Critical Knowledge Gaps for Coastal Systems

Research Priorities for the U.S. South Atlantic and Gulf of Mexico

EXECUTIVE SUMMARY

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Workshop

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Co-Chairs

Elizabeth Herndon
Oak Ridge National Laboratory

Kenneth Krauss
U.S. Geological Survey

Xingyuan Chen
Pacific Northwest National Laboratory

Havalend E. Steinmuller
Louisiana Universities Marine Consortium

Organizer

Brian Benscoter
U.S. Department of Energy

About BER

The Biological and Environmental Research (BER) program supports transformative science and scientific user facilities examining complex biological, Earth, and environmental systems for clean energy and climate innovation. BER research seeks to understand the fundamental biological, biogeochemical, and physical principles needed to predict a continuum of processes occurring across scales, from molecules and genomes at the smallest scales to environmental and Earth system change at the largest scales. This research—conducted at universities, U.S. Department of Energy national laboratories, and research institutions across the country—is contributing to a future of reliable, resilient energy sources and evidence-based climate solutions.

This executive summary is available at ess.science.energy.gov/southeast-coastal-systems-report/.

Full report coming in 2025.

Executive Summary

Critical and Highly Vulnerable Coastal Systems

Coastal watersheds and shorelines are home to 52% of the U.S. population and provide trillions of dollars of economic and ecosystem services each year. However, communities and ecosystems in coastal regions are increasingly vulnerable to tipping points driven by climate change and human modifications to the landscape. For example, sea level rise is increasing flooding and salinization of low-lying areas, and periodic storm surges push ocean water farther inland and increase salinity in freshwater resources. These impacts eventually drive systems past critical thresholds and lead to rapid and often irreversible transformation. Changing weather patterns, water management, and land cover all affect water and sediment flow to the coast in ways that exacerbate extreme flooding and drought. Degradation of coastal systems reduces their capacity to sequester atmospheric carbon, serve as habitat to diverse biota, filter continental runoff, provide natural resources, and buffer inland communities against storms. The economic costs associated with impacts to these coastal systems include recovery from hurricane damage (e.g., $79 billion in 2021), property lost to sea level rise (between $66 billion and $106 billion by 2050), and increased energy bills to handle rising temperatures (estimates range from $400 million to $12 billion per year).

People who live in the U.S. southeast coastal region along the South Atlantic and Gulf of Mexico are exceptionally vulnerable to the effects of changing climate due to overlapping high environmental risk and low community resilience. Rates of relative sea level rise in the southeast coastal region are higher than anywhere else in the United States and accelerating. The low relief that defines the southeast coastal plains facilitates extensive flooding in response to sea level rise, extreme tides, storm surges, and heavy rainfall. In addition, the U.S. southeast is frequently and increasingly impacted by hot weather and climate-related extremes such as hurricanes, tornadoes, and drought; fires (both natural wildfires and prescribed burns); invasive species proliferation; and land-use pressures from dense human populations and associated energy and transportation infrastructure.

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Communities within this region are vulnerable to the economic and health impacts of these environmental factors due to overall poor health and limited access to care, socioeconomic stressors such as low incomes, and deficiencies in infrastructures that bolster community resilience. In addition to human populations, the U.S. southeast coastal zone supports critical energy infrastructure (e.g., oil refineries, ports, the Strategic Petroleum Reserve), industry (e.g., forestry, fisheries, agriculture, shipping), and tourism. All these are increasingly threatened by ongoing environmental change and ecosystem degradation.

Although all coastal systems share fundamental and conceptual similarities, knowledge transferability from other U.S. coastal regions to the southeast is challenged by the region's distinct and highly diverse physical, ecological, hydrological, and climatic features. The southeast has vast flat plains that experience large gradients in temperature and precipitation, generating substantial ecosystem heterogeneity and making the region a hot spot for biodiversity, with more than 1,800 endemic species. Moreover, coastal systems in the southeast experience high frequency and intensity of compounding disturbances that push them toward uncertain trajectories. The properties of these heterogeneous systems and their interactions with each other and with regional and global change result in changes to the southeast that are unique from those of other U.S. coastal regions.

