Pleistocene hammocks and the open marshes surrounding them. This layer, observed from <1 m to >5 m below the surface, is impermeable and widespread and must have significant impact on the hydrologic pathways both from hammocks to marshes and within marshes as well. This linkage between marsh ecosystems, stratigraphy and hydrology will be pursued in the coming year, and the distribution of this impermeable layer will be mapped with greater detail. To start this process, we have collected transects and targeted cores near Marys Hammock (10 cores), Jacks Hammock (1 core) and PNi12 (e.g., Fishing Hammock, 4 cores). These cores have been subsampled for texture and AMS C-14 where material was available; samples will be analyzed in the coming year.

**Archeological studies**

*J. Turck (Ph.D. student, UGA)* and Alexander used a vibracorer to take six sediment cores from the marsh near one of our study hammocks (Marys Hammock, a Pleistocene hammock on the west side of the Duplin R.) in an attempt to locate former ground surfaces and understand the depositional history of the marsh surrounding the hammock as related to changes in sea level. The cores were split in half, photographed, X-rayed, and visually inspected. Three sets of sediment samples were taken from the cores at 10-cm intervals for stratigraphic and geochemical analyses. Particle size analysis was performed on one set of samples, to locate buried B soil horizons and stratigraphic discontinuities showing breaks in sedimentation. Loss on ignition was performed on the second set of samples to estimate organic matter, which can be used to locate buried A soil horizons. The third set of samples has been saved for a future pollen study.

Thompson and Turck also published a paper on the response of hunter-gatherer groups to changes in sea level and resource distribution. They suggest that, despite major destabilizing forces in the form of sea level lowering and its concomitant effects on resource distribution, cultural systems rebounded to a structural pattern similar to the one expressed prior to environmental disruption. They propose, in part, that the ability for people to return to similar patterns was the result of the high visibility of previous behaviors inscribed on the landscape in the form of shell middens and rings from the period preceding environmental disruption.

Finally, despite a return to similar cultural formulations, hunter-gatherers experienced some fundamental changes resulting in modifications to existing behaviors (e.g., ringed villages) as well as the addition of new ones in the form of burial mound construction. This work was published in the American Antiquity (2009).
Intensive hammock research

In 2008 two hammocks were selected for more detailed study: HNi1 is of Holocene origin and is located west of and adjacent to Blackbeard Island to the north of Sapelo; PCi29 was thought to be of Pleistocene origin and is located adjacent to the south end of Sapelo Island. These two hammocks are of similar size, with similar vegetation zones in the high marsh. We set up transects that run 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) and took cores at each site. Information from the stratigraphic data was used as a guide to install wells across a hydrologically connected sand layer.

The cores from HNi1 generally exhibit profiles consistent with a sand body deposited onto back-barrier marsh by storm processes. A single, continuous marsh deposit, dated by AMS C-14 at about 3500 y BP, underlies HNi1. Sedimentary structures in the cores suggest that energetic forces washed beach sand back onto the marsh, creating a shore-parallel, linear sand body that has been modified over the past few thousand years (see core 5 detail in Figure 11). This Holocene hammock consists of clean medium- to fine-grained sands that contain parallel to cross-bedded laminations. Cores from PCi29, along with AMS C14 and OSL dating, suggest

![Figure 11. Core 5 from Holocene hammock HNi1 west of Blackbeard Island. Panels show stratigraphic interpretation; average grain size; percent sand, silt and clay; photographs; and core location.](image-url)
that this hammock has had a complicated history spanning multiple environments of deposition.

Each hammock has eight wells installed from the upland, across the marsh-upland interface, and into the marsh. Water levels recorded in the wells placed along the transect from Blackbeard over HNi1 and into the marsh show features that suggest significant hydrologic interaction on some timescales and very little at others (Figure 12, top). Tidal signatures are evident in all records; dominant and subordinant tides can be recognized at spring and neap tides for the wells in Spartina and Juncus zones (wells 2, 3, 7 and 8), whereas both daily tides can be identified only at spring tides in Borrichia and upland zones (wells 1, 4, and 5). Large rainfall events are easily recognized in the record, with events on 10, 13 and 25 October creating abrupt increases in well water level.

