Coastal Resilience Workshop

Trans-disciplinary Collaboration to Enhance Coastal Resilience: Envisioning a National Community Modeling Initiative

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Abstract

An interdisciplinary, collaborative program is needed to facilitate predictions of the inter-connected factors that will impact coastal systems and the resilience of coastal communities over the next few decades. Two interdisciplinary workshops were held, in 2014 and 2015, to develop consensus as to the needs and scope that might be included in such a program. This report integrates the outcomes of those workshops with a review of recent literature on the subject. Workshop participants agreed that the program should focus on building innovative enhancements of objective decision-making utilizing model results. It must integrate natural and social sciences and facilitate a cyber-supported network of modelers, scholars and stakeholders from academia, federal agencies, local and state governments, non-governmental organizations and the private sector. Observational data, imagery, and numerical models should support trans-disciplinary research to advance resilience regionally and locally. Improved resilience of low-income communities in flood prone areas should be a priority. The scientific community at large can initiate and evolve a network of interdisciplinary scientists and supporting cyber-infrastructure with emphasis on complex coastal systems. Collaborations must be facilitated with rigorous data and model standards, open source model code, and effective communication with a hierarchy of scientists and operational end users. Model projections are needed to support local government officials in assessing resilience, planning for humanitarian assistance and identifying the most vulnerable communities, environments, and facilities. Integrative methodologies should utilize historical data, probabilistic analyses, physics-based numerical models, socioeconomic models and complex systems models. New cyber networks and workshops can enable scientists and stakeholders with diverse backgrounds to collaborate and share methods, standards and models for solving coastal problems. The most important outcome of this initiative must be: developing viable long-range resilience programs that enable continually evolving adaptive management strategies underpinned by advanced numerical modeling.

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1. Introduction

The academic community, collaborating with each other and with federal agencies, state and local entities, non-governmental organizations and the private sector, can play a pivotal role in facilitating the integration of natural and social sciences to better assess the vulnerability and resilience of coastal systems and help to mitigate future disasters. Coastal systems include human communities, subject to changing threats from rising seas, increased storm frequency and intensity, evolving societal pressures and demographics, land loss, altered river discharge and water quality degradation. Haidvogel *et al*. (2013) among others have emphasized the need for integrating social and natural sciences in environmental forecasting programs. Dearing *et al.* (2014) articulate regional-scale social-ecological interdependence. The overall goal of the envisioned community effort should be to integrate social and natural sciences to assist planning and data- and model- driven risk assessment of coastal communities threatened by both long-term and event-driven (*e.g.*, by severe storms) inundation, land loss, water quality degradation and resulting risks to human health and safety as well as declines in industries such as tourism, fisheries, agriculture and shipping. In the future, much greater attention must be paid to planning for and enabling the resilience of low-income communities in flood prone areas. A long-range vision of such a program is centered on the creation of a consortium, or network, of scholars and stakeholders along with a *virtual cyber domain* that enables multi-institutional teams of numerical modelers from the National Oceanic and Atmospheric Administration (NOAA), the U.S. Army Corps of Engineers (USACE), Department of the Navy, Department of Homeland Security, Bureau of Safety and Environmental Enforcement, U.S. and foreign universities and the private sector to work together to model coastal threats and community, ecosystem and infrastructural responses to future scenarios of environmental and socioeconomic change. The rapidly evolving world of "big data" offers ever-widening opportunities for collaboration and communication. The consortium that is created will need to flexible and responsive to emerging challenges, opportunities and understandings.

An interdisciplinary collaborative program can help guide development of models for forecasting the key factors that will impact coastal systems and the resilience of coastal communities over the next few decades. The envisioned program can also assess how model results can improve decision-making. Once models have repeatedly proven their reliability in real-world events and have undergone rigorous testing, inter-comparisons and refinements by way of collaborative testbed and proving-ground programs, governmental leaders and emergency managers should no longer ignore them, as they did in the days and hours before Hurricane Katrina made landfall in coastal Louisiana in 2005. However, the scientific community at large must nurture the essential enlightenment of leaders via careful and straightforward articulation of scientific evidence and predictions informed by a strong social science component. The envisioned consortium can also contribute to providing the general public with education about coastal hazards and disaster awareness. The challenges to, rationale for, and potential approaches to the creation of a *consortium for coastal resilience* are set out in what follows based on syntheses of relevant literature and outcomes of discussions at workshops (Southeastern Universities Research Association, 2015).

2. Guidance from Two Workshops

This report follows the recommendations resulting from two SURA-sponsored workshops to consider the elements of an interdisciplinary collaborative program. As a first step and to identify the priorities, science requirements, and long-term goals, the Southeastern Universities Research Association's (SURA) Coastal and Environmental Research Committee (CERC), brought together a diverse community of natural and social scientists from academia, government and Non-Governmental Organizations (NGOs) in a workshop on *Understanding and Modeling Risk and Resilience in Complex Coastal Systems* held in Washington, D.C. on October 29 & 30, 2014 (Southeastern Universities Research Association, 2015). The goals of the 2014 workshop were *to identify the most critical issues in assessing future risks, vulnerabilities and resilience of complex coastal systems that involve interdependent social, legal, biogeophysical and biogeochemical factors.* The consensus from the 2014 workshop was that a consortium to facilitate collaborations among an extended and distributed community of interdisciplinary modelers and researchers concerned with coastal resilience and representing numerous universities, federal, state and local agencies, non-governmental organizations and private companies is urgently needed. The envisioned consortium could be modified from the examples of existing non-profit consortia.

Workshop conveners felt that, in the beginning at least, they should identify a few geographically specific cases and explore ways that we might collaborate to address, or anticipate, future system responses to plausible scenarios of future changes in natural and social conditions at the selected location. At the invitation of the Environmental Planning and Community Resilience Division, Broward County, Florida, the second workshop was held in Broward County during a time of "King Tides" occurring with the full moon on October 27, 2015 beginning with visits to several sites subject to frequent inundation. The workshop created a step-by-step process to help workshop attendees visualize the issues and define courses of action for challenging topics addressed by Broward County government personnel, the South Florida Water Management District, the US Army Corps of Engineers and the U.S. Geological Survey. To ground workshop discussions to a foreseeable future two decades from now, participants were asked to read, in advance, a hypothetical future scenario (Danchuk, Nichols and Wright, 2015) that involved sea level rise, changed demographics and increased storminess along with optimistic developments in modeling, community collaboration and communication with government officials. The hypothetical 2035 scenario was driven in part by climate change predictions (*e.g.,* from the National Center for Atmospheric Research) and in part by statistical projections of future demographics and economics. The aim was not to actually solve a problem but rather to explore how to collaborate and consider the methodologies and processes that would be needed.

