

## **GCE-III Annual Report – Year Two (2014)**

### **What are the major goals of the project?**

The primary goal of GCE-III is to understand how variation in salinity and inundation, driven by climate change and anthropogenic factors, affect biotic and ecosystem responses at different spatial and temporal scales, and to predict the consequences of these changes for habitat provisioning and C sequestration across the coastal landscape. We divide our research into 4 inter-related programmatic areas: Climate and Human Drivers of Change (Area 1); Long-term Patterns within the Domain (Area 2); Response of Marsh Habitats to Changes in Salinity and Inundation (Area 3); and Integration and Forecasting (Area 4). Our major goals within these areas are as follows:

Area 1: To track long-term changes in climate (average conditions and extreme events like storms) and human actions (in the watershed and adjacent uplands), and to evaluate the effects of climate and human drivers on domain boundary conditions (riverine input, runoff and infiltration from adjacent uplands, sea surface height).

Area 2: To describe temporal and spatial variability in physical (stratification strength, estuarine salt intrusion length, residence time), chemical (salinity, nutrient concentration and speciation, organic matter lability), geological (accretion) and biological (organism abundance and productivity, microbial processes) properties within the domain and to evaluate how they are affected by variations in river inflow and other boundary conditions.

Area 3: To characterize the responses of the marsh habitats in the domain (Spartina marsh, fresh/brackish marsh, high marsh) to pulses and presses in salinity and inundation that might be expected in the coming decades.

Area 4: To describe current patterns of habitat provisioning and C sequestration and export in the GCE domain, and to evaluate how these might be affected by changes in salinity and inundation.

### **What was accomplished under these goals?**

The specific objectives associated with each of our main goals are listed below, along with the years over the 6-year course of the project during which we plan to address them. The initials of the primary PIs involved in each activity are also listed. AB: Burd, BS: Silliman, CA: Alexander, CC: Chris Craft, CH: Hopkinson, CM: Meile, DD: Di Iorio, JB: Byers, JH: Hollibaugh, JS: Schalles, MA: Alber, MG: Garbey, ML: Leclerc, PM: Medeiros, RC: Castelao, RP: Peterson, RV: Viso, SJ: Joye, SP: Pennings, VT: Thompson, WC: Cai, WS: Sheldon

Under the objectives that were targeted for year 1 of the project we summarize our activities and, where applicable, include significant results and plans for the next reporting period.

**Area 1: Drivers of Change** – We collect long-term measurements of A) climate, water chemistry, oceanic exchange, and B) human activities on the landscape in order to document how boundary conditions that affect the domain vary over time.

#### Area 1A Objectives

1. Install and maintain an eddy covariance flux tower in the Duplin River (yr 1-6) DD, ML, WS  
Year Two Activities: GCE operates an eddy covariance tower in the Duplin River that measures CO<sub>2</sub> and H<sub>2</sub>O fluxes along with atmospheric, soil and water properties. Since the wind patterns change seasonally, we added a 2nd LICOR unit facing the other direction. We also added a pressure transducer to measure water levels in the adjacent creek.
2. Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge (yr 1-6) WS, DD, MA  
Year Two Activities: A series of meteorological stations are used to characterize the GCE domain (Fig. 1 ). The station at Marsh Landing serves as our primary station for ClimDB. This year we deployed a ceilometer (purchased with Supplemental equipment funds) and a sodar to evaluate boundary layer conditions as an aid to interpretation of flux tower data.  
Significant Results: Initial results from the ceilometer show complicated patterns of atmospheric mixing and how the boundary layer can be influenced by the presence of fog (Fig . 1), which may have implications for estimating surface CO<sub>2</sub> flux.
3. Collect monthly samples of Altamaha River water entering the GCE domain, and analyze it for dissolved inorganic nutrients, DIC, alkalinity and pH (yr 1-6) MA, WC, SJ  
Year Two Activities: We collect monthly samples of the river water entering the GCE domain via the Altamaha River for analysis of dissolved inorganic nutrients, DIC, alkalinity and pH.  
Significant Results: Schaefer (2014) evaluated N input and export in the 7 subwatersheds of the Altamaha River and found that cumulative upstream population density was an excellent predictor of both NO<sub>3</sub> and total N concentrations and loads, and that there was little evidence for N processing during transit. Takagi et al. (submitted) analyzed long-term GCE observations of nutrients in the main tributaries and also found that dissolved inorganic N loads are driven by human population density. Taken together, these results suggest that N derived from human wastewater in the upper portion of the watershed is the primary contributor of in-stream N in the lower river.
4. Measure exchange between the mouths of the estuary and the coastal ocean (yr 2-4) DD, RC  
Year Two Activities: We carried out 3 research cruises on the RV Savannah during which we deployed acoustic Doppler current profilers with CTD sensors. The data from these moorings will be used to help understand exchange with the coastal ocean and to inform our hydrodynamic model of the region. We also sampled nutrients and C to characterize fluxes through the system.
5. Measure exchange between the Duplin River and Doboy Sound (yr 1-6) DD  
Year Two Activities: We have had difficulty identifying a location for deployment of a horizontal ADCP that does not interfere with boat traffic.  
Next Reporting Period: We will survey the channel area near Marsh Landing to find an appropriate place to drive a new piling for the ADCP, and then proceed with permitting and deployment.

#### Area 1B Objectives

1. Conduct structured interviews of McIntosh County residents about environmental change (yr 1) MA  
Year Two Activities: This objective was completed in yr 1. We are collaborating with N. Heynan, who runs the CWT LTER Listening project, to use this work as the basis for a GCE Listening

project.

2. Evaluate market and non-market values of natural resources in McIntosh County (yr 1) MA  
Year Two Activities: This objective was completed in yr 1 (see Schmidt et al. 2014).
3. Incorporate information on human activities in the GCE database (yr 1-6) CA, VT, WS  
Year Two Activities: Data from an archeological survey documenting human occupation of hammocks around Sapelo Island and a radiocarbon database for the entire Georgia coast were both uploaded to the GCE catalog.  
Significant Results: We see a large-scale decline in the radiocarbon record for specific types of human settlements at around 3800 BP. We are working on a paper documenting this shift, which we believe relates to large scale environmental change.
4. Assess changes in Native American economic systems over time and their impact on the coastal Georgia landscape (yr 1-4) VT  
Year Two Activities: We continued our investigations of human population growth in the domain (both Native Americans and historic EuroAmericans) in the context of ecological change.  
Significant Results: We see a large-scale decline in the radiocarbon record for specific types of human settlements at around 3800 BP. We are working on a paper documenting this shift, which we believe relates to large scale environmental change.

**Area 2: Patterns within the Domain** - We collect data documenting key ecosystem variables within the GCE domain. Major activities in this area consists of A) field monitoring of water and marsh attributes at our core monitoring sites, B) remote sensing of productivity and habitat shifts, and C) hydrodynamic modeling of water and salt transport.

#### Area 2A Objectives

1. Continue the GCE core monitoring program in the water column, which consists of continuous measurements of salinity, temperature and pressure at 9 sites, and quarterly or monthly CTD profiles and measurements of nutrients, chlorophyll and suspended sediment at 11 sites (see Table 1) (yr 1-6) This will be augmented to include Secchi depth, pH, DIC and total alkalinity (starting yr 1); an additional sonde in the Duplin (installed yr 2); and documenting salinity intrusion in the Altamaha (starting yr 1) WS, DD, MA, SJ  
Year Two Activities: We maintain sondes at 9 GCE sites (Fig. 2 ). We also take CTD measurements and water samples according to the schedule in Table 1. This past year we added measurements of pH, DIC and alkalinity, and began documenting salinity intrusion into the Altamaha.  
Next Reporting Period: We received supplemental funding to purchase a state-of-the-art SeapHOx instrument, which will provide continuous measures of pH that can be used to evaluate ocean acidification. The instrument also has oxygen, temperature and salinity sensors, and will be used instead of the sonde that we originally proposed to deploy. The instrument, which is being calibrated, will be installed at the mouth of the Duplin River. The final addition to the core water quality monitoring program (Secchi depth) will also be added this coming year.
2. Continue the core monitoring program in the marsh, which consists of annual measurements of soil accretion, accumulation, compaction and decomposition; disturbance to plant communities; and plant and animal biomass, densities, and community composition in the marsh associated with each core site (yr 1-6). This will be augmented to include monitoring mixed plant communities; brackish/salt plant distributions; and barnacle recruitment (starting yr 1) SP,CC, BS  
Year Two Activities: We monitor plants, invertebrates, and sediment elevation at each core site (Fig. 2) as well as plant mixtures and barnacle recruitment at sites established in Yr 1. We also continued monitoring recovery from a wrack disturbance experiment.  
Significant Results: Wieski and Pennings (2014) completed an analysis of the influence of river

discharge, local precipitation, sea level and temperature on annual variation in the biomass of *Spartina alterniflora*, the dominant plant in the GCE domain. (See Major Accomplishments)

3. Add a core monitoring station in tidal fresh water (yr 1-2) CC

Year Two Activities: We established a new core monitoring station (2 0.1-ha plots) in a tidal forest area of the Altamaha River (Fig. 2, GCE 11). We are inventorying tree species and have installed dendrometer bands, litterfall traps and an RSET.

Significant Results: Over time, saltwater intrusion converts tidal forest to brackish marsh. A comparison of the GCE tidal forest site with an area on the Darien River where saltwater intrusion is occurring showed a large reduction in woody biomass and species richness and a concomitant increase in herbaceous species (Table 1).

4. Characterize groundwater flow into the Duplin River (yr 1-3) RP, RV, CM

Year Two Activities: We have collected sediment cores to constrain groundwater radon end-member activities and sediment characteristics in the Duplin.

Significant Results: Based on radon data, Carter (2013) found that the highest groundwater input to the Duplin River occurs in the upper portion of the system (Fig. 2).

5. Assess seasonal dynamics of ammonium oxidizing archaea (yr 1-2) JH

Year Two Activities: We collected weekly water samples at Marsh Landing on Sapelo Island for measurements of AOA, ammonia and nitrite oxidizing bacteria, and DIN.

6. Assess seasonal dynamics of blue crabs (yr 3-6) SP, BS

Year Two Activities: We began weekly monitoring of blue crab abundance in 2 tidal creeks. We are also obtaining data on commercial catch in major channels.