The relative lack of historical model development and evaluation focused on coastal systems of the U.S. southeast means that Earth system models (ESMs), including the U.S. Department of Energy (DOE)–supported Energy Exascale Earth System Model (E3SM), may not accurately represent key processes and vulnerabilities in the region. Therefore, advancing predictive understanding of the Earth system requires specific understanding of the foundational attributes and processes of U.S. southeast coastal systems, their vulnerabilities, and their response to individual and compounding stressors.

Coastal Research Focus in the U.S. Southeast

The need to improve predictive understanding of critical coastal systems in the southeast is well aligned with research priorities of DOE's Biological and Environmental Research (BER) program. Within BER, the Earth and Environmental Systems Sciences Division (EESSD) strategically supports basic research to address key uncertainties and enhance multiscale representation and predictability of the Earth system. EESSD has a long history of using large-scale, long-term field studies, model development, and advanced analytical and computational capabilities to provide the fundamental science needed to tackle DOE mission–relevant scientific and energy challenges. Coastal systems in the southeast present a unique opportunity to engage DOE capabilities and collaborate with regional and interagency partners to address Earth system understanding across a hierarchy of scales, targeting a crosscut of EESSD strategic science priorities in a region important to the nation's environmental and energy security.

Recent BER investments are improving fundamental understanding and predictability of coastal systems, generating novel scientific insights, and stimulating advances in model development. While ongoing funding for research is currently focused on other U.S. coastal regions, a dedicated focus on the southeast is warranted to capture the region's unique hot and humid climate, flat landscape, highly diverse and spatially heterogeneous ecosystems, and perturbation from frequent and intensifying disturbances (e.g., hurricanes). Moreover, the dynamic processes and land–water interactions that are inherent to coastal systems are not yet represented in ESMs. These challenges preclude adequate predictive understanding of coastal systems and their feedbacks among land, ocean, and atmospheric systems at local to global scales.

To identify research needs and opportunities for improving predictive understanding of coastal systems in the southeast, EESSD's Environmental System Science program held a workshop in March 2024 on "Critical Knowledge Gaps for Coastal Systems: Research Priorities for the U.S. South Atlantic and Gulf of Mexico." The workshop brought together a community of researchers from diverse disciplines to identify (1) major vulnerabilities of coastal systems in the southeast; (2) critical gaps in knowledge, data, and modeling that limit the ability to predictively understand these systems; and (3) key research priorities for the region. This workshop complemented an August 2023 BER workshop and report on "Optimizing DOE

Opportunities to Research Land–Atmosphere Interactions in the Southeast," which focused on land–atmosphere interactions in this region.

This report, which represents the outcomes of the coastal workshop, defines the U.S. southeast coastal zone as extending south along the Atlantic Ocean from the Virginia–North Carolina border and west along the Gulf of Mexico to the Rio Grande River. This area, which includes upland and wetland systems within the coastal plains, spans eight states that contain a quarter of the U.S. population and substantial energy infrastructure. These systems exist along gradients of salinity (freshwater to saline) and inundation (infrequent to consistent) and are shaped by both marine influences and processes throughout watersheds that drain into the coastal plain.

Vulnerability Driven by Compounding Disturbances

Coastal systems in the southeast are uniquely challenged by the convergence of several overlapping stressors, disturbances, and events that occur at high frequency and/or high magnitude and can push systems toward tipping points. For example, sea level rise is a critical stressor that drives inland migration of coastlines and coastal ecosystems by increasing flooding frequency, submerging land, raising groundwater tables, and increasing salinization of surface and groundwater. Even minor changes in sea level rise impact large areas of the flat coastal plain, where low relief is compounded by ground subsidence associated with reduced sediment loads from river, land development, and belowground resource extraction. Consequently, uplands and freshwater wetlands in the southeast are converting to saline wetlands and open water more than in any other region in the country, leading to rapid ecosystem transition and land-cover loss. Continued submergence of coastlines across the southeast region over the next few decades will flood beachfront properties and shrink natural buffer areas that mitigate the effects of hurricanes and storm surges on inland communities.