Salinity recorders are present in 3 of the wells on HNi1 (Figure 12, bottom). Significant freshening in the hammock well (5), where salinities are 13-15, can be observed in comparison to well 4, in the Borrichia zone some tens of meters away and several meters lower in elevation, where salinities are 30-35. Interactions between these closely adjacent wells will form a focus for the coming year.

Monthly monitoring of wells at the two hammocks began in August 2008. It is unclear at this point how hydrologically connected the wells actually are. Chemical constituents are at least an order of magnitude higher in the groundwater than in surface water collected from the sites. Concentrations of dissolved organic carbon (DOC) as high as 15 mM have been observed in the groundwater, and DOC in nearby surface water (~2 mM) exceeds that in open sound water (hundreds of µM). Concentrations of dissolved inorganic nitrogen tend to be dominated by ammonium, which is not surprising since the groundwater is anoxic and sulfidic.
**Plant Community**

In the hammock survey of 2007, we used sub-meter accuracy GPS units to map the hammock upland border and the extent of the upper marsh (from the hammock border to the upper edge of *Spartina alterniflora*, i.e. the marsh “halo”). Plants within the halo were also characterized. Analyses of these observations by Hladik and Alber showed that the area of the high marsh plant community adjacent to the upland area of the hammocks was positively related to hammock area (Figure 13), and was larger in Holocene and Pleistocene hammocks than those of other origins. *Borrichia frutescens* and *Juncus roemerianus* were most often the dominant plants in these areas, but there were differences related to hammock size and origin. This work will be presented at the LTER ASM and the 2009 CERF meeting.

In order to help parameterize the plant model for Burd, Pennings and Anstead collected data on high marsh plant communities and associated soils. In 2009 we collected light profiles and associated data on plant heights and densities in stands of *S. alterniflora*, *J. roemerianus*, and *B. frutescens*. These data will provide information on how stands of different plant species at different densities affect the light environment for other plants (one mechanism of competition among plants). We also collected data on soil porewater content and porewater salinity from stands of the same three plant species. These data will provide information on how the physical environment experienced by each plant species varies over space and time. To determine if plants are in fact rooting in the soils that we are sampling, we collected pre-dawn xylem pressure potential readings on all three species of plants. (In theory, pre-dawn XPP readings are in equilibrium with soil water potentials).

Pennings and Anstead are also conducting a greenhouse experiment to evaluate the sensitivity of three common salt marsh plants, *S. alterniflora*, *J. roemerianus*, and *B. frutescens*, to varying levels of shade (0 to 80% of light blocked) and salinity (0 to 60). Monthly measurements of plant size and photosynthetic rate over the course of the 2009 growing season will help inform the model about how the three plant species respond to competition for light (as simulated by shade cloth) and salinity. This information will also be used in plant modeling efforts.

**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 species across the GCE domain. These include 1) a close correlation with salinity (most plants, marine invertebrates), 2)
densities decreasing from the barrier island to the mainland (most marine invertebrates), 3) densities low at mid-estuary sites (grasshoppers), and 4) no systematic spatial variation (beetles). We are using a combination of recruitment studies, transplant studies, and genetic approaches to begin to understand these patterns. This portion of the project is being led by Pennings in conjunction with Silliman, J. Wares (UGA), and D. Bishop (UGA).

**Mechanisms explaining plant distributions**

Guo and Pennings are conducting a series of transplant experiments to explain patterns of vegetation composition, diversity and productivity in the GCE domain (see above, Q3). Over the years 2007, 2008 and 2009, Guo transplanted three salt marsh plants, *Spartina alterniflora*, *Batis maritima* and *Salicornia virginica*; three brackish marsh plants, *Juncus roemerianus*, *Spartina cynosuroides*, and *Schoenoplectus americanus*; and three fresh marsh plants, *Pontederia cordata*, *Zizaniopsis miliacea*, and an unidentified species, to replicate fresh, brackish and saline sites, with and without competition. Plants were transplanted in March of each year and harvested, dried, and weighed each October after 7 months of growth. Sites were categorized into 5 regions of salinity (fresh, brackish, low salinity, medium salinity, and high salinity) based on GCE water column monitoring and porewater salinity data collected by Guo. The strength of competition among transplanted plants and background