Significant Results: Nifong and Silliman (2013) found that blue crabs are a frequent component of the diets of alligators that live in estuaries. The presence of alligators reduced blue crab abundance through predation and influenced blue crab behavior, resulting in reduced foraging. This translated to increased survival of periwinkles and ribbed mussels, and demonstrates the cascading effects of an apex predator through the salt marsh food web.

7. Characterize DOM composition and predominant sources of estuarine water (yr 1-3) PM

Year Two Activities: We collected DOM samples from the GCE domain and analyzed their organic composition with ultrahigh resolution mass spectrometry.

Significant Results: Preliminary results indicate that interannual variability in river discharge plays a dominant role in controlling DOM composition variability in the system. During drought conditions, the influence of marsh-derived organic matter imprints a clear signature in the estuarine DOM.

## Area 2B Objectives

1. Create high resolution maps of site bathymetry and habitat distribution (yr 1-6) CA, MA, RV, DD

Year Two Activities: We collected high resolution imagery of a portion of the domain that can be compared with a Dec 2012 flyover by the Georgia coastal imagery consortium. We also conducted bathymetric surveys of tidal creeks to improve our DEM of the Duplin watershed.

Significant Results: Analysis of bathymetric and backscatter intensity data suggest differences in sediment type or variability in seafloor hardness along the Duplin. We are working to apply a computer automated bottom classification scheme to these observations, which will be presented at the 2014 American Geophysical Union meeting.

2. Assess patterns of marsh productivity using satellite imagery (yr 1-6) JS, SP, AB, MA, WS

Year Two Activities: We are using Landsat images to evaluate vegetation patterns. We developed filters for tidal stage and atmospheric conditions and a rigorous processing scheme, and now have ~ 500 images that cover the past 3 decades.

Significant Results: We are examining relationships between hydrologic and climatologic indices and various vegetation indices derived from LANDSAT imagery (NDVI, SAVI, MSAVI 2, etc.). We have documented strong correlations between Palmer Drought Index (3 and 6 month averages) and scene-averaged size classes of *Spartina* and *Juncus* ( $r^2$  values above 0.6).

Area 2C Objectives

1. Implement FVCOM in the Duplin River (yr 1-6) DD, RC

Year Two Activities: The 3D hydrodynamic FVCOM model for the Duplin River watershed is currently running for 30 days with a 0.5 s time step, with tide, temperature and salinity forcing on the open boundary.

2. Implement FVCOM in the larger GCE domain (yr 1-6) RC, DD

Year Two Activities: FVCOM has also been implemented in the GCE domain and is currently being validated using the salinity time series at multiple sondes collected as part of the LTER program.

Significant Results: Model runs for 2008 show the effects of river discharge and wind forcing on surface salinity over the course of the year, with lower salinities in the estuary during times of high discharge, which get transported either northward or southward depending on the wind (Fig 3).

**Area 3: Responses to Salinity and Inundation** - We work in each of our key marsh habitats to assess how they will respond to changes in salinity and inundation. A) In the *Spartina* marsh we will assess marsh-atmosphere and marsh-creek exchange; monitor and model *Spartina* primary production; assess organism interactions; and evaluate ecosystem metabolism. B) In the fresh/brackish marsh our work involves long-term observations along the transect of the Altamaha River, and a large-scale field manipulation to evaluate how pulses and presses of salt water affect a tidal freshwater marsh. C) In the high marsh our work involves a field survey of high marsh areas, an experimental manipulation of runoff to the high marsh, and modeling of plant communities.

Area 3A Objectives

1. Characterize temporal variability in marsh-atmosphere exchange of CO<sub>2</sub> (yr 2-6) ML, DD, CH, WS

Year Two Activities: We have developed routines to check and process the data stream from the flux tower so that we can calculate fluxes. We are now testing algorithms for footprint modeling, which will be linked to vegetation characteristics. We are also interested in whether the presence of surface fog affects marsh-atmosphere interactions (see Results Fig. 1).

2. Evaluate *Spartina* plant phenology (yr 1-6) MA, JS, WS and above- and below-ground production (yr 1-4) SP

Year Two Activities: The phenocam camera collects images every 30 min. Samples of *S. alterniflora* are collected on a monthly basis so that flux tower observations can be linked to vegetation. This year we timed plant sampling to correspond with Landsat overpasses so that our findings can ultimately be scaled up.

Significant Results: Analysis of PhenoCam images using the green chromatic index showed the seasonal cycle of plant production and revealed that dates of spring green-up and fall senescence differ by marsh zone (Fig. 4).

3. Quantify lateral C exchange through a small tidal creek (yr 1-3) CH, WC, DD, RC, MA

Year Two Activities: This past year we conducted quarterly field campaigns to measure total DIC in the creek that floods the flux tower. We sample water over the course of a tidal cycle for analysis of CO<sub>2</sub>, pH and total alkalinity, measure water height, and deploy an ADCP to measure water flow.

Significant Results: DIC in the ebbing creek water was higher than in entering floodwater, due to respiration by marsh flora and fauna and diffusion of DIC-rich pore waters while the marsh was flooded. Presumably CO<sub>2</sub> flux to the atmosphere was reduced by an amount equivalent to that gained by the water column.

4. Evaluate net ecosystem metabolism and quantify net C exchange in the Duplin R (yr 1-4) CH, WC, MA

Year Two Activities: As part of our quarterly field campaign we conducted rapid surveys along the length of the Duplin River at dawn and dusk to evaluate diurnal changes in total CO<sub>2</sub> and DO to estimate GPP, total system respiration, and NEP. We also collect DIC, pH and TA samples on a bimonthly basis.

Significant Results: We see substantial diurnal changes in DO and DIC in the Duplin River, signifying a high level of system metabolism. We also see deviation from saturation, which provides evidence for large air-sea exchanges as well as the overall heterotrophic nature of the Duplin system. There are also large downstream gradients in DO, DIC, chlorophyll and DOC, which suggest the export of materials to Doboy Sound and presumably the coastal ocean.

5. Conduct a blue crab removal manipulation (yr 4-6) BS, SP

Year Two Activities: Begins yr 4

6. Monitor headward erosion in tidal creeks (yr 1-4) SP

Year Two Activities: We continued monitoring the growth of 16 headward-eroding creeks, distinguished by an unvegetated basin at their head that supports high populations of burrowing crabs.

Significant Results: Annual monitoring of creeks in the GCE domain for 4 y has revealed that growth rates vary substantially among years (Fig. 5). We will continue to monitor creeks annually in order to determine the drivers of annual variation in growth rate.

7. Develop a Spartina physiological model (yr 1-3) AB

Year Two Activities: Tests of our Spartina model suggested that a more detailed below-ground component is required. We are therefore measuring soluble carbohydrates in above- and below-ground tissue in order to track allocation of resources.

Next Reporting Period: Data on soluble carbohydrates will be used to refine the existing model of Spartina growth.

8. Develop a model to predict porewater salinity (yr 1-3) CM

Year Two Activities: We have incorporated precipitation, evapotranspiration, salt exchange, drainage, groundwater, tidal inundation, and surface runoff into our porewater model. We also developed an algorithm to determine the water level at which the marsh floods.

Significant Results: Using the critical-flooding algorithm, analysis of marsh topography revealed that the marsh platform has many depressions (on the order of 10% of the domain area) that do not flood until the tidal elevation is well above the depression elevation.

### Area 3B Objectives

1. Assess changes in community composition along the salinity gradient of the Altamaha (yr 1-6) MA, CC

Year Two Activities: In 2012 we began an annual survey to document the transition in bankside vegetation from *S. cynosuroides* to *S. alterniflora* along the salinity gradient of the Altamaha.

Significant Results: Segarra et al. (2013 a,b) studied methane fluxes and methane oxidation in

freshwater and brackish sediments along the Altamaha. Rate measurements of sulfate reduction and the anaerobic oxidation of methane (AOM), two processes not typically considered relevant in low salinity habitats, revealed their importance in freshwater settings.

2. Conduct field manipulation of salt water intrusion in a low-salinity tidal marsh (yr 1-6) CC, SP, BS  
Year Two Activities: In the GCE SALTEx (Seawater Addition Long Term) experiment we began dosing experimental plots with saltwater (press and pulse plots) and are monitoring porewater, vegetation, herbivores, soil surface elevation, and gas exchange. In a companion experiment, we exposed mixtures of plants from tidal fresh and brackish marshes to water of differing salinity and for different lengths of time in the greenhouse.  
Significant Results: Porewater salinity in the press plots has increased from 0 to about 4. Some plant species, especially forbs, are visibly stressed, and hydrogen sulfide emissions are evident. In the greenhouse, plant community composition was highly sensitive to salinity regime. We will monitor mixtures again in the spring to assess overwintering survival.
3. Apply SLAMM to the GCE domain (yr 1-3) CC, CA, MA  
Year Two Activities: New inputs were acquired for SLAMM, including updated LiDAR, bathymetry and ground-truthed RTK data in the Altamaha River. Modeling runs are underway using various scenarios of sea level rise and river discharge.

### Area 3C Objectives

1. Continue to monitor groundwater salinity, temperature and pressure on instrumented hammocks (yr 1-2) CA, CM, WS  
Year Two Activities: We continued our analysis of the pressure data collected at groundwater wells installed along an upland-to-marsh transect. However, the sensors in these wells continue to fail under harsh coastal conditions.  
Significant Results: We have separated out tidal influences on the pressure signals by fitting the signal using constituents with known tidal frequencies. We also corrected erroneous ground elevations. Although the identification of other driving forces is ongoing, we have determined that marsh topography has a critical impact on the pressure signal.  
Next Reporting Period: We have halted data collection due to sensor failure. The manufacturer is working to design more robust sensors that can be field-tested at the GCE site.
2. Survey high marsh characteristics in sites with different land-use categories (yr 1-2) MA, JB, CA, SP  
Year Two Activities: We analyzed plant and animal distributions, sediment, porewater nutrients, parasite loads, and microbial community from samples collected during the yr 1 high marsh survey. We also continued working with a cross- LTER group to evaluate the ecological impacts of coastal armoring.  
Significant Results: Elevations at bulkheaded, developed sites are lower than those at either unarmored developed sites or forested areas, and have a higher % cover of *S. alterniflora* (Fig. 6). The sediments at these areas are finer-grained, suggesting that transfer of sandy upland materials has been cut off by the installation of armoring.
3. Conduct upland manipulation of water flow to high marsh areas (yr 3-6) SP, MA, JB, CA  
Year Two Activities: Begins yr 3
4. Develop a clonal plant model to explore vegetation dynamics (yr 3-5) MG  
Year Two Activities: Begins yr 3

**Area 4: Integration and Forecasting** - We use a combination of integrative modeling, empirical observations, and remote sensing to produce an integrated picture of habitat provisioning and carbon flow across the landscape, and evaluate how changes in salinity and inundation may change these services in the future. Major activities include A) develop an integrative model that uses a hydrodynamic model (FVCOM), a soil model, and 3 different semi-empirical plant models to predict salinity and inundation patterns, porewater salinities, and plant responses over different time scales, and B) use combined model output to evaluate habitat provisioning and C flow under different scenarios.