Discussions during the Broward County workshop focused on four major challenge questions: *Challenge 1: Roles of Universities in Resilience Planning and Emergency Response/Preparation; Challenge 2: Community Resilience in Dania Beach;*

Challenge 3: Allocating resources/ redistributing functions across county community; Challenge 4: Water Resource Contamination (linking hydrodynamic and hydrologic models). With regard to Challenge 1, it was concluded that one prominent role should be to facilitate information sharing and the development of a knowledge base. Other important roles include technical review of contingency and disaster plans, research and education on disasters and policy, extension and outreach, and integrating university resources with agency capabilities. University-government collaborations, would contribute solutions to Challenges 1, 2 and 3 in several ways including development of planning data bases, providing a testbed for model assessment and comparisons, coupling social and physical models, identifying information gaps and providing High Performance Computing (HPC) resources for applying advanced, large domain numerical models including complex systems models.

Participants at the workshops concluded that as the coastal science community goes forward toward the creation of a *Consortium for Coastal Resilience* (or similar entity), there needs to be a clear focus on the nature of the connections and methods we hope to foster. Based on the outcome of the presentations and ensuing discussions at the two workshops, there was clear agreement that before a meaningful collaborative program could be launched, several fundamental questions needed to be addressed via a literature review. First, was to agree on a widely acceptable definition, or set of definitions, of resilience applicable to complex coastal systems. Following this, the steps in program initiation, an inventory of currently applied predictive models, needs for essential cyber support, and the target beneficiaries need to be considered. In what follows, we consider current thinking and strategies for promoting collaboration to enhance coastal resilience. We do this by way of a review of recent literature on coastal resilience and related matters, including integration of natural and social sciences and trans-disciplinary collaboration.

3. Defining Resilience as it Relates to Coastal Systems

"Resilience is the capacity of a system, be it an individual, a forest, a city or an economy to deal with change and continue to develop" (Stockholm Resilience Centre, 2014; www.stockholmresilience.su.se). According to a recent National Academies report on disaster resilience (National Academies, 2012), *"Resilience is the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events."* Resilience involves the ability to adapt to constantly changing environmental, economic, and social stressors. It does *not* imply constancy, stasis or resistance to change. It is the capacity to change and adapt continually yet remain viable. Humans and nature are interdependent and, through collaboration, natural and social scientists, and stakeholders can improve coastal resilience. According to the Stockholm Resilience Centre, "Resilience thinking embraces learning, diversity and above all the belief that humans and nature are strongly coupled to the point that they should be conceived as one social-ecological system." Low risk is not necessarily requisite for high resilience but risk and resilience should both be considered in planning future mitigation strategies. Coastal risk assessment is considered in detail in a recent NRC report (National Research Council, 2014a). Considering the complex interdependence of many factors, community

resilience and ecosystem resilience must be considered together, not as separate problems. Furthermore, since the built infrastructure and related services are integral components of communities, infrastructure resilience must be considered in relation to both communities and ecosystems (National Institute of Standards and Technology, 2015).

For natural ecosystems, such as wetlands, biodiversity is a source of enhanced resilience. Similarly, economic diversity probably results in increased community diversity. One well-known vulnerability index considers vulnerability to environmental hazards (Cutter, 1996). Arkema *et al.* (2013) discuss the roles that natural habitats can play in enhancing natural resilience of communities. As noted by the National Research Council (2006), the loss of coastal wetlands over the decades preceding Hurricane Katrina, substantially enhanced the vulnerability of New Orleans to that event. The Louisiana Coastal Protection and Restoration Authority (2007) is attempting to address this problem.

The US Army Corps of Engineers (USACE), Engineer Research and Development Center (ERDC) is developing a tiered set of coastal resilience metrics that integrate engineering, environmental and community resilience (Rosati, Touzinsky, and Lillycrop, 2015). Rosati, Touzinsky, and Lillycrop (2015) describe expert elicitation, data driven, and tiered methods to quantify resilience. Expert elicitation is somewhat subjective while the data-driven methods rely on a combination of historical data and numerical modeling. The USACE's approach considers preparation, resistance, recovery, and adaptation depending on factors such as need, time, space, and available funding. The three-tiered approach includes expert elicitation, field data and simple models, and rigorous assessment based on probabilistic analyses (Schultz, McKay, and Hales, 2012). An important aspect of any viable long-range resilience program is that it must enable continually evolving adaptive management strategies underpinned by advanced numerical modeling. The USACE has provided extensive guidance for engineering responses to sea level rise including regionally specific estimates of change (US Army Corps of Engineers, 2014).

4. Enhancing the Resilience of Vulnerable Communities

One urgent aspect of effectively intersecting social and natural science in this program is to anticipate and plan better for the future impacts of climate change on low-income communities living in flood-prone areas. The tragedy that unfolded in 2005 when Hurricane Katrina made landfall along the Louisiana and Mississippi Gulf Coast, was most acute in the flooded low lying and low-income neighborhoods of New Orleans, particularly the Ninth Ward. Nearly 2,000 people died and hundreds of thousands were displaced. The most severely affected African-American population has still not fully recovered ten years later. Elliott and Pais (2006) have articulated the tragedy of the inadequate concerns for the African American community in relief efforts following Hurricane Katrina.

As sea levels rise, low-lying vulnerable urban areas throughout the world will be more frequently flooded by storms. Wealthy populations will migrate to higher ground and the value of these higher elevation properties will escalate. Low-income families will be forced to move into higher density areas or to low-lying, flood-prone areas. Frequent street flooding of low-lying neighborhoods can paralyze traffic, sewers can be flooded, drinking water may be contaminated and water-borne pathogens may be spread throughout neighborhoods. And, as was the case in New Orleans in the days following Katrina, extensive inundation of neighborhoods can impede rescue operations following disasters.