The U.S. southeast also experiences frequent, high-intensity hurricanes and tropical storms; 10 hurricanes (five at Category 3 or higher) made landfall in this region between 2020 and 2023. These storms bring high winds and heavy rain that uproot, flatten or defoliate vegetation; generate pulses of saltwater intrusion into freshwater resources; and cause deposition, erosion, and sediment redistribution. Episodic seawater flooding from storm surge and extreme tides exacerbates chronic salinization from sea level rise and groundwater extraction. Since 2000, high tides alone have increased flooding frequency by 400 to 1,000% in the South Atlantic and Gulf regions. Seaward flooding is compounded by heavy precipitation events over land (e.g., tropical storms or derechos) that generate large freshwater flows toward the coast

The southeast is also vulnerable to rising air temperatures, increased temperature variability, and thermal extremes. For example, mangroves are migrating northward at the expense of tidal marshes as freeze events decrease in frequency and intensity. This vegetation shift affects ecosystem structure and function by impacting nutrient and carbon cycling, marsh elevation, coastal protection, and coastal food webs. Extreme heat and drought events alter freshwater flows to the coast and drive ecosystem transitions that have cascading effects to ecological function.

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In addition, nearly every coastal system within the southeast region has been modified to support increasing population density and associated resource requirements. Rivers are extensively dammed for hydroelectric power generation, recreation, and flood control; dredged to support navigation; and constrained by levees to prevent flooding. Groundwater and fossil fuel extraction contribute to land subsidence and saltwater intrusion. Developed areas and shrublands have greatly expanded over the last few decades with comparable decreases in forests, agriculture, and wetlands.

These changing patterns of land use and land cover modify water, sediment, and nutrient delivery to the coast. Moreover, coastlines have been directly altered to support residential and commercial developments as well as infrastructure meant to preserve beaches. These alterations have the potential to constrain ecosystem migration, influence ecosystem function, and drive state change to different ecosystems, potentially reducing their capacity to provide services, such as water filtration, erosion control, and carbon storage, and economic benefits such as tourism, fishing, and storm mitigation.

Key Gaps in Data, Knowledge, and Modeling

Predictive understanding of the function and trajectory of coastal systems in the U.S. southeast is limited by interconnected gaps in data, knowledge, and modeling. These critical gaps include uncertainties in the distribution and connectivity of coastal systems, biogeochemical processes underlying ecosystem function, and response to compounding stressors and disturbances. Dedicated efforts are needed to address these key gaps by using model-informed experiments and observations to improve quantification and predictive understanding of system attributes and process interactions.

Distribution and Connectivity of Coastal Systems

Drivers and Consequences of Shifting Ecosystem Distributions

The southeast coastal plain hosts diverse and unique ecosystems that are gaining, losing, or shifting geographic areas under the pressures of sea level rise, tropicalization, intensifying weather extremes, land-cover change, and other disturbances. The extent of these ecosystem changes is poorly described, and the magnitude of ecosystem area losses and gains over time is unknown. These gaps challenge efforts to accurately assess current states and predict future trajectories. Accompanying the need to characterize current ecosystem ranges at finer spatial resolution is the need to anticipate their changing distributions within the region. Identifying the current and future ranges of diverse ecosystems within the southeast is critical for understanding how their distributions are shaped by environmental drivers and for defining their contributions to local ecosystem services and globally relevant processes (e.g., carbon storage and greenhouse gas fluxes).

Processes Controlling Land-Surface Elevation

Land-surface elevation relative to mean sea level and tidal ranges determines ecosystem exposure to flooding and salinization associated with sea level rise. Current predictions of land-surface elevation and changes over time rely on empirical relationships that cannot adequately capture underlying processes. These processes include sediment transport and deposition, groundwater extraction, organic matter accumulation, and belowground productivity (e.g., root growth) but are highly variable across the region because of pronounced differences in vegetation and sediment dynamics. Furthermore, humans routinely modify land-surface elevation by building structures that affect water and sediment flow to the coastline. Process-based understanding and model representation of factors driving vertical accretion or collapse of the land surface and their response to diverse environmental drivers are needed to predict interactions of sea level rise with land-surface elevation, vegetation, and coastal hydrology at scales necessary for Earth system predictability and climate resilience planning.