#### Area 4A Objectives

1. Run FVCOM to predict salinity and inundation (yr 3-4) DD, RC  
Year Two Activities: Begins yr 3
2. Run the soil model to predict porewater salinity (yr 4-5) CM  
Year Two Activities: Begins yr 4
3. Run the plant models to predict vegetation response yr (2-6) AB, MG  
Year Two Activities: We have developed scenarios and the model infrastructure for the Spartina model. However, biomass predictions in initial runs diverged from observations after 18-24 mo, partly because resource allocation was not incorporated into the model. (See Obj. 3A7).

#### Area 4B Objectives

1. Develop scenarios (yr 3) MA, AB, CA, VT  
Year Two Activities: Begins yr 3
2. Evaluate C flow (yr 3-6) WC, CH, ML, MA, CC  
Year Two Activities: Begins yr 3
3. Evaluate habitat provisioning (yr 3-6) MA, RC, DD, CA  
Year Two Activities: Begins yr 3

### **What were the Key Outcomes and Accomplishments?**

**Climate Drivers.** Freshwater delivery is an important factor determining estuarine characteristics and may be influenced by large-scale climate oscillations. J. Sheldon and Burd (2014) investigated the effects of seven climate signals on the precipitation and river discharge patterns of the Altamaha River watershed, which provides most of the freshwater to the GCE site. They found statistical linkages between three climate signals (the Bermuda High, the ENSO cycle, and the Atlantic Multidecadal Oscillation), precipitation and river discharge. Additional analyses revealed that the complex, seasonally alternating pattern of climate signals that affects precipitation and river discharge in the Altamaha River watershed also extends to the neighboring Ogeechee, Satilla, and St. Marys watersheds (Fig 1). Thus, changes in large-scale climate signals as well as the interplay among them have the potential to affect the amount and seasonality of freshwater entering these estuaries, which in turn will affect downstream ecosystems. This connection was borne out by Wieski and Pennings (2014) who showed that river discharge was the most important driver of *S. alterniflora* net primary production at almost all GCE sites, with high primary production in years following high river discharge. The next step will be to assess relationships between climate signals, salinity, and survey data for shrimp and crabs.

**Habitat Mapping.** The production of accurate habitat and elevation maps for low-lying coastal areas such as salt marshes is critically important for flood inundation mapping, coastal hazard assessments and modeling sea level rise. We used a combination of LiDAR and hyperspectral imagery to produce both an accurate DEM and an improved habitat classification for the marshes on the Duplin River (Hladik and Alber 2013). This map served as the basis for a detailed evaluation of the relationship between marsh platform geomorphology, vegetation composition and biomass, and invertebrate patterns (Schalles et al. 2013). Building on this effort, Hladik and Alber (2014) compared the use of remote sensing-derived metrics for the prediction of salt marsh vegetation type with classifications based on field-collected edaphic variables. Their results suggest that a combination of elevation, slope, distance to mean high water, and distance to upland, all of which can be obtained through remote sensing, can be used to predict vegetation types in a salt marsh, and that they are more effective than field-collected edaphic variables (Fig 2). This finding is exciting because the edaphic parameters are spatially and temporally limited and are more labor-intensive to collect than remote sensing. Hence, this method will be useful to researchers and coastal managers interested in predicting ecosystem-wide characteristics over space and time. This approach also has potential for predicting the effects of sea level rise on salt marsh plant distributions.

**Latitudinal variation in herbivory.** GCE investigator S. Pennings has been working for over a decade on the interactions between predators, herbivores and plants in salt marsh sites distributed along the east coast (including study sites within the PIE, VCR and GCE domains), in what represents the most extensive study of latitudinal variation in community ecology for any system. Although herbivores are more abundant and do more damage to plants at low versus high latitudes (Pennings et al. 2009), low latitude plants are tougher and less palatable (e.g. Pennings et al. 2001), perhaps as an evolutionary response. Differences in plant palatability affect the performance of individual herbivores, which exhibit poorer growth on low-latitude plants (Ho and Pennings 2013). However, latitudinal variation in plant quality is less important than latitudinal variation in top consumers and competition in mediating variation in food web structure (Marczak et al. 2011, Marczak et al. 2013). The most recent paper on this topic (Wieski and Pennings 2014) examined herbivory, plant defenses and tolerance to herbivory of the shrub *Iva frutescens* across the entire latitudinal gradient. Herbivory, and spatial and temporal variation in herbivory, was greatest at low latitudes, as were both constitutive and induced defenses in plants (Fig. 3). However, plant tolerance to herbivory did not depend on geographic origin. These findings underscore the importance of considering multiple ways in which plants can respond to herbivores when examining geographic variation in their interactions.

**Carbon in coastal systems.** The sources and sinks of carbon in the coastal ocean are important, but little understood, components of the global carbon budget (Cai 2011). Hopkinson et al. (2012) reviewed available information on the amount of C stored in coastal vegetated wetlands (marshes, mangroves, and sea grass beds). Areal rates of C burial in these systems are extremely high and they are important C sinks on a global scale. They warn that sea level rise and coastal armoring coupled with a rise in global temperature will all result in decreased C storage in these systems. Jiang et al. (2013) evaluated C export to the South Atlantic Bight. They found that terrestrially-derived CO<sub>2</sub> from both rivers and intertidal marshes was exported to the continental shelf, with highest inputs closest to shore (Fig. 4). This past year, GCE investigators published a major review paper on the coastal ocean in *Nature* (Bauer et al. 2013) that attests to the extremely high level of metabolism of wetland-dominated estuarine systems in the global ocean and the overall importance of organic C burial in wetland sediments. This blue carbon burial represents a significant portion of the net air-sea flux of CO<sub>2</sub> to the coastal ocean. Although there is still much uncertainty in global estimates, they suggest that intertidal wetlands also act as a net source of C to estuaries, which then export both organic and inorganic C to continental shelves. They point out that

changes in river discharge, the loss of coastal wetlands, and increasing atmospheric levels of CO<sub>2</sub> will all alter shelf-atmosphere-open ocean C exchange in the future.

### What is the impact on the development of the principal discipline(s) of the project?

GCE scientists have published 36 journal articles and 8 book chapters and other one-time publications in 2013-14. Papers published this past year cover a broad range of topics, including plant distribution (e.g. Li et al. 2013), biodiversity (e.g. Hensel and Silliman 2013), disturbance (e.g. Baas et al. 2014), and consumer-plant interactions (e.g. Atkins et al. 2013). Our research program has examined a variety of estuarine processes at spatial scales ranging from individual plots (e.g. McFarlin and Alber 2013) to individual estuaries (e.g. Reader and Miller 2014) to the entire Atlantic coast (e.g. Wieske and Pennings 2014). We also have publications on mixing models (e.g. Loftis and Meile 2014), remote recording devices (e.g. Nifong et al. 2013) and information management (e.g. Campbell et al. 2013). A complete list of publications can be found at [http://gce-nas.marsci.uga.edu/public/app/biblio\\_query.asp](http://gce-nas.marsci.uga.edu/public/app/biblio_query.asp). Key accomplishments this past year include research on the influence of climate drivers on freshwater input to estuaries; the development of remote sensing tools to map salt marshes; a focus on salt marsh as a model system for the study of plant-herbivore interactions; and syntheses of the sources and sinks of carbon in the coastal ocean.

### What is the impact on other disciplines?

The GCE is an interdisciplinary program, with biologists, geologists, chemists, physicists, and anthropologists engaged as PIs on the project.

### What is the impact on the development of human resources?

There are currently 15 undergraduate students, 24 graduate students and 8 post-doctoral scientists associated with the project. We had 4 REU participants this past year, including 1 identified through the Peachstate Louis Stokes Alliance for Minority Participation (LSAMP) program. We also have active collaborations with international students and scientists in Czech Republic (CZ Univ. of Life Sciences), China (East China Normal Univ, State Ocean Administration, and Xiamen Univ), India (Central Rice Research Institute), Israel (Kinneret Limnology Laboratory), France (Univ of Rennes), Germany (Leibniz Center for Marine Tropical Ecology, and University of Oldenburg), United Kingdom (Univ of Liverpool).

### What is the impact on physical resources that form infrastructure?

The GCE has installed an extensive boardwalk system that provide access to plots associated with our long-term salinity addition experiment (SALT<sub>ex</sub>). We also installed boardwalks and photovoltaic cells in support of our eddy covariance flux tower, which is a 30 foot tall tower located in a salt marsh adjacent to Sapelo Island. We maintain sondes that continuously measure conductivity, temperature and salinity at

10 water quality monitoring sites in Altamaha, Sapelo, and Doboy Sound, and in the adjacent marshes we have RSETs that measure sediment elevation (there are also RSETs in the SALTex plots). We also have groundwater wells installed along 2 transects that run from the uplands to the marsh. We partner with the Sapelo Island National Estuarine Research Reserve to run our weather station and to provide support for both an NADP station and a USGS water quality monitoring station. We also operate a wireless, outdoor data server on Sapelo to acquire, store and relay real-time data from the flux tower and other field instruments to servers at UGA.