![Figure 14. Results from 2007 transplant experiments of salt (*Spartina alterniflora*), brackish (*Juncus roemerianus*), and fresh (*Zizaniopsis miliacea*) marsh plants into different salinity zones, with or without neighbors.](image1)

![Figure 15. Results from 2008 transplant experiments of salt (*Batis maritima*), brackish (*Schoenoplectus americanus*), and fresh (*Pontederia cordata*) marsh plants into different salinity zones, with or without neighbors.](image2)
vegetation was calculated for each salinity zone as Relative Interaction Intensity (RII), which is calculated as \((\text{Biomass with neighbor} - \text{Biomass without neighbor})/(\text{Biomass with neighbor} + \text{Biomass without neighbor})\).

Results from 2007 (\(S.\ alterniflora, J.\ roemerianus\) and \(Z.\ miliacea\), Figure 14) and 2008 (\(B.\ maritima, S.\ americanus\) and \(P.\ cordata\), Figure 15) indicate that the freshwater plants were excluded from saltier sites by physical stress (they died with or without neighbors, indicated in figures by “N/A”), 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 (positive values of RII) at the saltiest sites. The third set of transplants in 2009 is underway and appears to show similar results.

**Mechanisms explaining animal distributions**

In 2008, the Silliman lab surveyed the GCE domain and found that densities of both periwinkles and barnacles were highest in the barrier-island marshes followed by mid-estuary and then mainland marshes (\(P < 0.01\), all cases, Figure 16). The pattern was consistent across both species and life stages (adults and recruits). There was also a strong main effect of zone (\(P < 0.01\), all cases), but no interaction between zone and site. Adult snail density was always higher in the short zone, whereas barnacle and snail recruits were always most abundant in the tall zone. These patterns suggest a strong recruitment shadow effect, where larval supply to marshes is highest closest to the ocean source and trails off toward the mainland. Combined with our tethering experiments (ongoing), which suggest strong predation in the tall zones at all sites but lower predation rates in the short zones, these data suggest that high densities of marsh invertebrates occur in areas where recruitment is high enough to overcome losses due to high predation, i.e., short \(Spartina\) zones on barrier islands.

To further assess the relative effects of habitat quality, larval transport, and predation in governing invertebrate densities along the off-shore, on-shore gradient, the Silliman lab is assessing recruitment rates (using integrative methods) and adult densities (using quadrats) for all major marsh invertebrates at all sites. Ongoing work includes transplanting tethered periwinkle snails, ribbed mussels and mud snails with animals of each species in paired uncaged and caged areas across the GCE domain, both with and without predator/competitor access (2009-2010). We will use a multiple regression model to compare separate and combined effects of recruitment rates and predation rates as assessed by tethering all invertebrates at all sites. When completed, this work will be integrated with work by the Pennings laboratory on grasshopper distributions to compare drivers of distribution between marine and terrestrial invertebrate taxa.
**Genetic structure across the GCE domain**

The Wares lab conducted a survey of the genetic structure of organisms in the GCE domain. The results illustrate the importance of examining processes of site diversity and diversification at multiple scales and levels of biological organization. *Spartina alterniflora* showed no significant pattern across the domain. As might be predicted based on the larval life history of most of the invertebrate species, there is little to no significant differentiation of marine invertebrates across GCE sites. Figure 17 shows the distribution of pairwise estimates of Wright’s Fst from mitochondrial data in the invertebrate species; only a few pairs of populations have statistically significant results, but these results are neither consistent across taxa nor reliable when you consider the effect of multiple comparisons (i.e. after Bonferroni correction). Contrasts of Fst > 0.10 are summarized below with the initials of each species and the pair of populations exhibiting that value (Li = *Littoraria irrorata*; Up = *Uca pugnax*; Mb = *Melampus bidentatus*).