Model projections can support local government officials in making resilience assessments to plan for more effective humanitarian assistance by interagency partners and help to identify the most vulnerable communities, environments, and facilities. The coastal scientific community must consider what kinds of data, model predictions, management policies and governmental investment strategies might prevent future dire circumstances similar to those faced by low income residents of New Orleans in 2005. It is now possible to predict "street by street" flooding probabilities utilizing detailed topographic data (Blumberg *et al*., 2015) and projected sea level rise as well model predictions of future demographics. Human health aspects, such as the feasibility of immunizations against water-borne diseases, must also be considered. What kind of protective structures such as sea walls or dikes might help protect low-lying neighborhoods if the "triaged" allocation of limited resources is more favorable to low income communities? What are some of the ways that the academic community can assist governmental agencies at local, state and federal levels in making long-range plans that serve all residents?

Today, the National Hurricane Center classifies hurricanes on a scale of 1 to 5 (the Saffir-Simpson scale, which indexes relative wind stress and the potential wind damage to structures). However, these levels apply only to wind intensity and likely impacts on structures and do not distinguish among the contrasting impacts that these storms may have on human communities, ecosystems, water quality or infrastructure other than buildings. For example, a Category 3 hurricane can be devastating to a low lying coastal city subject to widespread inundation by storm surge, with a fragile transportation infrastructure, a delicate coastal ecosystem and a poor community with low societal and economic resilience. The same storm may be but a short-lived nuisance to a more affluent community on high ground, surrounded by robust infrastructure and a healthy, resilient coastal ecosystem. In these two cases, the impacts of that Category 3 storm will be dramatically different. Similarly, the decadal impacts of alternative climate change scenarios will vary with regional and local circumstances. If community impacts were to be gaged on the levels of 1 (low impact) to 5 (severe impact) the storm impact in the first case might be level 5 but in the second case the impact might be a less catastrophic level 2 or 3.

Future decisions as to how to triage the distribution of limited mitigation resources, post-storm recovery assets and disaster relief should be prioritized on the basis of total predicted storm *impact*, not simply storm intensity and stress on structures. At present, the impacts are assessed after the fact but are not rigorously anticipated in advance. Defining objective and meaningful indices of such impacts must precede the eventual application to real time or foreshadowed events. The Hazus® Program of the Federal Emergency Management Agency (FEMA) represents the present "state of the art" in estimating potential losses from earthquakes, floods and hurricanes (FEMA, 2009a and 2009b). However, many aspects of this program are regionally specific and have not been implemented for many coastal communities. Hopefully, in the future, the academic community will be able to contribute to Hazus® in meaningful ways via the envisioned coastal resilience consortium. Finally, on a positive note and as is explained in the forthcoming Section 9 of this document, the widespread advent of smart phones combined with "big data" and social media capabilities will allow more effective real time decisions as to the deployment of emergency and rescue resources during future disasters.

5. The Science of Collaboration

According to Marinez-Moyano (2006) "Collaboration is a function of the recursive interaction of knowledge, engagement, results, perceptions of trust, and accumulation of activity over time." If the collaborative program we envision is to be successful and persist over a long enough timeframe to make a difference, the collaboration strategies and methodologies that we build must be as rigorous as the models and understanding they are designed to facilitate. The intent is not only to facilitate collaborations within the academic community but, most importantly, between universities and federal, state and local governmental agencies. To accomplish this we must ensure that a rigorous and broadly embraced protocol is established and followed. Collaboration involves much more than simply talking to and helping each other. To be effective it must involve mutual acceptance of a common set of goals, critical assessments of diverse approaches, iterative updates and incremental improvements to understanding and predicting, promotion of new paradigms and effective communication with a hierarchy of operational end users. A fairly comprehensive collection of essays on collaboration can be found in a book edited by Schuman (2006).

Rigorous and generally accepted standards are crucial and, in accordance with earlier coastal testbed experience, we should adopt the standards of the Open Geospatial Consortium (OGC; http://www.OpenGeospatial.org). The OGC is an established consensus standards organization and an international consortium of 371 companies, government agencies (including NOAA), and universities that develop publicly available interface standards. These services make complex spatial information and data services accessible, interoperable and useful to multiple applications. An ongoing OGC testbed activity is focused on Urban Climate Resilience. The early SURA Coastal Ocean Observing and Predicting Program (SCOOP; Bogden *et al.* 2007) adhered closely to OGC standards and the current SURA-led and NOAA-IOOS funded Coastal and Ocean Modeling Testbed (COMT; Luettich *et al.*, 2013) has evolved from that tradition.

The need for new approaches to facilitating collaborative interdisciplinary research and education was highlighted in a recent National Research Council (NRC) report on “Convergence” (National Research Council, 2014b). As emphasized in this NRC report, “Convergence” is intended to imply integration of knowledge, tools and ways of thinking from several disciplines. It is not simply the “patching together” of results from one single discipline as an input to another discipline. Centers and institutes are one way to promote collaboration among disciplines and are not as constrained as traditional departments. “Enterprise” entities that promote interdisciplinary synergies but also are designed to evolve as science and needs change may be better models. Fischer (2012) and Redden (2013) describe the notion of a *Center for Research, Education and Innovation (CREI)* where the “CREI” or “enterprise” can facilitate the inclusion of industry and governmental entities along with academics. This concept is being applied by the Skolkovo Institute of Science and Technology (Skoltech), a private university outside of Moscow. The enterprises are theme-based and may be virtual as opposed to centrally located. Focus areas for this type of research could include climate change drivers and coastal resilience. Enterprise themes can change or adapt as new needs and understandings unfold.

Recent collaborative research projects conducted by investigators from different disciplines in the natural sciences have successfully created new conceptual, theoretical, methodological, and translational innovations that address complex coastal problems by integration. With funding from NOAA’s U.S. Integrated Ocean Observing System Program (IOOS®), SURA has facilitated strategic collaborations to build and guide the Coastal and Ocean Modeling Testbed or COMT (Luettich *et al.*, 2013). The COMT has demonstrated considerable success in orchestrating collaboration among more than 20 universities along with agency representation from NOAA, Navy, EPA and the U.S. Army Corp of Engineers. The resulting COMT is now one of 11 official NOAA testbeds. The overarching goal of the COMT is to accelerate the transfer of research results to improve operational coastal ocean modeling and forecasting skill. SURA has advanced the COMT to evaluate the readiness of coastal and marine forecasts of low dissolved oxygen, flooding from storm surge, and coastal wave conditions. However, the COMT has not yet been extended to include social science or economic models. The capabilities that COMT supports include:

- Quantitative data on the behavior and implementation requirements of models;
- An archive of observations, model inputs and model results that can be used for testing and evaluating current and future models;
- Tools that use community standards to enable access, visualization and skill assessment of multiple model results; and
- A research environment where researchers and operational agencies can work together on selected modeling applications.