### What is the impact on institutional resources that form infrastructure?

The UGA Marine Institute (UGAMI) on Sapelo Island provides the base of field operations for the GCE LTER. The project has 3 technicians who work at UGAMI, and all of our scientists use the facility while in the field. Several GCE labs (Pennings, Alber, Schalles) maintain year-round housing and operations at UGAMI and at any given time there are students, technicians and other personnel at the facility. We maintain two 22' small boats, two Kawasaki mules and 2 trucks at the field station to access sampling sites. We also operate a GIS lab at UGAMI in collaboration with the Sapelo Island National Estuarine Research Reserve.

### What is the impact on information resources that form infrastructure?

The GCE Information Management program has developed a number of software products, database systems and web applications that have been released as open source software. These tools, including the GCE Data Toolbox for MATLAB, our Metabase Metadata Management System, our bibliographic database, our file archive and our geospatial library, are widely used across the LTER Network and in other environmental informatics programs. The GCE Data Toolbox software has been downloaded by over 3500 registered users (545 since 2012) and is actively used at 8 other LTER sites for sensor data harvesting, data analysis or general data processing tasks. Notably, both the CWT and AND LTER programs have standardized on the GCE Data Toolbox for all environmental sensor data processing. Also, the Metabase metadata management system was adopted by 3 other LTER sites (CWT, MCR and SBC) this past year.

### What is the impact on technology transfer?

We provide user training and other support resources for the GCE Data Toolbox for MATLAB software. This past year we added an API Guide and QA/QC Flagging Reference to the toolbox support website, conducted a training session in the CUAHSI Virtual Workshop on Field Data Management Solutions, contributed to the Open Source Data Turbine (OSDT) web site describing use of the GCE Data Toolbox with OSDT for streaming data QA/QC and management, and participated in the ESIP EnviroSensing Cluster working group, which included the GCE Data Toolbox application for sensor data as part of the Best Practices Guide released in 2014 ([http://wiki.esipfed.org/index.php/EnviroSensing\\_Cluster](http://wiki.esipfed.org/index.php/EnviroSensing_Cluster))

### What is the impact on society beyond science and technology?

The GCE website and public data portal is used to disseminate publications, reports, research data, photographs and remote sensing imagery. Over 1 million distinct web visits have been recorded since 2001, with over 418,000 page views from 203,000 visitors this past year. In addition, GCE scientists

regularly give seminars and public presentations, contribute articles to newsletters and other popular publications, and talk to the media about coastal issues. Our Schoolyard program brings K-12 teachers to the field site, and this past year our children's book and accompanying lesson plans were distributed to approximately 200 grade school teachers and environmental educators. GCE outreach is served by partial support of the Georgia Coastal Research Council (GCRC, [www.gcrc.uga.edu](http://www.gcrc.uga.edu)), which works to promote science-based management of Georgia coastal resources by facilitating information transfer between scientists and managers. Senator Sheldon Whitehouse toured the field site this past April and included GCE climate change research in a speech on the Senate floor.

## Publications

### Books

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Langman, Owen and Craft, Christopher B. (). Carbon and nutrient cycling of created and restored wetlands. *Encyclopedia of Wetlands. Volume 3. Wetland Management* . Status = AWAITING\_PUBLICATION; Acknowledgement of Federal Support = No ; Peer Reviewed = Yes

Turck, John A. and Thompson, Amanda R. and DePratter, Chester (2013). *Entangling Events: The Gualala Landscape and the Spanish Missions. Life among the Tides: Recent Archaeology of the Georgia Bight* Thompson, Victor D. and Thomas, David Hurst. Anthropological Papers of the American Museum of Natural History. New York. . Status = PUBLISHED; Acknowledgement of Federal Support = Yes ; Peer Reviewed = Yes

### Conference Papers and Presentations

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Pennings, Steven C. (2013). Computer science meets biology: using volunteer scientists to map salt marsh plant communities. Workshop on complex adaptive systems. La Rochelle, France. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

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Wieski, Kazimierz and Pennings, Steven C. (2014). Latitudinal variation in resistance and tolerance to herbivory of a salt marsh shrub. *Ecography*. 37 763-769. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: 10.1111/ecog.00498

### **Thesis/Dissertations**

Carter, Matthew. Characterization of Submarine Groundwater Discharge in a Back Barrier Tidal Creek. (2013). Coastal Carolina University. Acknowledgement of Federal Support = Yes

Schaefer, Sylvia C.. Controls on nitrogen inputs, loads, and in-stream concentrations in the Altamaha River, Georgia, and beyond.. (2014). University of Georgia. Acknowledgement of Federal Support = Yes

Slaughter, Julia B.. Factors influencing groundwater and surface water hydrogeochemistry with a special emphasis on the importance of sediment geology. (2013). University of Georgia. Acknowledgement of Federal Support = Yes

# GCE Significant Results 2014

## Area 1: Drivers of Change

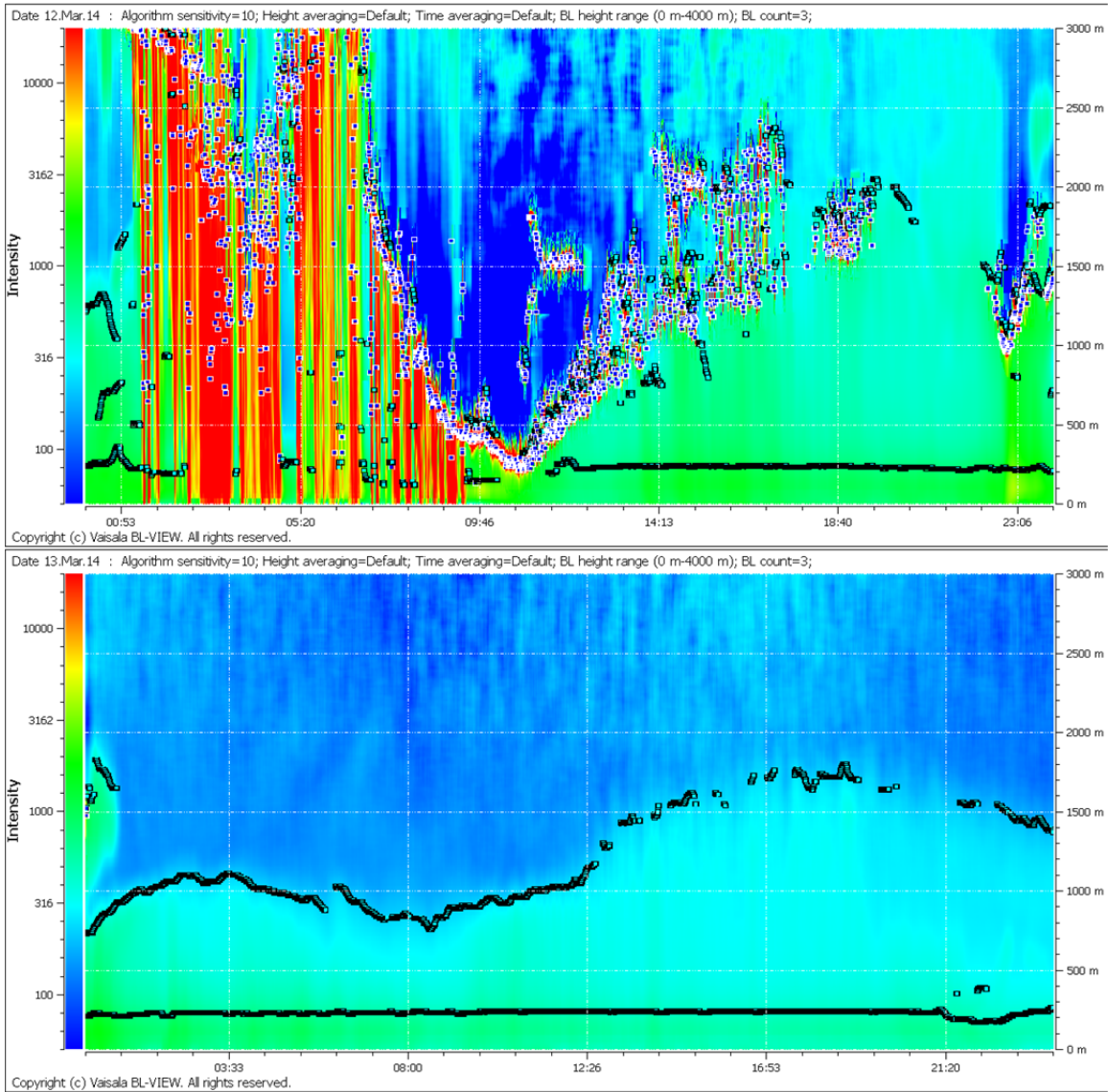


Fig. 1. Ceilometer output from Sapelo Island, GA showing signal intensity at varying elevations over the course of two days. Red indicates a large decrease in signal due to the presence of fog or precipitation; black lines show boundary-layer height; white dots indicate cloud height. The area is much more dynamic on 3/12 (top), which has implications for CO<sub>2</sub> flux measurements. Corresponds to Objective 1A.2: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

## GCE Significant Results 2014

### Area 2: Patterns within the Domain

Table 1. Canopy and understory species in the GCE tidal forest (unimpacted) core monitoring site compared to an impacted area that has experienced salt water intrusion. Corresponds to Objective 2A.3: Add a core monitoring station in tidal fresh water.