Spatial Heterogeneity in Lateral Exchange

Coastal boundary dynamics (i.e., land–water exchange) are not explicitly represented in current ESMs; their inclusion is difficult because of their spatial heterogeneity relative to the typical grid size of ESMs, the need to represent lateral exchange, and active modification of boundaries by anthropogenic activities and sea level rise. Lateral fluxes of water, sediment, solutes, and other biotic and abiotic constituents from uplands into coastal plains, between terrestrial and aquatic compartments, and through coastal systems to the ocean are difficult to measure and poorly quantified. When flux data are available, they often represent large areas, limiting attribution to any one system or component. There is a pressing need to better characterize lateral flow through watersheds and between land and open water, particularly in response to compounding sea level rise, extreme precipitation events, and tropical cyclones. Moreover, the ability to represent exchange between grid cells and between land and ocean models remains a key challenge. Novel approaches and methods to capture the high spatial heterogeneity of the southeast coastal plain and to measure and model lateral fluxes need to be developed to fully capture how an intensifying hydrologic cycle impacts flooding and biogeochemical cycling in these coastal systems.

Biogeochemical Processes Underlying Ecosystem Function

Dynamic Carbon Storage and Fluxes

Coastal systems in the southeast (e.g., mangroves and salt marshes) have exceptional potential to remove carbon from the atmosphere and store it in plant biomass and soil organic matter. Carbon storage is enhanced in depositional and saturated environments, such as the wetlands that comprise more than 20% of land area in the region, where organic matter is buried under anoxic conditions that slow decomposition. Accurate and verifiable quantification of plant biomass and soil carbon stocks across these coastal watersheds is still lacking, as is an understanding of coupled interactions between carbon and other biogeochemical cycles in response to disturbances. For example, carbon stocks may decrease in response to altered hydrology, increasing temperatures, changes in nutrient loads, fire, erosion, and plant mortality, among other factors.

Associated with the need to understand controls on carbon stocks is a need to improve estimates of greenhouse gas fluxes. Freshwater wetlands emit high quantities of methane, a potent greenhouse gas produced under anoxic conditions. Methane production decreases with increasing salinity but increases with warming and saturation, and methane emissions to the atmosphere are modulated by vegetation, wind, and inundation. These complexities generate uncertain trajectories in methane emissions across the southeast where increasing temperatures, pervasive flooding, salinization, and changes in land cover and land use are driving shifts in the extent and function of different wetland types.

Redox Processes Across Upland to Wetland Gradients

Electron transfer (i.e., redox) reactions provide the energy needed for biogeochemical processes but depend on the availability of electron donors and acceptors. Coastal systems possess gradients of water saturation and salinity that create high spatial and temporal variability in redox reactants. As a result, coastal biogeochemistry is often dominated or influenced by spatial or temporal pulses of high activity (e.g., hot spots and hot moments). Redox conditions in soil and sediment have typically been assessed at discrete times and locations, resulting in uncertainty as to how these processes vary across heterogenous environmental conditions caused by complex, intersecting gradients and disturbances. It is unclear how redox gradients vary spatially across soil pore networks and as a function of hydrologic flow paths, soil bulk density, and plant root structures unique to the diverse soil types and ecosystems that exist across southeast coastal systems. More complete quantification of redox variability and biogeochemical reactions is needed to constrain carbon storage, greenhouse gas emissions, nutrient cycling, and sulfide toxicity and their responses to various stressors and disturbances.