6. Launching a Collaborative Program: Initial Steps

Formulating a comprehensive plan for an enduring coastal resilience program can begin with determining areas where interdisciplinary synergies can be most readily applied, facilitating the infrastructural advances that are needed to accommodate future modeling and preparing a research plan for moving forward as a community. The scientific community at large can initiate and evolve a network of interdisciplinary scientists and supporting cyber-infrastructure with emphasis on understanding and modeling complex coastal systems and communicating the results to operational end users. A key role for the facilitating Consortium will not be to execute models but to provide the virtual environment within which modelers and non-modeling scholars from different disciplines can interconnect. Quite simply, coastal systems science must bring together different components of the system and integrating them.

Some crucial steps in this process include the following:

Step 1: Articulating the interconnections of socio-ecological systems and identifying the societal, legal, biophysical and biogeochemical criteria needed to model resilience in specific coastal regions.

- Refine understanding and articulation of interconnections of human and natural coastal processes.
- Advance understanding of the linkages between regional and ocean systems and scale-dependent inter-connections among societal, biophysical and biogeochemical factors.
- Develop criteria for assessing changes in *ecosystem services* and the impacts that these changes may have on rural and urban socioeconomic systems.
- Following the International Geosphere Biosphere Programme example, develop an analytical framework that is relevant to policy and decision-making at different levels and takes account of legal issues and constraints.

Step 2: Identifying the systems science requirements for future coastal risk and resilience programs.

- Catalyze interdisciplinary collaborations.
- Prioritize coastal threats (by region).
- Identify well-defined, integrated research questions and the required modeling, analysis and visualization products to address these questions.
- Identify and prioritize legal factors that may impact community resilience or vulnerability.
- Assess and refine social resilience indices as they pertain to both urban and rural coastal communities.
- Develop feasible data management structures for trans-disciplinary integration and communication.

Step 3: Creating an accessible and extensible cyber infrastructure for cross-disciplinary communication and collaboration

- Identify design criteria for a collaborative web portal for cross-disciplinary communication.
- Identify the search tools needed to effectively access existing data sets and model outputs.
- Develop a cyber template(s) to enable social and natural scientists, managers and legal scholars to share information in mutually

understandable formats (*e.g.,* utilization of NOAA big data for decision making).

- Define the needs for more effective data and model output visualization.

7. Anticipating Changes in Coastal Processes and Threats

Predictive models will necessarily underpin our ability to plan future adaptive strategies on decadal time scales. Event-scale forecasts will likely continue to depend on operational agencies such as the National Weather Service (NWS) and the National Hurricane Center (NHC) but improved tools from the appropriate collaboration-facilitating consortium can help to make those forecasts more reliable and relevant. At both long-range and event time scales, we should expect advances to be made progressively not only in modeling specific phenomena such as storm surges and demographic shifts but also in linking models and model outputs in ways that highlight feedbacks and non-linear connections. These will be complex systems models and the modelers will very likely need access to HPC resources. For all of the modeling activities, agreed upon sets of standards for the models as well as the observational data used to assess the models will be essential.

7.1 *Physical and Ecologic Models*

The ongoing Coastal and Ocean Modeling Testbed (COMT) has involved a fairly comprehensive suite of numerical models for predicting natural coastal phenomena, particularly coastal inundation by storm surge and waves as well as estuarine and shelf water quality and dissolved oxygen dynamics. The models tested, compared and refined during the first three years of COMT (Luettich *et al.* 2013) are summarized as follows:

a. *Inundation, Surge and Waves*- ADCIRC (Dietrich *et al*. 2010; Luettich *et al.,* 1992); FVCOM (Chen *et al.,* 2003); SELFE (Zhang and Baptista, 2008); SLOSH (Jelesnianski, Chen, and Shaffer 1992); SWAN (Booij, Ris, and Holthuijsen, 1999; Zijlema, 2010); WWMII (Roland *et al.*, 2009); WAVEWATCHIII (Tolman, 2009).

b. *Shelf Hypoxia*- ROMS (Fennel *et al.*, 2011; Haidvogel *et al.,* 2008); FVCOM (Chen, Liu, and Beardsley, 2003); NCOM (Ko *et al.*, 2008); HYCOM (Prasad and Hogan, 2007); NGOM-POM (Lanerole and Patchen, 2011; Oey, 1996).

c. *Estuarine Hypoxia*-Chesapeake Bay ROMS (Scully, 2013; Xu *et al.,* 2012); Chesapeake Bay Operational Forecast System (Lanerolle, Patchen, and Aikman, 2011); EFDC (Hong and Shen, 2012); CH3D-ICM (Cerco, Kim, and Noel, 2010); 1-term DO model (Scully, 2013).

Inundation, surge and wave models were compared with each other and with observational data from Hurricanes Rita and Ike in the Northern Gulf of Mexico during years 1-3 of COMT. Two-dimensional and three-dimensional models using both structured and unstructured grids were involved. Three unstructured grid models of coupled surge-wave effects were: ADCIRC+SWAN, FVCOM+SWAN, and SELFE+WWM. These models were run using identical unstructured grids with 424,485 nodes. Although those models yielded better results than the operational, long-standing two-dimensional SLOSH model used by NOAA for several decades, SLOSH continues to be the operational model of choice because it is well accepted, fast and does not require HPC resources. An important lesson to be learned from such results is that as we go forward with future collaborations between academia and governmental agencies, we must remain sensitive to the ever-present trade off between accuracy, computational efficiency and familiarity.