	Species	Unimpacted	Impacted
Canopy	<i>Acer rubrum</i>	x	
	<i>Carpinus caroliniana</i>	x	
	<i>Fraxinus pennsylvanica</i>	x	
	<i>Liquidambar styraciflua</i>	x	
	<i>Magnolia virginiana</i>	x	
	<i>Nyssa aquatica</i>	x	
	<i>Nyssa biflora</i>	x	x
	<i>Quercus lyrata</i>	x	
	<i>Saururus cernuus</i>	x	
	<i>Taxodium disticum</i>	x	x
	<i>Cicuta maculata</i>	x	
Understory	<i>Cyperus globulosus</i>		x
	<i>Eleocharis tuberculosa</i>		x
	<i>Polygonum</i>		x
	<i>Pontederia cordata</i>		x
	<i>Rhynchospora corniculata</i>		x
	<i>Sagittaria laniflora</i>		x
	<i>Typha latiflora</i>		x

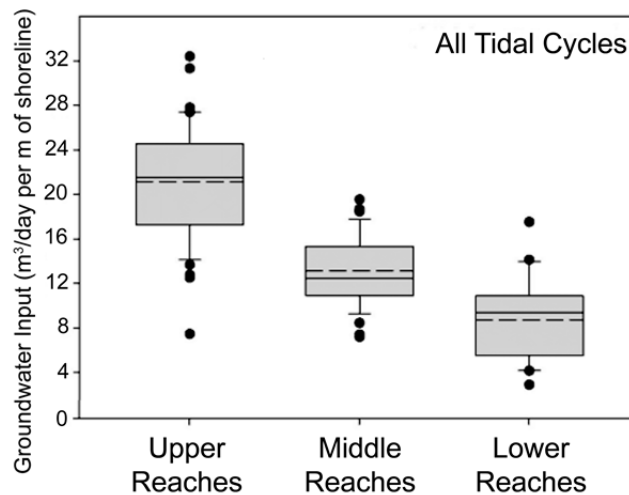
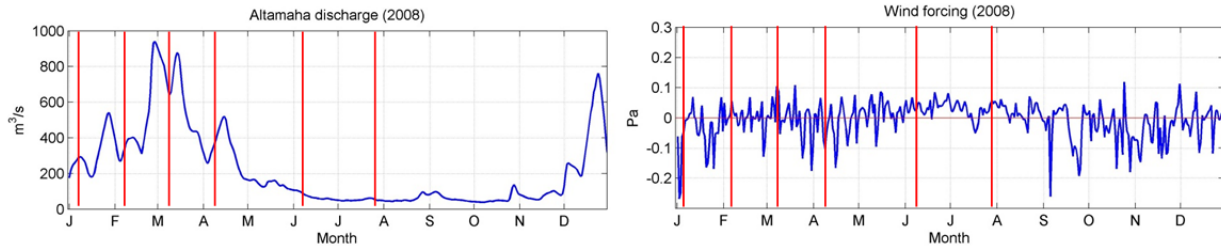


Fig. 2. Box-and-whisker plots showing normalized daily groundwater discharge totals per meter of main channel in each section of the Duplin River in June 2013. The largest groundwater inputs occur in the upper reaches of the Duplin River. Corresponds to Objective 2A.4: Characterize groundwater flow into the Duplin River.

## GCE Significant Results 2014



### SURFACE SALINITY AT SEASONAL SCALES

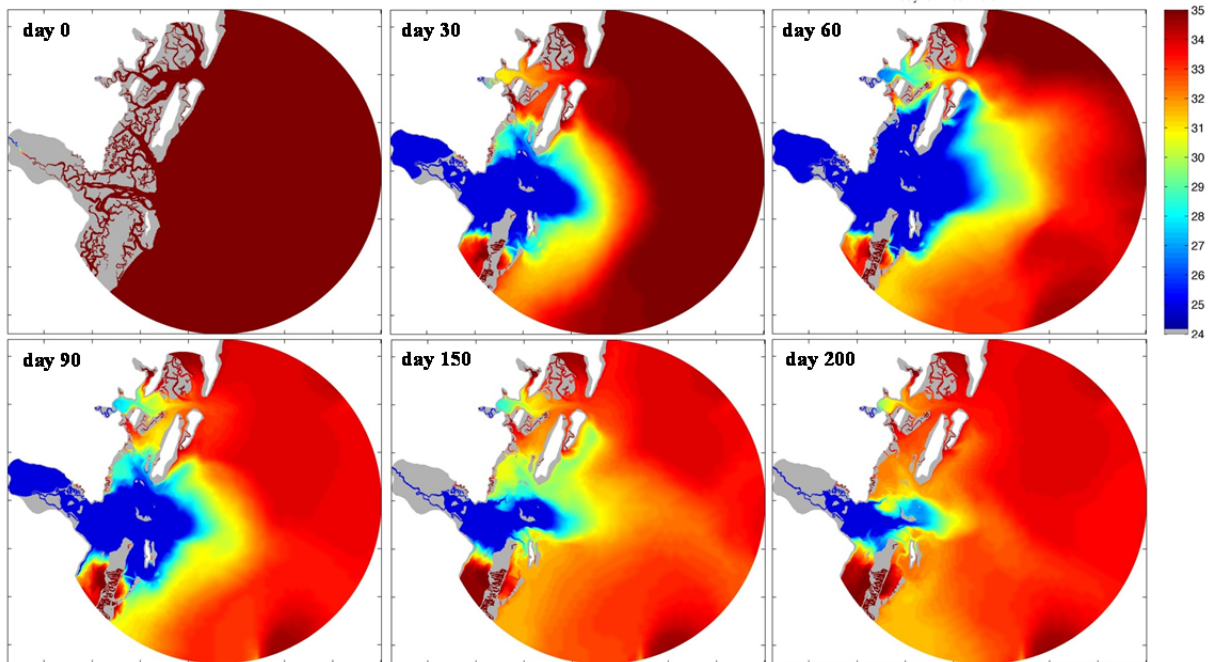


Fig. 3. Surface salinity in the GCE domain during a model run. Top panels show river discharge and alongshore component of the wind forcing. Red lines show timing of salinity plots, below. Corresponds to Objective 2C.2: Implement FVCOM in the GCE domain.

### Area 3: Responses to Salinity and Inundation

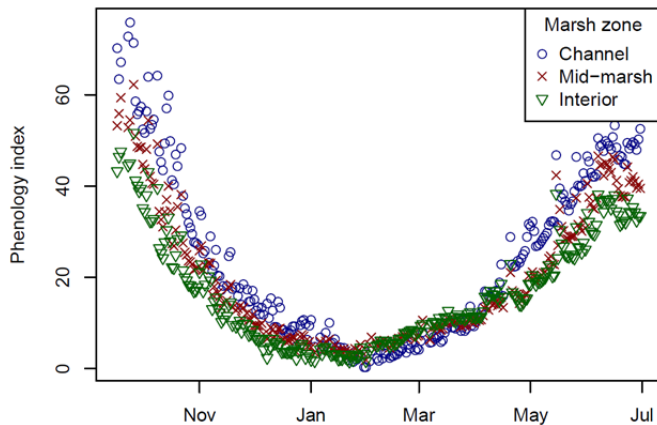


Fig. 4. A plot of a PhenoCam phenology index ( $2G\_RBI$ , i.e.  $2 \times \text{green channel digital number (DN)}$ ) - (red DN + blue DN) by marsh zone. A low phenology index indicates reduced green vegetation and inflection points correspond to dates of marsh green-up and senescence (see Richardson et al. 2007). Corresponds to Objective 3A.2: Evaluate *Spartina* plant phenology.

## GCE Significant Results 2014

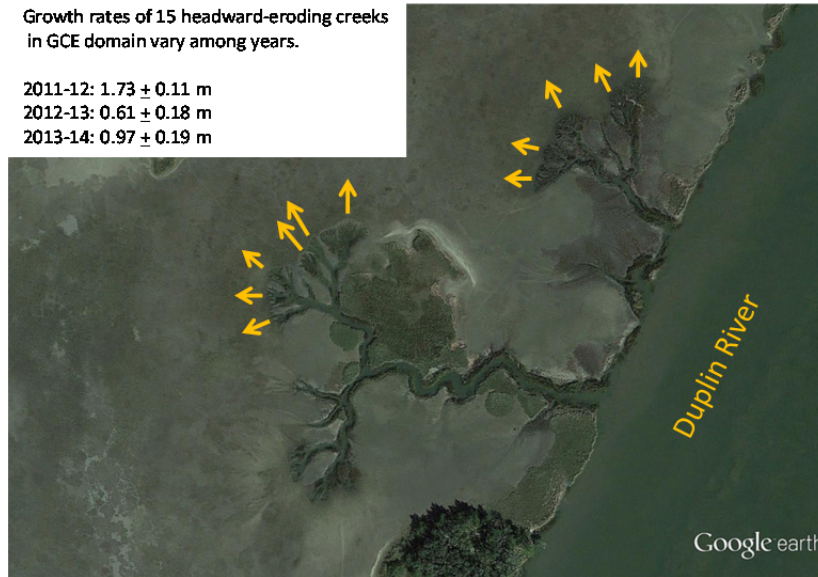


Fig. 5. Headward eroding creeks in the GCE LTER domain. Arrows show direction of growth. Semi-circular features at the heads of the creeks are bare areas created by crab (*Sesarma*) herbivory. Inset table shows that creek growth rate varies substantially among years (long-term average is around 2 m per year). We will continue to monitor to determine why growth rates vary from one year to the next. Corresponds to Objective 3A.6: Monitor headward erosion in tidal creeks.

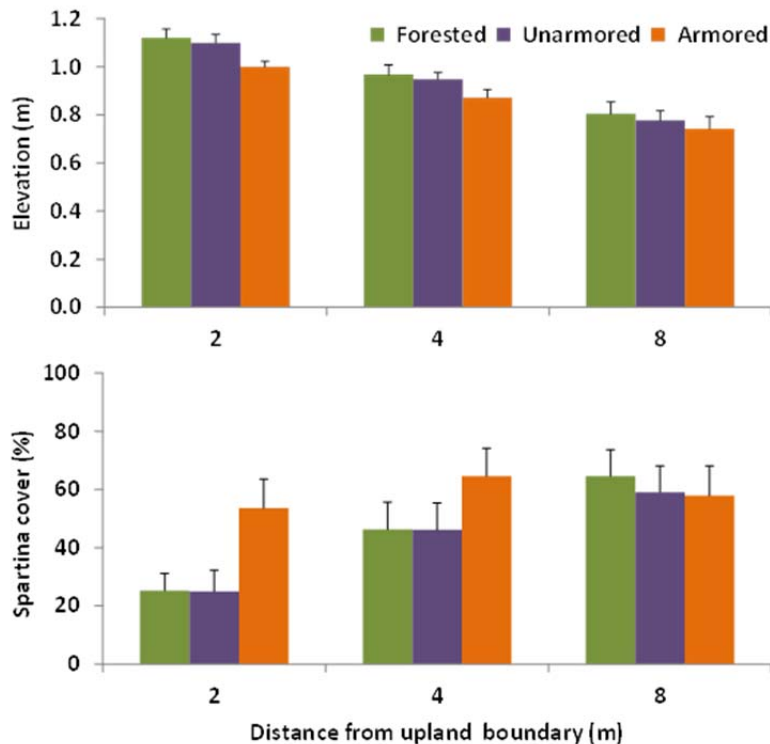


Fig. 6. Elevation (top) and % *Spartina* cover (bottom) in salt marshes surveyed along the GA coast in 2013 where the adjacent upland was either forested, unarmored (but developed) or armored (and developed). 20 marshes of each upland type were sampled at 2, 4, and 8 m from the upland boundary; error bars represent standard error. Corresponds to Objective 3C.2: Survey high marsh characteristics in sites with different land-use categories.