Although there was little genetic differentiation among sites, detailed examination of the data revealed two interesting patterns. First, examination of nucleotide diversity (a measure of the amount of polymorphism harbored in a DNA sequence data set) indicated that populations closer to the ocean side of the domain were more than twice as diverse on average as populations in the interior or mainland regions of the domain. This preliminary result suggests that even if sites in the GCE domain were not evolutionarily differentiated from one another (and thus adaptation was not driving ecological differences), some element of larval recruitment or other effect of the environment on diversity at a site was important. Second, the spatial pattern of nucleotide diversity across all sites and eight species, including the invasive porcelain crab *Petrolisthes armatus*, was strongly correlated with site species diversity (using previous GCE data for molluscan and plant diversity at each site). Although the pattern was only marginally significant for *Geukensia demissa* and a couple of other species, the combined analysis suggested a highly significant relationship between genetic and taxonomic diversity at GCE sites (as well as between appropriate measures of genetic and species richness when only the molluscan species data were included). These results were published in Estuaries and Coasts (Robinson et al. 2009).

![Figure 17. Distribution of pairwise estimates of Wright’s Fst from mitochondrial data in invertebrate species (see text for details).](image-url)
Project Management

GCE administration

Day-to-day project administration is shared by Alber and Pennings, with support from the GCE Executive Committee (J.T. Hollibaugh (UGA), Joye, W. Sheldon, Burd). Project 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 project personnel, and writing letters of support for collaborative projects. We also continue to provide GCE support for leveraged projects.

We conducted our annual GCE-LTER meeting in January 2009 in Athens, GA. The meeting was attended by the following members of our scientific advisory committee: Iris Anderson (VIMS/VCR), Jane Caffrey (UWF), Wim Kimmerer (SFSU), Cathy Pringle (UGA) and Mark Hay (Georgia Tech). George Jackson (TAMU) was unable to attend the meeting but continues to serve on the committee.

Pennings continued administrative duties related to field efforts, including supervising field technicians at Sapelo Island and overseeing repair and maintenance of boats and field instruments.

Network interactions

GCE scientists are active at the network level:

- Pennings continues his term on the LTER Executive Board.
- Alber served on the planning committee for the LTER Science Council Meeting in San Diego, CA (May 2009). Pennings and Craft also attended the meeting.
- Burd served on the planning committee for the LTER All Scientists Meeting in September 2009.
- Alber gave a talk at the NSF LTER mini-symposium in February 2009 on coastal climate change. She also gave a plenary talk on this topic at the Science Council Meeting in May, which she co-chaired with C. Hopkinson (PIE). Alber and Hopkinson also helped to organize a working group on this topic at ASM and have taken the lead on developing a prospectus for NSF.
- Alber participated in the Social-Ecological Systems cross-site workshop in Puerto Rico in December 2008. She contributed to the synthesis document that came out of that effort (“The Common Denominator”) and is also participating in the “Maps and Locals” initiative.
- 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.
• Hollibaugh chaired a workshop at the ASM meeting on microbial diversity and ecosystem dynamics across sites. He and Booth are also collaborating with L. Amaral-Zettler (MBL) on the MIRADA project.

• Shalack collected samples for Josh Heward (Brigham Young University) and Mark Williams (Colorado University) for cross-site comparisons.

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

• Sheldon served as co-chair of the LTER Network Information System Advisory Committee, which is developing a cyber-infrastructure implementation plan for the LTER network.

• Sheldon chaired a working group on CI implementation at the 2009 LTER IM committee meeting.

• Sheldon collaborated with the LNO Network Information System team to develop and test a data access server (DAS) architecture to log access to LTER site data centrally through proxy data URLs in EML metadata.

• Sheldon 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 57 USGS stream flow gauging stations are automatically harvested on a weekly basis for 11 LTER sites (AND, BES, CWT, FCE, GCE, KBS, KNZ, LUQ, NTL, PIE, SBC) and one USFS site.

• Sheldon continues to provide near-real-time USGS streamflow data harvesting for the CWT site (http://coweeta.ecology.uga.edu/ecology/hydrologic_data/hydrologic_data.html), including automated plots and metadata generation for acquired data sets for 5 stations.