Notably, Broward County Florida is also using ADCIRC and Delft 3-D together with a suite of models for predicting ground water and hydrologic responses to sea level variations, "King tides" and rainfall events. Ground water models are particularly concerned with salt-water intrusion into the aquifer. Research focused on the coupling of human and natural system processes will help refine our ability to understand how human systems affect the natural system and natural systems affect human systems. This is a prominent example of a situation where a diverse team of academic scientists can work closely with local government to solve real problems and enhance understanding of the complexity of coastal socio/ecological/physical systems.

7.2 *Societal Considerations*

Existing models of inundation, water quality, coastal erosion, ecosystem dynamics and related impacts will be needed in future assessments of resilience. However, while physical and ecosystem modelers are predicting natural threats, the affected communities are also changing. The ways their economies and cultural behaviors evolve changes the community's risk. Changes in the age of the population and in its cultural heritage also change the risk factors. One challenge to social scientists: help predict what socio-economic changes are coming in the next 10-20 years. As in the case of the natural sciences, the past few years have seen significant advances in understanding and modeling societal factors and changes that can impact community resilience (*e.g.,* Gunderson and Holling, 2002). Van Zandt *et al.* (2012) consider neighborhood resilience in relation to social vulnerability and housing. Norris *et al.* (2008) offer a treatise on the psychology of community resilience as it impacts disaster readiness. More recently, Cutter, Ash, and Emrich (2014) and Cutter, Burton and Emrich (2010) have evolved the concept of *Baseline Resilience Indicators for Communities (BRIC)* as empirical metrics for gaging the resilience of communities to disasters. Berkes *et al.* (2003) offer in depth analyses of social-ecological complexity in assessing community resilience. Guillard-Gonçalves *et al.,* (2014) have developed a Social Vulnerability Index" (SoVI) which can be readily applied to most regionally specific communities.

7.3 *Interdisciplinary Intersections*

Beyond obvious organizational and governance challenges, effective interdisciplinary integration of models will require the convergence of an extensive and uncommonly diverse suite of scientific, demographic, economic, legal and cultural data and information. As the program matures, the challenges of "big data" and its management will necessitate the provision of sophisticated cyber analytics and services to ensure that the information is accessible and understandable to users with a wide range of backgrounds. Answers to questions such as: "How will the risk of flooding during an extreme event be exacerbated in various sea level rise scenarios?" will depend on where people with different vulnerabilities are living in the future. Recent advances in detailed modeling of "street-level" flooding in well-mapped neighborhoods (Blumberg *et al.,* 2015) can contribute to answering such questions as can similar advances in modeling the timing of storm surges in relation to tides (Georgas *et al.,* 2014). Intersecting predictions of inundation with patterns of social vulnerability such as that indexed by the "Social Vulnerability Index" (SoVI; *e.g.,* Guillard-Gonçalves *et al.,* 2014) would represent a valuable contribution to disaster planning.

The International Geosphere Biosphere Programme (IGBP) has articulated the importance of intersecting social and natural sciences and has evolved the "Anthropocene" paradigm that considers human and natural earth processes to be interdependent and to function and change as a complex system (Bondre and Gaffney, 2015). The idea of complexity is now widely accepted by modelers of dynamic systems involving the non-linear interdependence of multiple processes (Bar-Yam, 1997; Liu *et al.,* 2007). The coupling of societal, biogeophysical, biogeochemical, and ecological processes constitutes a prominent example of complexity. Over the next few years, advances in our ability to anticipate, plan for and mitigate the impacts of adverse changes in coastal processes and coastal communities will increasingly require not only continued refinements of natural science and social science models but also on development and application of complex systems models (*e.g.,* Janssen, 1998; Nicolis and Prigogine, 1989) that account for a hierarchy of interconnections and non-linear feedbacks. To enable such transformational advances, the scientific community should begin by assessing:

- Existing knowledge of human-environment complex system dynamics;
- The ability to model socio-ecological interactions at different scales;
- Relevance of existing models and analyses to policies and management practices;
- The potential impact of legal structures on community resilience to hazards;
- Development and assessment of "social vulnerability indices;"
- The applicability of complexity theories to analyzing interconnectedness of socio-ecological systems and addressing coastal sustainability.

8. A Cyber Infrastructure to Support a Virtual Modeling Community

Several researchers (*e.g.,* Plag *et al.,* 2015) have pointed out the need for international collaboration and virtual research environments to enable knowledge creation in response to societal needs**.** Cloud computing technologies facilitate the creation of cyber-supported "playing fields" where it is easier to work with others. An earlier attempt at establishing such an infrastructure is described by Bogden *et al.,* (2007). The infrastructure should link societal benefits to essential variables. There are numerous cyber tools and toolkits available to help make linkages, provide visualization, archive and retrieve data *etc*. However, the community needs a tech support network and training in how to utilize the tools. The envisioned coastal resilience consortium (or "collaboratorium") should help with these technical services. A cyber-infrastructure supported by an independent consortium can provide the playing field for developing, validating, communicating, and generally advancing the interdisciplinary collaboration between natural and social sciences for modeling risk and resilience in complex coastal systems. The supporting cyber services should include HPC resources for running models, a platform for accessing, sharing and archiving data and model outputs as well as for accessing and sharing open-source model codes, and a catalogue of and access to analysis routines and visualization tools.

An independent community-shared consortium can help the community to take a first step in addressing questions of risk and resilience by facilitating the creation of an open-source base of empirical and numerical model data along with a rigorous set of data standards and an extensible cyber infrastructure for managing, and accessing the necessary information. This will support a combination of discipline-specific and cross-disciplinary numerical modeling, coupling the outputs from physical process models with ecosystem and socioeconomic models, and statistical analyses of socioeconomic factors that might ultimately determine the resilience of communities to expected stressors. In addition, modeling protocols could be extended to enable the potential impacts (positive or negative) of engineering approaches or management decisions to be assessed. Over the course of the next few years, it is possible to accommodate most or all of the cyber needs.

As an example, the ongoing COMT, has had significant success in evolving an appropriate supporting cyber infrastructure. The primary purpose of the COMT cyber infrastructure has been to develop a unified search, access, analysis and visualization environment that allows scientists to run and compare different models with each other and with observational data (Luettich *et al.,* 2013). Among other things, this has involved maintaining a web site, a data archive, providing high-performance computing resources, and custom code to perform tasks such as skill assessment and format conversions. Researchers have shared algorithms through COMT that are used to reconstruct and understand natural hazards such as tropical cyclones and, of course, resulting phenomena such as flooding into discrete systems that can be solved by distributed computer systems. This type of community modeling complements observational and descriptive research.