# GCE Activities 2014

## Area 1: Drivers of Change

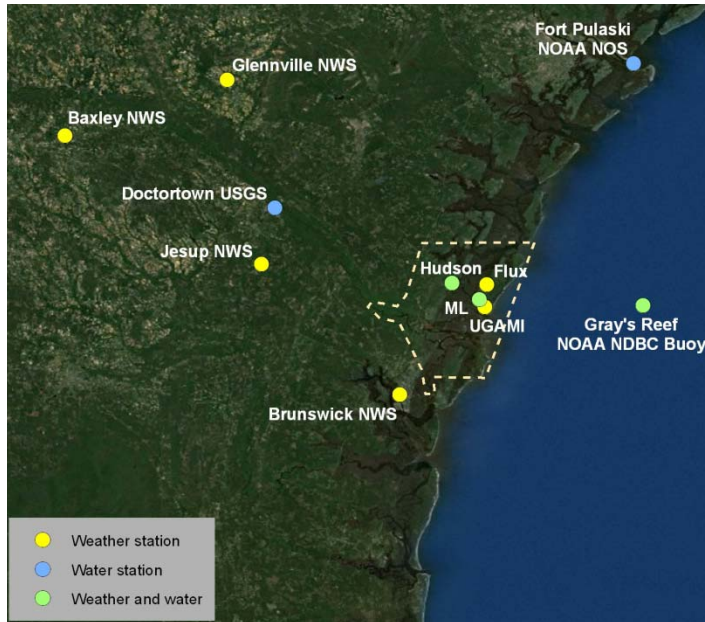


Fig. 1. Locations of observing stations used for boundary conditions (ML is Marsh Landing; UGAMI is UGA Marine Institute). Corresponds to Objective 1A.2: Collect ongoing information on climate and oceanographic conditions, sea level, and river discharge.

## Area 2: Patterns within the Domain

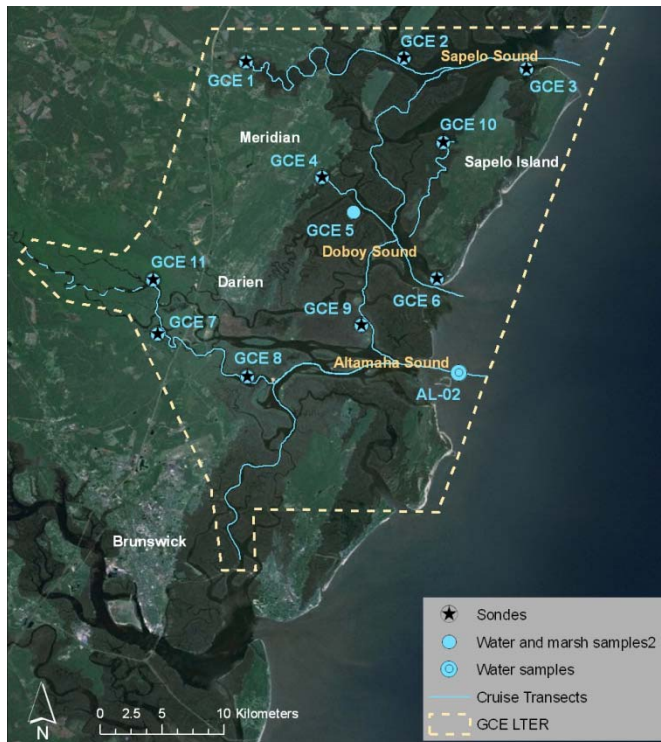


Fig. 2. GCE domain showing core monitoring stations. Corresponds to Objective 2A.1: Continue the GCE core monitoring program in the water column and Objective 2A.2: Continue the core monitoring program in the marsh.

## GCE Activities 2014

Table 1. Monitoring program for GCE-III. Initials of PIs responsible for supervising each aspect of the monitoring program are indicated in parentheses. LTER core areas are 1: primary production, 2: populations, 3: organic matter cycling, 4: inorganic nutrients, 5: disturbance. GCE PIs: AB: Burd, BS: Silliman, CA: Alexander, CC: Craft, CH: Hopkinson, CM: Meile, DD: Di Iorio, JB: Byers, JH: Hollibaugh, JS: Schalles, MA: Alber, MG: Garbey, ML: Leclerc, PM: Medeiros, RC: Castelao, RP: Peterson, RV: Viso, SJ: Joye, SP: Pennings, VT: Thompson, WC: Cai, WS: Sheldon. Corresponds to Objective 2A.1: Continue the GCE core monitoring program.

Type	Location	Frequency	Core Area & Variables Measured
<b>Area 1 Atmospheric</b>			
Weather stations, with SINERR, USGS (DD)	Sites 4, 6, flux tower	Every 15 min	Abiotic driver of 1-5. > level 2 stations: PAR, temp, rH, precip, wind speed and direction, barometric pressure, total solar and long wave radiation; flux tower also measures CO <sub>2</sub> , humidity and heat fluxes
Wet deposition, with SINERR, NADP (MA)	Site 6	Weekly	4. Hydrogen (acidity as pH), sulfate, nitrate, ammonium, chloride, base cations (such as calcium, magnesium, potassium, sodium)
<b>Area 1 Water</b>			
Altamaha River chemistry (MA, WC)	Head of tide	Monthly	3, 4. Dissolved inorganic nutrients (NO <sub>x</sub> , NH <sub>4</sub> <sup>+</sup> , HPO <sub>4</sub> <sup>2-</sup> , H <sub>2</sub> SiO <sub>4</sub> <sup>2-</sup> ) and organics (DOC, TDN, DON, TDP, DOP), particulate CN, DIC, alkalinity, pH
<b>Area 2 Water</b>			
Sound chemistry (MA, WC)	Sites 1-5; 8-11, AL-2	Quarterly	1, 3, 4. Dissolved inorganic nutrients (NO <sub>x</sub> , HPO <sub>4</sub> <sup>2-</sup> ) and organics (DOC, TDN, DON), particulate CN, DIC, alkalinity, pH, Secchi depth, chlorophyll a
	Sites 6-7	Monthly	1, 3, 4. Dissolved inorganic nutrients (NO <sub>2</sub> <sup>-</sup> , NO <sub>3</sub> <sup>-</sup> , NH <sub>4</sub> <sup>+</sup> , HPO <sub>4</sub> <sup>2-</sup> , H <sub>2</sub> SiO <sub>4</sub> <sup>2-</sup> ) and organics (DOC, TDN, DON, TDP, DOP), particulate CN, DIC, alkalinity, pH, Secchi depth, chlorophyll a, total suspended sediment
Sound hydrography (DD)	Sites 1-4, 6-11	Every 30 min	Abiotic driver of 1-5. Salinity, temperature, pressure at moorings; CTD profiles at all stations in conjunction with sound chemistry; sea level station at GCE4
Duplin-domain exchange (DD)	Mouth of Duplin R.	Every 15 min	Abiotic driver of 1-5. Continuous horizontal ADCP measurements of water flux
<b>Area 2 Marshes</b>			
Soil accretion (CC)	Sites 1-11	Annual	3. Sediment accretion, elevation, compaction
Plant productivity (SP)	Sites 1-11, 2 zones	Annual	1. Stem density, height, flowering status, calculated biomass, in 2 marsh zones
	Flux tower	Monthly	1. Monthly measurements of biomass in short, med, tall <i>Spartina</i> using Jim Morris's methods (cite)
Disturbance (SP)	Sites 1-11	Annual	5. Wrack and biotic disturbance in permanent vegetation plots
Plant composition (SP)	Site 3, 6, 7, 8, Altamaha	Annual	2. Community composition in 4 types of salt marsh, 2 types of low-salinity and 2 types of high marsh vegetation mixtures
Marsh Invertebrates (SP BS)	Sites 1-11, 2 zones	Annual	2. Density and size of benthic macroinvertebrates in 2 marsh zones
Recruitment (BS)	Sites 1-11	Quarterly	2. Recruitment of barnacles to standard substrates