• Sheldon served as a lead software developer for an LTER research project database working group, and designed XQueries, XSLT stylesheets and example XHTML code to support embedding project search and display forms on any LTER site’s web page.

• Sheldon participated in a working group that is developing a controlled vocabulary of keywords for annotating LTER metadata documents.

• Sheldon and Carpenter provided training and consultation to the new CWT IM team to help them leverage GCE-developed software, databases and approaches for enhancing their information system to support new data collection activities.

• Carpenter served as a lead developer of a cross-site, web-based mapping application for the LTER GIS working group, and coordinated collection of GIS data describing research areas for all 26 LTER sites.
Information Management

Overview
Information Management at the GCE site is led by W. Sheldon (UGA); J. Carpenter (UGA) assists Sheldon and serves as our GIS specialist. A major focus of our Information Management effort during the past year has been updating the GCE information system to support more comprehensive management of research project information linked to over-arching research questions, personnel, LTER core areas and research products (data, publications, reports, imagery). We also developed interactive mapping applications for the GCE web site to provide geospatial context for study sites and data sets and to support map-based data search and retrieval. In addition, we have actively participated in several LTER working group initiatives to improve standardization of data search and access across LTER sites through adoption of controlled vocabularies and common interfaces.

IT Infrastructure
We currently manage three production servers to support GCE research and operations, including a general database server (running SQL Server 2000), web server (running IIS 6 and Apache 2.2) and enterprise geodatabase server (running ESRI ArcSDE 9.2, SQL Server 2000 and license servers for ArcGIS and GPS software). We also operate an additional server running Apache 2.2, Subversion 1.6.5 and eXist 1.2.6 (a native XML database) to support GCE software development and testing. All servers are equipped with RAID-5 hard drive configurations and uninterruptible power supplies to provide fault tolerance, and are backed up daily to disk and weekly to tape to protect against data loss. We added an additional 3 TB of storage to the geodatabase server this year, expanding available storage for GIS data and disk-to-disk backups to over 4 TB in the RAID-5 array.

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

Spatial Data Management and GIS
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.

The primary focus of spatial data management activities this year was developing an interactive Internet mapping application to enable users to search for GCE data geographically (http://gce-lter.marsci.uga.edu/public/gis/gcewebmap.html). We used the Google Maps™ Application Programming Interface (API) to develop this web application based on performance, seamless satellite imagery, lack of cost, familiarity to the public and large developer community. We currently provide access to several GCE spatial datasets through this application, including study sites and sampling locations, land use/land cover, and a digital elevation model (Figure 18).
In addition to these spatial datasets, we also include links to relevant GCE tabular data and study site information in the informational balloons for each spatial feature, allowing users to discover related GCE research products using this map interface.

After prototyping these map applications, Carpenter presented the results to a working group of LTER GIS specialists. The group chose to adopt this approach to develop an Internet map to provide standardized geographic information for all 26 LTER sites and Carpenter led this effort (demo available at http://gce-lter.marsci.uga.edu/public/gis/LTERmaps.html).

We continue to maintain a comprehensive collection of reference GIS data (e.g. aerial and satellite imagery, elevation, land use/land cover) and GCE spatial data in two ArcSDE geodatabases. A 1 m² elevation dataset of the Duplin River is now available in .grid and .img formats for compatibility with several common GIS software packages. Examples of reference data stored in two primary geodatabases include Georgia Land Use Trends, aerial and satellite imagery, elevation, and topographic images.

A third production geodatabase was established in 2009 for managing GPS data collected for GCE research projects. Metadata for all GIS datasets is created regularly and updated when new information becomes available. General GIS files are distributed in various formats through the GCE file archive (http://gce-lter.marsci.uga.edu/public/app/resource_search.asp); research GIS
data from the Hammock study is currently being processed for inclusion in the GCE Data Catalog.