9. "Big Data" Modeling of Linked Societal and Cyber Systems

The emergence of a data intensive society commonly referred to as "big data" presents an unparalleled opportunity for significant advances in the understanding and modeling of human behavior (Mayer-Schönberger & Cukier, 2013). This new paradigm has been famously referred to as the "new oil" that drives the information age society. Digital data produced by human activity is exploding at a rate that is estimated to be doubling about every two years (EMC Digital Universe, 2014). Social scientists suddenly have available data that was unimaginable a few years ago about human communications, mobility, commerce, health, and other important areas of societal life. Importantly, this data holds the promise of identifying and developing highly useful models of individual and community behaviors that will be able to interface more effectively with the modeling efforts from the physical and biological sciences (Bloem, Van Doorn, Duivestein, Van Manen, & Van Ommeren, 2012; Kallus, 2014). In order to exploit the potential of this trans-disciplinary approach, social scientists need to form teams with data scientists in order to advance their modeling to a level that will make it possible to effectively link societal with physical and ecological models. Alex Pentland (2014) at MIT's Human Dynamics Laboratory is among a growing list of scholars who are suggesting such a paradigmatic change that is based on the recognition that a data intensive society represents a new reality and that it can be studied in new and powerful ways because of the availability of massive amounts of information about the human existence. He lays out a landscape for the study of data driven cities and data driven societies that have a new capacity to adapt to emerging challenges including those from the physical and biological realms.

In order to fully appreciate the profound implications that "big data" has for the adaptability of human organizations and communities it is useful to consider its dimensions and complexities. While "big data" is often viewed primarily by its massive volume, it can also be considered in terms of other dimensions. For example, "big data" is of many different types: traditional, governmental and business datasets, social media, data from sensors, digitized commerce data, GIS data, satellite imagery, genetic sequencing, monitoring of environmental conditions, mobile data, individually collected images, such as smart phone photos, and other sources. "Big data" is also driving the development of technologies to collect, store, and process information. The rapid growth of high performance computing and especially cloud computing, the advent of wearables, the internet of us (IoUs) and the internet of things (IoT) are all examples of technologies and devices that result in the growth of data. Finally, the time dimension is also important. We are now able to access and utilize data in real or near real time and the demand and utility of real time data greatly expands our capacity for data impact. Much of online commerce is operating in real time frameworks. There also seems to be a strong human desire for anticipating the future and the combination of "big data" with predictive algorithms is pushing the utilization of data to predict future individual and collective behavior.

There is gathering evidence that data intensity may encourage and enable organic and self- organizing responses to extreme situations such as natural disasters and/or terrorists events. In the realm of collective action facing these type of critical events, big data has the potential to enhance rapid response and resilience (Colander & Kupers, 2014), and also have expanded the frontier for multidisciplinary research. Recently, it is common to find cases of social media usage to promote community-based response during natural disasters such as hurricane Sandy, Japanese Tsunami, or Pakistan earthquake, social media became an important aspect of disaster response and community resilience (Keim & Noji, 2011; Kongthon, Haruechaiyasak, Pailai, & Kongyoung, 2012; Landwehr & Carley, 2014). In similar fashion, "big data" enterprises such as Uber are emerging as important self-organizing forces during emergency situations. Uber was utilized during the recent Paris terrorist incident to evacuate individuals from the site of the terrorism. An even more adaptive example is the recent Indian based "Uber-like" service Ola that responded to the flooding in Bangladesh by including boats to evacuate people during the Bangladesh flooding.

Big data has been utilized by multidisciplinary teams in the recovery process in areas affected by natural disasters. A glimpse of this was quite evident in a recent study of several million geo-located tweets collected during Hurricane Sandy (Edwards, Mohanty, & Fitzpatrick, 2015). The researchers found that twitter was being used to meet needs often provided by first responders and relief agencies. Twitter users were asking for assistance, reporting on others that needed assistance, offering their help including equipment and supplies, and organizing groups of individuals to meet and assist storm victims. This was all done from the bottom up without any assistance from governmental or other entities (Colander & Kupers, 2014). The researchers were also able to capture thousands of photographs of the storm taken by smart phones that were useful in assessing the extent of damage and flooding at specific locations throughout the impacted area. In addition, individuals were reporting on power outages, thereby informing their neighbors of the power situation at different locations and providing the researchers with a near real-time understanding of the geographic spread of power outages.

10. Broward County Florida: A Microcosm of Coastal Complexity

Whereas the first workshop focused on universal issues and questions of resilience and collaboration, the second workshop in Broward County was more of an experiment in how to intersect a diverse academic community with local government managers and problem solvers. One of the main reasons for using Broward County as a venue was to explore solutions to immediate and emerging threats in a specific geographic area with a diverse population and subject to frequent inundation. Broward County covers an area of 3,186 square kilometers and includes the city of Ft. Lauderdale and several other smaller cities. It is bounded on the east by the Atlantic Ocean and on the west by the Everglades. The present (2015) population of nearly 2 million people is expected to increase 18% over the next 20 years and consists of 44% white/non-Hispanic, 25% Hispanic, 26% African-American and 5% other races. The most vulnerable residents include 260,000 people over 65 years old and 202,000 living below the poverty line. Statistics were obtained from the Broward County Planning Services Division (2002; 2015; http://bit.ly/1SeRcBE).