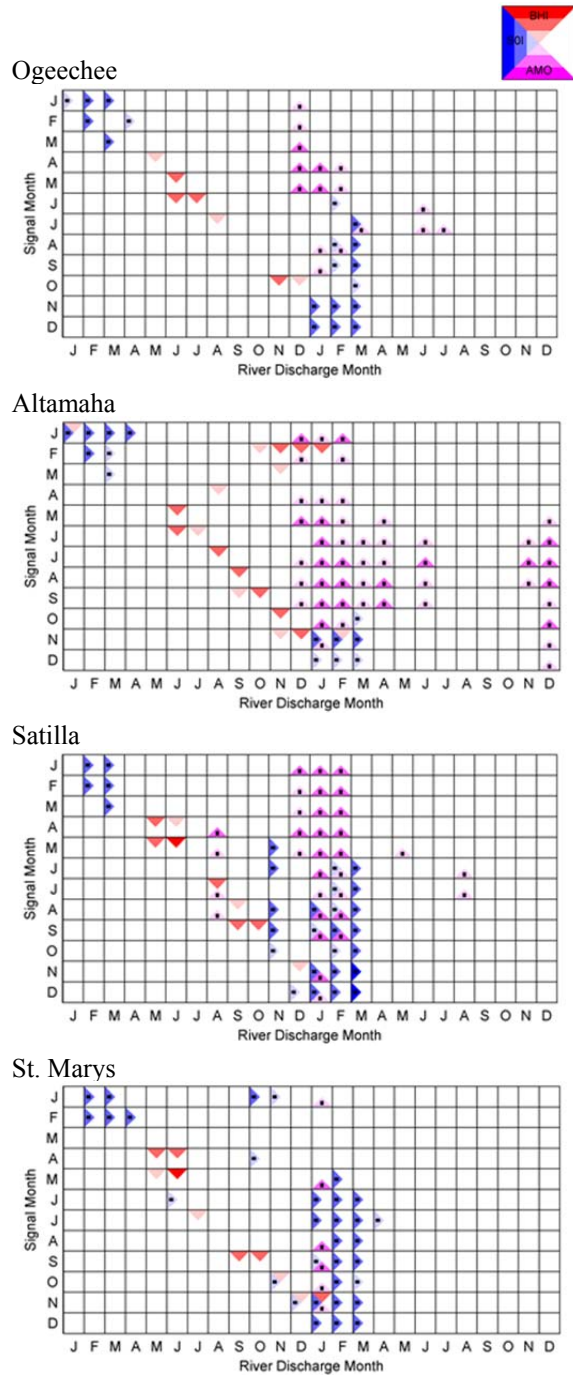


Fig. 1. Monthwise correlations between climate signals and river discharge into 4 Georgia riverine estuaries. In each square, the left triangle is the Southern Oscillation Index (ENSO), the top is the Bermuda High Index, and the bottom is the Atlantic Multidecadal Oscillation. The intensity of the triangle color denotes the strength of the correlation (weak:  $0.1 < |r| < 0.3$ , moderate:  $0.3 < |r| < 0.5$ , strong:  $|r| > 0.5$ ), and negative correlations are indicated by a dot within the triangle. From Sheldon and Alber (2013) and Sheldon and Burd (2014).

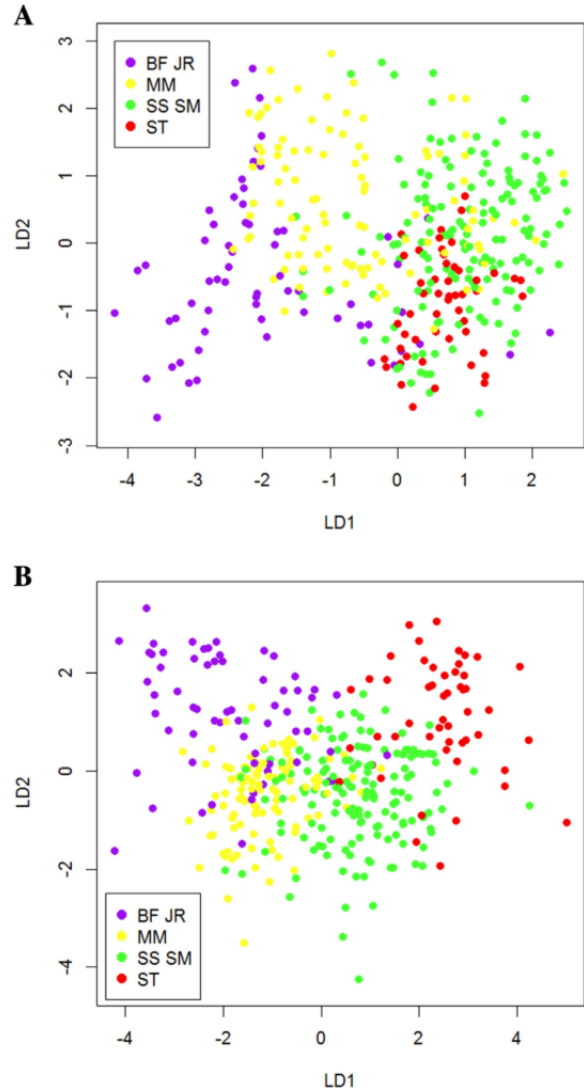


Fig. 2. Biplots of linear discriminant function one (LD1) and two (LD2) for (A) edaphic predictor variables (water content, salinity, and redox) and (B) remote sensing-derived predictor variables (DEM elevation in relation to MHW, slope and distances to MHW and uplands). Colors indicate LDA class assignments. ST: tall *S. alterniflora*; SS-SM: short and medium *S. alterniflora*; MM: marsh meadow; and BF-JR: *B. frutescens* and *J. roemerianus*. From Hladik and Alber (2014).

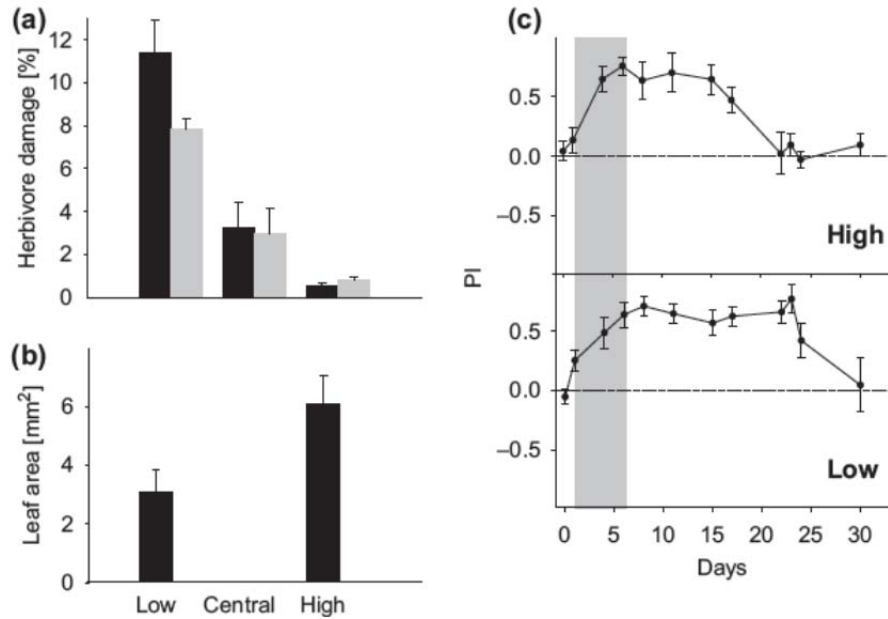


Fig. 3. Latitudinal variation in herbivory patterns and plant defenses in marsh elder (*Iva frutescens*); a: both average herbivore leaf damage (black bar; error bar = SE) and temporal variation in standard deviation (grey bar; error bar = SE) in leaf damage in *I. frutescens* are higher in low latitudes; b: in 2-choice feeding assays *P. aterrima* beetles consumed more leaf area of *I. frutescens* from high over low latitudes; c: *P. aterrima* preferred leaves from undamaged *I. frutescens* from both high and low latitudes; however, in lower latitudes this preference developed faster and lasted longer. From Wieski and Pennings (2014).

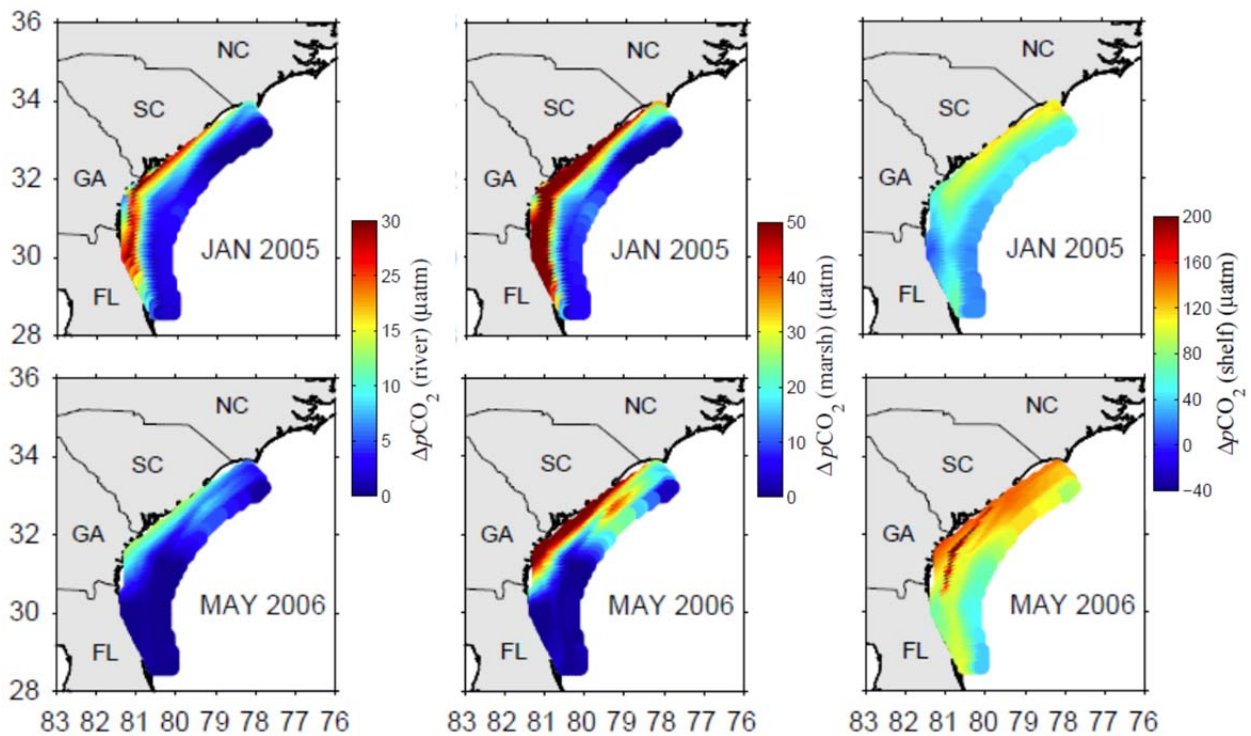


Fig. 4. Spatial distributions of  $\Delta p\text{CO}_2$  inputs (referenced to 23.11°C) from rivers (left), marshes (middle) and shelf (right) during January (top) and May (bottom). From Jiang et al. (2013).