**Website Development**

A major redesign of the GCE web site was completed in 2008, so with the exception of the interactive map described above only minor refinements were made this year to support new initiatives. For example, additional metadata search options were added to the GCE Data Catalog (http://gce-lter.marsci.uga.edu/public/app/data_catalog.asp), such as study theme, location name, and author name, to support data search links in Google Earth KML files and broader text-based searches. New guidelines on data search interfaces were established by the LTER network in 2008 to address disparities in data search and access across the network, and work is currently underway at GCE to implement search and browse interfaces (based on controlled keyword vocabularies) that are more similar to the LTER Network data catalog (e.g. http://metacat.lternet.edu:8080/knb/style/skins/lter/index_advancedsearch.jsp). These modifications to the GCE data catalog will allow us to support more generic search interfaces, while still retaining our existing interface for refining and ordering search results.

We also developed a series of REST and SOAP web services this year for accessing information in GCE databases to support various applications. For example, web services are available for retrieving tide predictions across the GCE domain (as XML), geographic information for GCE study sites and point locations (as KML), personnel directory information (as EML) and data sets (as XML). These web services are used to provide daily tide information on the GCE web site home page and to provide dynamic mapping links on data set detail pages, study site pages, and location search result pages. The interactive Google Maps on study site pages (e.g. http://gce-lter.marsci.uga.edu/public/app/sitedetails.asp?site=GCE10, Figure 19) also use REST web services to retrieve polygon coordinates and generate Google Earth files dynamically for each study site.

We are currently designing comprehensive new web pages to describe the GCE research program, including detailed descriptions of each overarching research question and our approach, with links to information about each component project and associated products (data, publications and reports). Sheldon, working in collaboration with other LTER information managers, recently developed an XML schema and web-based application for managing research project information. He also developed a relational database, database interface forms, and web services to generate the XML documents for GCE projects, and we are currently populating the database. In addition to providing more detailed information about GCE research, this addition to our web site will provide a powerful new way to discover and access data and information resulting from our work, and will support cross-site searches for related LTER research.

**Software Development**

We have continued to enhance the GCE Data Toolbox for MATLAB software and offer a compiled version of 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). We also provide source code on request to LTER affiliates for examination and customization. This software can be used to search and download data from the GCE Data Catalog and GCE Data Portal as well as import data from various sources, and then perform metadata-based analysis, transformation,
integration and visualization. Users can also retrieve data from any USGS, ClimDB/HydroDB or NOAA Hydro-meteorological Automated Data System station directly over the Internet, using either command-line functions or graphical dialogs, and then integrate these data with GCE data sets or their own data on demand. Nearly 3000 web visitors have downloaded the toolbox package since the initial release in July 2002.

Support for EML Metadata

We continue to support the XML-based EML metadata standard adopted by LTER in all GCE databases, allowing us to dynamically generate EML for all data sets in our catalog as well as species lists, personnel entries and bibliographic citations. Our EML implementation is among the most comprehensive in LTER, supporting metadata-mediated data access and integration (Level 5 in the EML Best Practices guidelines, a document created by a 2004 working group chaired by Sheldon). In 2009 we updated our EML implementation to support version 2.1.0 of the standard to improve compatibility with modern XML editors and code libraries.

We also collaborated with LTER Network Information System developers at LNO to develop and test a network-wide Data Access Server (DAS), to provide centralized, audited access to LTER data in accordance with the LTER data access policy. We now provide proxy data URLs in EML stored in Metacat to enable EML-based data access to be logged at LNO (after user registration) as well as in the GCE database to support data use reporting. However, data access through Metacat dropped sharply after implementing this change (possibly due to the new login
requirement or unresolved usability issues with the current DAS architecture), so we are currently reviewing suitability of this service for disseminating GCE data going forward.