Broward County is especially relevant because of observed rates of sea level change coupled with frequent street flooding, salt water intrusion into the aquifer and episodic shortages of fresh water to homes. The mean range of the mixed, mainly diurnal tide for Broward County is 0.62 m and increases to approximately 1.2 m during "King Tides" (NOAA, 2015). The maximum heights of these King Tides are increasing annually because of superimposition of other non-tidal effects that contribute to the coastal flooding (*e.g.*, Ezer, 2013). Recurring flooding of streets, historic sites, and homes occurs during perigean high tides. Such flooding was prominently active during the workshop on October 26, 2015. For Florida as a whole, the rise in mean sea level over the past century has been around 21 cm (Maul, 2015), but this rate is likely accelerating due the steric effects of warming seas. The US Army Corps of Engineers (2011, 2013) estimates that by 2030 sea level will be roughly 18 cm higher than at present while Boon and Mitchell (2015) conclude that by 2050 mean sea level in South Florida could be on the order of 50 cm higher. These estimates do not take account of any unexpected glacial melting or calving in Antarctica or Greenland. Regional contributions to non-tidal water levels include long-term changes in global mean sea level, atmospheric-pressure and wind induced changes, fluctuations in offshore Ekman transport caused by fluctuations in Gulf Stream transport intensity (Ezer, 2013; Ezer and Atkinson, 2014), storm surge, wave-induced set up, and land sinking. Annual fluctuations in coastal sea level of up to one meter are attributed to aperiodic variations in Gulf Stream transport with higher sea levels corresponding to times of Gulf Stream slackening.

A particularly complex aspect of the challenges facing Broward County pertains to the interplay of surface hydrology, ground water hydrology, fluctuations in sea levels at different time scales and spatial and temporal variations in demand for fresh water by county residents. In the years around 1900 the Everglades was roughly twice as large as today and provided a much greater volume of fresh water to recharge the Biscayne Aquifer that immediately underlies Broward County. Reductions in that recharge have allowed the penetration of seawater into the aquifer. Today, the South Florida Water Management District maintains a complex engineered system involving levees, drainage canals, containment ponds and pumping stations. This system serves the multiple functions of mitigating flooding during heavy rainfall events, ensuring adequate distribution of freshwater to local communities and limiting seawater intrusion into the aquifer. Future modeling efforts on the part of collaborating teams of university and government modelers, decision makers and planners, should involve linking surface hydrologic, ground water, ocean inundation and sociologic models to optimize and prioritize solutions to this complex suite of problems. This would exemplify one of the roles that the envisioned consortium could play.

11. Challenges for the Future

Beyond the considerations just summarized, some overarching challenges must be overcome before the envisioned consortium can mature. There are also other factors that should guide the long-term direction of the program. No simple answers exist for most of these concerns but the program needs to encourage solutions to unfold as the program evolves. Meeting these challenges will require setting aside many traditional, but very constraining, ways of thinking and solving complex problems. But the communal benefits of doing this justify abandoning the comfort of "business as usual" and reductionist approaches of the past.

11.1 *The Challenges of Trans-disciplinary Collaboration*

Participants at the SURA coastal resilience workshop in October 2014, agreed with the urgency of adopting far-reaching interdisciplinary approaches to modeling future risks and resilience of socio-eco-techno-logical systems, as articulated by the IGBP and the Stockholm Resilience Centre. The complex interdependence among human communities, coastal ecosystems, climate and ocean physics is accepted as axiomatic by the vast majority of the scientific community. However, many universities are not up to the task of true interdisciplinary research. Part of the problem relates to the accreditation system and its discipline-specific standards. This impedes interdisciplinary work at many traditional universities. Multi-discipline papers with many authors are not really valued and young untenured faculty who engage in too much interdisciplinary work may be denied tenure. The discipline-based distribution of faculty on campuses is also a discouraging factor: social scientists and natural scientists may be based on opposite sides of large campuses or even on different campuses of multi campus state universities. The world is likely to be very different in 2050, as will the missions of universities that remain relevant**.**

11.2 *Outreach to Policy Makers, Politicians and the Public*

As *Hurricane Katrina* bore down on New Orleans in 2005, numerical models, were predicting high storm surges and waves for Coastal Louisiana (via the now discontinued *OpenIOOS* website and NOAA's NWS; *e.g.* Bogden *et al.*, 2007). Data buoys and integrated observing systems such as Wave-Current-Surge Information System for Coastal Louisiana in the Gulf of Mexico verified wave predictions. Those predictions were readily accessible in real time on the Internet in the form of color-coded animations and numerical data, but they were largely ignored by local, State and Federal leaders as well as by many emergency managers. In 2016, long-range scientific projections of climate-related phenomena and their impacts continue to be widely denied by many politicians and decision makers. Fortunately, in 2012, short-term wind, storm surge and wave forecasts were heeded as Super Storm Sandy moved up the U.S. East Coast and approached New York Bight and this undoubtedly saved many lives. But substantial improvements in communication and trust are still needed.

The scientific community at large must nurture the enlightenment of politicians and decision makers. This may be the largest challenge of all, but the scientific community must work diligently to persuade emergency managers and leaders at all governmental levels to trust science-based model predictions. This will require careful and well articulated, non-jargonized communication over a prolonged period combined with clear and repeated demonstrations that numerical models really work and are not a hoax. So the question is: How do we do that? One obvious way is to get to know the leaders and gain their trust through regular one on one visits, open forums involving bi-directional exchanges but not "lectures," and clear demonstrations of mutual respect among academics, local, state and federal government officials and politicians. And, of course, patience and persistence are essential. The envisioned "Coastal Resilience Consortium" should be able to greatly broaden the scope of outreach to officials by developing an accessible and extensible web site and cyber tool kits that serve clear graphical and textual explanations of long-and short-term model results.

A critical, and commonly overlooked, facet of outreach to enhance resilience involves educating the general public, particularly lower income and undereducated communities, about hazards and how to respond to them. A few U.S. universities already offer programs focused on helping communities become more disaster resilient through practical education. A prominent example is the *Center for Hazards Assessment, Response and Technology (CHART)*, an applied social science hazards center at the University of New Orleans (http://scholarworks.uno.edu/chart). Among other activities CHART staff provide risk literacy as a component of more general adult literacy programs. A network of collaborating university-based coastal resilience researchers and educators could provide web-accessible resources to other programs that share the goals of UNO's CHART.