Plant–Microbe–Soil Interactions

The composition and function of microbial communities change in response to saturation, salinity, and shifts in plant communities that alter belowground carbon allocation and nutrient uptake. Expected shifts in plant communities and introduction of tropical species to coastal regions of the southeast will have unknown effects on rhizosphere and soil microorganisms and their interactions with the soil matrix. Furthermore, plant and microbial communities may exhibit asynchronous responses to changing environmental conditions that are not well constrained. Investigating interactions between plants, microbial communities, and their soil environment in response to environmental drivers is necessary to determine impacts on carbon storage, nutrient cycling, and greenhouse gas emissions.

Response to Compounding Stressors and Disturbances

The U.S. southeast is experiencing pronounced sea level rise and saltwater intrusion that occur within the context of previous modifications to the landscape and concurrently with a variety of other disturbances that compound their effects on coastal systems. Uncertainty emerges from the interactions of multiple stressors and disturbances that occur at variable frequencies and generate unexpected effects on ecosystem structural losses and recovery potential. Coastal ecosystem structure and function and associated biogeochemical processes need to be understood within the context of a range of environmental conditions (specifically related to compounding and anthropogenic factors) that drive the trajectory of ecosystem function and transitions. Novel approaches are needed to evaluate interactions among various stressors, disturbances, and events within the context of antecedent conditions.

In particular, human modifications to the coastal southeast are widespread and substantially impact natural processes, necessitating consideration of how human activities fit within the broader understanding and representation of these systems. Land use and land cover are changing rapidly in the southeast, due largely to declining forest cover from increased development. In addition, human water use and flood mitigation efforts have significantly modified surface and subsurface hydrology. Research efforts need to consider current and future anthropogenic changes to the landscape, which will add stressors to these already altered systems as populations grow and the built landscape continues to displace natural coastal ecosystem features and functions.

Science Priorities and Research Opportunities

The diverse and dynamic nature of coastal systems in the U.S. southeast provides a unique and transformative opportunity to advance predictive understanding of coastal systems globally by refining representation of key processes across distinct environmental settings and compounding disturbances. Two-way interactions between modeling and experiments (a ModEx approach) are key to advancing predictive understanding of these systems. Access to higher-performance computing, along with flexible and adaptive mesh capabilities, is enabling model representation of coastal systems in more dynamic, realistic, and place-specific ways. These capabilities in turn can deliver vital information to local decision-makers while also constraining critical feedbacks to the whole Earth system.

Ongoing advances in autonomous field instrumentation enable continuous observations of environmental parameters that can be used to inform models in real time, while model outputs and uncertainty quantification assist development of laboratory- to field-scale investigations of critical knowledge gaps. Molecular-scale measurements available through multiple DOE user facilities (e.g., synchrotron light sources, neutron sources, the Joint Genome Institute, and the Environmental Molecular Sciences Laboratory) support mechanistic understanding of multiscale observations. Artificial intelligence and machine learning (AI/ML) approaches can be used to extract patterns from increasingly complex datasets and facilitate development of a process-based, integrated modeling framework. Workshop participants identified several key priorities for scientific research in southeast coastal systems that would take advantage of these capabilities to address critical gaps:

Determine Impacts of Compounding and High-Frequency Stressors and Disturbances

Although the effects of compounding stressors and disturbances on coastal systems can be difficult to discern from observations alone, the development of big data and AI/ML approaches presents a new opportunity to identify complex patterns through analysis of complementary, high-resolution datasets. These approaches require substantial data synthesis efforts to align disparate datasets collected across multiple agencies and at different spatial and temporal scales. In addition to synthesizing historical and real-time data streams, ecosystem-scale experiments targeting natural and manipulated gradients will be instrumental in understanding how different systems respond to diverse stressors and disturbances. Aggregating and synthesizing historical and near-real-time data through collaborative efforts across disciplines, agencies, and stakeholders are critical to identify remaining data and knowledge gaps, advance model development, and ultimately enable science-based decisions.