**Web Site and Data Access Statistics**

Public downloads of GCE data sets from Fall 2001 to Fall 2009 are listed in Table 2, broken down by data set theme and user affiliation. Downloads by GCE participants are not currently tracked, due to open data access policies within the project. As mentioned above, we observed a major drop in data requests through external metadata catalogs, such as the LNO Metacat server, in 2008-2009. This may be due to the Data Access Server issues already mentioned, or due to the ending of the SEEK project and reduction in use of GCE and other EML-described data to develop, test and demonstrate the Kepler workflow software. We also saw a drop in data access by educational users, although downloads by these groups typically wane in summer and resume in late fall, when over half of all data downloads typically occur.

| Table 2. Public downloads of GCE data sets, 2001-2009, by theme and affiliation. |
|---------------------------------|----------|----------|----------|----------|----------|----------|----------|----------|
| **Annual Data Downloads by Theme** | 2001     | 2002     | 2003     | 2004     | 2005     | 2006     | 2007     | 2008     | 2009     | All       |
| Theme                          |          |          |          |          |          |          |          |          |          |
| Various (custom file)          | 0        | 0        | 0        | 0        | 1        | 5        | 12       | 7        | 2        | 27        |
| Terrestrial Insect Ecology     | 4        | 7        | 3        | 12       | 15       | 27       | 29       | 40       | 16       | 153       |
| Real-time Climate              | 0        | 0        | 0        | 4        | 78       | 29       | 54       | 55       | 31       | 251       |
| Pore-water Chemistry           | 0        | 0        | 0        | 2        | 8        | 4        | 5        | 3        | 2        | 24        |
| Plant Ecology                  | 0        | 13       | 9        | 19       | 97       | 28       | 29       | 65       | 44       | 304       |
| Phytoplankton Productivity     | 0        | 0        | 1        | 17       | 42       | 20       | 5        | 57       | 2        | 144       |
| Physical Oceanography          | 0        | 2        | 2        | 54       | 312      | 128      | 83       | 244      | 62       | 887       |
| Organic Matter                 | 0        | 5        | 1        | 13       | 17       | 12       | 27       | 66       | 16       | 157       |
| Meteorology                    | 12       | 27       | 8        | 20       | 22       | 13       | 31       | 47       | 33       | 213       |
| Hydrography                    | 0        | 0        | 0        | 4        | 6        | 5        | 11       | 1        | 27       |
| Geology                        | 0        | 0        | 0        | 0        | 2        | 18       | 6        | 5        | 31       |
| General Nutrient Chemistry     | 0        | 7        | 5        | 8        | 31       | 11       | 8        | 20       | 8        | 98        |
| Fungal Productivity            | 0        | 2        | 1        | 1        | 13       | 1        | 3        | 4        | 3        | 28        |
| Chemistry                      | 0        | 0        | 0        | 0        | 6        | 2        | 8        | 5        | 2        | 23        |
| Bacterial Productivity         | 0        | 0        | 4        | 15       | 36       | 16       | 39       | 115      | 10       | 235       |
| Aquatic Invertebrate Ecology   | 0        | 0        | 12       | 137      | 110      | 94       | 101      | 122      | 18       | 594       |
| Algal Productivity             | 0        | 0        | 0        | 0        | 1        | 13       | 9        | 13       | 1        | 37        |
| **All Themes**                 | **16**   | **63**   | **46**   | **302**  | **793**  | **411**  | **466**  | **880**  | **256**  | **3233**   |

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Web site activity was very consistent with 2008 levels. Over 5000 visitors viewed 20,000-35,000 web pages each month (excluding malicious requests and hits from web indexing spiders). Since January 2001, over 1.5 million GCE web pages have been viewed by more than 400,000 visitors from 207 distinct countries and territories (based on web log analysis and DNS resolution). Following the home page, the file archive, bibliography, EML metadata and personnel directory pages were the most popular pages requested in 2008-2009, respectively.
Journal Articles


First, M.R. and Hollibaugh, J.T. (in press). The model high molecular weight DOC compound, dextran, is ingested by the benthic ciliate, Uronema marinum, but does not supplement ciliate growth. Aquatic Microbial Ecology. 57:79-87. (DOI: 10.3354/ame01338)


Books and Book Sections


**Conference Proceedings (Published Papers and Abstracts)**


**Theses and Dissertations**


**Conference Posters and Presentations**


Alber, M. 2007. Presentation: The Earth has one big ocean with many features. Georgia Association of Marine Educators, 10/07, Tybee Island, GA.


Alber, M. 2008. Presentation: The Earth has one big ocean with many features. National Marine Educators Association, 7/08, Savannah, GA.


**Newsletter and Newspaper Articles**