## GCE Dissemination of Results 2014

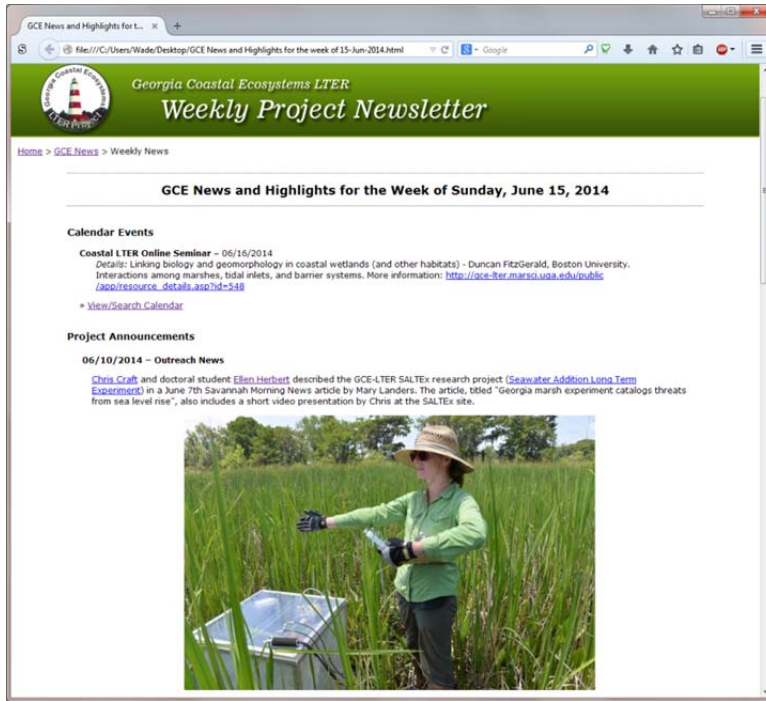


Fig. 1. GCE Weekly Project Newsletter, which is distributed via email to all GCE participants, advisers and interested parties every Sunday. The newsletter includes upcoming calendar events, announcements, recent publications and data submissions, and is generated dynamically from content in the GCE Information Management System.

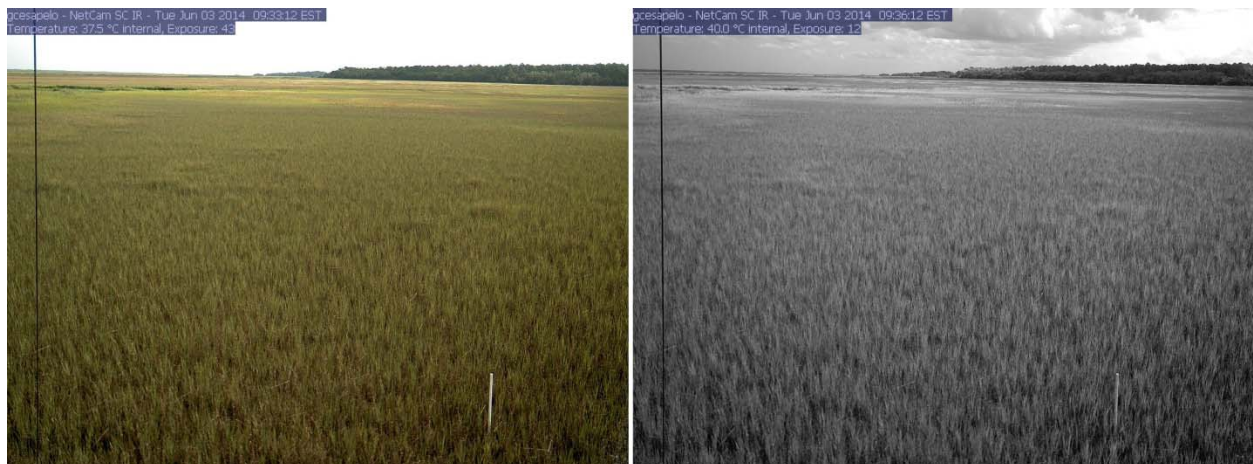


Fig. 2. PHENOCAM images are recorded every 30 min at the GCE Eddy Covariance Flux Tower site and transmitted to UNH automatically. Capture of RGB images was initiated in 2013, and Campbell logger code was developed in 2014 to enable capture of corresponding IR images.

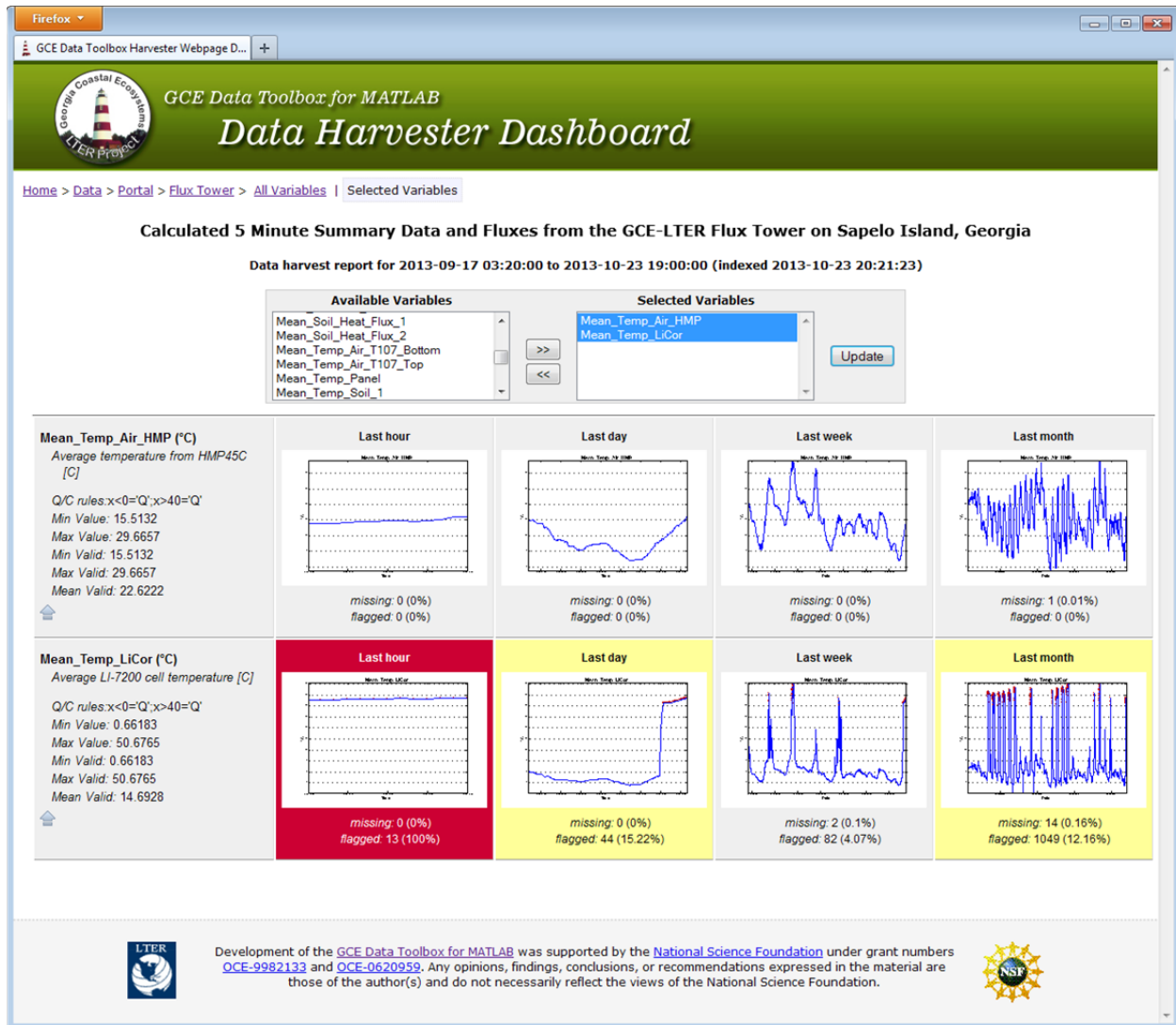


Fig. 3. Real-time data dashboard webpage generated by the GCE Data Toolbox for MATLAB software. Data statistics, QA/QC rules, number and percentage of missing and qualified values are summarized for each sensor over multiple time intervals. Quality problems exceeding set thresholds are highlighted to alert staff to potential sensor or communications issues. This feature, developed in Oct 2013, was improved in 2014 to automatically select and highlight all sensors exceeding QA/QC tolerances to alert monitoring technicians to problems more quickly.

## GCE Dissemination of Results 2014

Table 1. Total public data file downloads for 2012-2014 and 2001-2014 by data set theme and user affiliation, excluding GCE participants, metadata and GCE-to-LNO file transfers. Note that data distribution through the LTER Network Information System (NIS) just began in September 2013.

<b>Downloads by Data Set Theme</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2001-2014</b>
Algal Productivity	3	25	154	220
Anthropology	0	32	150	182
Aquatic Invertebrate Ecology	74	232	2825	3833
Bacterial Productivity	1	149	1325	1713
Chemistry	0	17	151	193
Fungal Productivity	0	25	225	279
General Nutrient Chemistry	17	43	177	423
Geology	3	17	143	202
Geospatial Analysis	0	25	306	341
Hydrography	1	14	80	131
Meteorology	12	89	536	830
Multi-Disciplinary Study	29	24	242	303
Organic Matter/Decomposition	0	103	590	864
Physical Oceanography	66	829	6743	8803
Phytoplankton Productivity	0	56	718	941
Plant Ecology	54	180	2119	2698
Population Ecology	0	4	59	63
Pore-water Chemistry	11	26	181	245
Real-time Climate	142	79	114	777
Terrestrial Insect Ecology	63	96	789	1287
Various (custom file)	3	7	0	58
<b>Downloads by User Affiliation</b>	<b>2012</b>	<b>2013</b>	<b>2014</b>	<b>2001-2014</b>
Academic Research Program	151	42	129	1741
Educational Program (K-12)	4	7	10	113
Educational Program (Post-secondary)	126	26	33	776
Environmental Advocacy Group	1	0	0	8
Government Agency	4	3	1	397
International LTER Site	11	1	2	46
LTER Network Office (Metacat)	51	9	3	1196
LTER Data Portal (LTER NIS/PASTA)	0	1823	17337	19160
Other LTER Site	29	29	3	255
Other/Unspecified	102	132	109	694
<b>Total Data Downloads</b>	<b>479</b>	<b>2072</b>	<b>17627</b>	<b>24386</b>