Examine Shifting Biotic Communities and Biogeochemical Impacts Associated with Ecosystem State Changes

Across the diverse and spatially heterogeneous coastal zones of the southeast, there is a need to define current ecosystem distribution and function and observe long-term trajectories of ecosystem transitions. Such knowledge would enable predictive understanding of sequential state changes associated with a combination of environmental drivers that include relative sea level rise. Shifting vegetation and microbial communities associated with these state changes feed back to biogeochemical processes including carbon and nutrient storage, transformation, and fluxes. Direct field-scale manipulation would enable comprehensive assessment of how ecosystems as a whole respond to key variables that impact coastal systems. Improved representation of these processes in predictive models will inform experiments targeting key uncertainties and enable exploration of how ecosystem transition or loss will propagate to ecosystem function (e.g., genomic indicators of microbial structure and function, biogeochemical reactions, carbon and nutrient cycling, and hydrologic cycling).

Understand Watershed Impacts on Coastal Dynamics

An integrated perspective is needed to understand how coastal dynamics are shaped by watershed processes, particularly in understudied watersheds that drain into the South Atlantic and Gulf of Mexico. Water, sediment, and solute transport from uplands to the coast affects the structure and function of coastal systems but is modified by changes in land use and land cover and climate extremes that include heavy precipitation and drought. Observation and modeling efforts should emphasize connectivity between and among upland and wetland ecosystems, including interactions among climatic and anthropogenic drivers, shifting vegetation distributions, lateral transport of water and carbon, vertical accretion and surface elevation, and belowground geochemical and microbial processes.

Integrate Southeast Coastal Processes and Observations into Multiscale Models

Aligned with these priorities, there is a specific need to advance model frameworks capable of representing processes and integrating observations across scales to tackle fundamental questions in coastal science. The southeast region's diverse coastal systems and disturbances present a unique opportunity to capture a range of processes relevant to coastal systems more broadly. Several existing model frameworks represent physical and biogeochemical processes at resolutions ranging from the pore scale to tens of kilometers and within modeling domains that include individual patches and hillslopes to the globe. However, true multiscale integration requires bridging the gaps in scale and process specificity across modeling approaches.

Models at finer spatial scales, such as AquaMEND and those enabled by the DOE Systems Biology Knowledgebase (KBase), represent microbial and geochemical reactions in mechanistic detail, providing a foundation for parameterizing these processes within models operating at larger spatial scales. Models at intermediate scales (e.g., PFLOTRAN and the Advanced Terrestrial Simulator) that resolve three-dimensional and multiphase flow and reactive transport could be used to evaluate connected surface and subsurface systems of saline marsh, bottomland freshwater wetlands, transition zones, and adjacent uplands. Models at larger spatial scales, such as the Functionally Assembled Terrestrial Ecosystem Simulator (FATES) and E3SM's Land Model, represent forest cohort demography, system interactions, and lateral connectivity while supplying coordinated boundary conditions and integrated effects of lateral process connections to models at fine scales. Important gaps must be addressed to update representation of processes specific to the southeast and integrate knowledge transfer among these models to accurately capture coastal system complexities and feedbacks.

Path Forward

Southeast coastal systems are uniquely vulnerable to the compounding effects of changing climate and anthropogenic factors.

Coastal systems in the U.S. southeast region provide substantial economic and environmental value to the nation but are uniquely vulnerable to compounding effects of changing climate and anthropogenic modifications. Predictive understanding is needed to evaluate the full range of how diverse southeast coastal systems function and respond to ongoing environmental pressures in order to identify impacts on coastal populations, critical energy infrastructure, and industries including fishing, shipping, and tourism. Current understanding and representation are limited by crosscutting gaps in data, knowledge, and modeling, driven in part by the complexity of coastal systems. However, ongoing development and integration of high-performance computing, process-based modeling, AI/ML, autonomous sensors, remote sensing, and molecular-scale techniques present an opportunity to advance predictive understanding of the highly diverse coastal systems in the southeast and their interactions with global processes. Dedicated efforts using two-way model-experiment integration (i.e., ModEx) can refine scientific understanding and provide predictive capabilities needed to enable science-based decisions. Research focused on southeast coastal systems presents an opportunity for BER to advance critical science needs, engage and facilitate interagency collaboration, and provide tools and insights needed for addressing regional climate resilience and DOE mission–relevant challenges.