11.3 *Identifying and Engaging Potential Beneficiaries*

The envisioned community effort can directly contribute to NOAA's stated goal of *Resilient Coastal Communities and Economies,* but will require a thoughtful, and possibly lengthy, process involving an uncommonly diverse assemblage of social and natural scientists, engineers, legal scholars, health scientists, stakeholders and decision makers. For the ongoing COMT program, the target beneficiaries have been operational agencies (particularly NOAA) and the main product has been the transfer of methodologies and models from research to operations. For the proposed consortium, the potential stakeholders may include the State Sea Grant Programs, re-insurers, county governments, state governments, health workers, emergency managers, resource managers, FEMA, NGOs such as Nature Conservancy and the Sierra Club, educators, the general public- and operational agencies (particularly NOAA and USACE). Although the specific needs of each of these stakeholders differ, the universal nature of the most urgent questions should enable the facilitating consortium to focus firstly on problems that are important to a broad range of beneficiaries. In some cases, however, it may be necessary to concentrate on a subset of stakeholders who have a narrow definition of "acceptable benefits" that communities actually value. Risk reduction is one such benefit. County and local government agencies charged with planning for future threats may be among those most willing to engage with the consortium.

12. The Next Steps

Over the years ahead, pursuits of this initiative and its evolution to become the mature, comprehensive program envisioned in this report will begin with some relatively straightforward and inexpensive steps followed eventually by the creation of an extensible cyber infrastructure and formal establishment of a distributed network of scientists, managers and stakeholders. We should strive to eventually build a comprehensive geospatial network and structure that not only supports collaboration among modelers and managers but also provides a "Google-style" connective platform for the general public in the event of a coastal disaster by utilizing social media to enable community-based response during natural disasters. The immediate, and modest, plans for the next three years include the following:

12.1 *Future Workshops*

Future workshops are planned through 2018. Collaborative teams will be multidisciplinary and have access to cyber tools to develop courses of action to address specific scenarios. During the scenarios, participants will apply research, communication and advocacy skills to improve governmental approaches to coastal resilience. Scenario-based analyses allow participants to estimate the impact of different factors, with the intent of getting an objective sense of resilience. Follow-up workshops are expected to focus on the following coastal regions:

Middle Atlantic Bight and Chesapeake Bay – Scenarios include environmental conditions represented by low-lying barrier islands, low-lying coastal plains, estuaries, and cuspate forelands fronted by wide, low gradient continental shelf and subject to rising sea levels, tropical and extra-tropical storms, high storm surges and frequent beach erosion. Water quality is also an important issue to be characterized. Among the societal factors for scenario development are coastal urban and rural communities with a mix of affluent and low-income populations. A diverse economic base includes military bases, tourism, commercial fisheries, aquaculture, agriculture, universities, technology and business.

Northern Gulf of Mexico and Mississippi Delta –Representative environmental conditions for scenario development include a major deltaic coast which experiences a diurnal microtidal regime and relatively low wave energy except during episodic storms and hurricanes. Environmental characterizations includes natural deltaic processes of growth and retreat as a result of sediment deposition from the Mississippi river change rapidly in response to hurricanes, sea level rise, and reduction of new river sediment supply by levees and river mouth jetties. Sea level rise and engineering works combine to reduce the Mississippi river's flow into certain areas impacting the natural land-building power of the river. Increased salt-water intrusion from the Gulf of Mexico into freshwater wetlands has negative impacts on freshwater ecosystems. Societal factors for scenario development include coastal urban and rural communities with a mix of affluent and low-income populations. Louisiana's economy relies heavily on tourism, recreational activities, and the oil and gas industry. A diverse economic base includes military installations, tourism, commercial fisheries, aquaculture, agriculture, universities, shipping and ports, technology and business.

South Atlantic Bight – Natural environmental conditions for a science-based scenario include low-lying barrier islands, low-lying coastal plains, estuaries, and tidal marshlands subject to a mesotidal regime, rising sea levels, tropical and extra-tropical storms, high storm surges and frequent beach erosion. Water quality is also an important issue. Coastal urban and rural communities are represented by a mix of affluent and low-income populations. The scenario distinguishes among a variety of regional socioeconomic characteristics where a strong economy relies heavily on tourism, recreational activities, and commercial fishing. A diverse economic base includes military training facilities and ports, tourism, commercial fisheries, aquaculture, agriculture, universities, shipping and commercial ports, technology and business.

The future workshops are intended to help make the regional coastal communities safer and more resilient to hazards. The workshops will bring together organizations from all sectors and foster partnerships for community collaboration. The scenario-driven workshops enable natural and social scientists to collaborate across disciplinary "boundaries", share best practices, and adopt resilience measurements that are appropriate to their specific coastal realms. The major goals and objectives are to:

- Reduce the impact of coastal hazards to coastal communities, ecosystems and economies.
- Improve the regional capacity to identify, plan, and respond to natural hazards.
- Develop better communication, awareness, and understanding of coastal hazards.

- Foster community resilience through outreach, education and innovative product development.
- Allow stakeholders to develop a common understanding and best practices to identify resilience metrics appropriate for their region.

12.2 *Creating an Advisory Committee*

Over the long term, the coastal research community should be encouraged (and supported) to work together with agencies toward the development of plans or actions that improve preparedness, and promote recovery and/or adaptation within multiple coastal jurisdictions or locations throughout the United States coastal zones. As one forthcoming example of such preparedness plans, The National Institute of Standards and Technology (NIST) has recently published a *Community Resilience Planning Guide for Buildings and Infrastructure Systems* (National Institute of Standards and Technology, 2015). To ensure that the proposed consortium is well-informed, rigorous and objective, a Science and Requirements Advisory Committee (SRAC), composed of well-established and non-conflicted experts, should be established to provide advisory opinions, analyses, data standards and collaborative integration of coastal resilience science and technology in different regions of the U.S. The SRAC can lead the evolution of a research plan focused on how science could enable the United States' to anticipate and address the consequences of changing climates, environments, sea levels and coastal demographics and on how separate research teams can strengthen each other through independently-facilitated collaboration. The trans-disciplinary nature of the SRAC can benefit three important issues common to existing resilience programs: (1) prioritizing funding; (2) highlighting new approaches to stimulating science, technology, and innovation; and (3) communication of data, model output and methodologies among diverse disciplines and between academia and operational agencies. This approach also highlights how federal, state, and local governments can draw on university resources to prepare, resist, recover, and adapt to natural and man-made disturbances.

12.3 *Defining Metrics for Success*

An initial task of the SRAC should be to work with the scientific community and stakeholders to define an appropriate and realistic set of performance metrics by which to gage the progress and success of the Consortium and of the workshop series. These metrics, and the associated sets of data and model standards, will be critical to the acceptance of future model predictions by government officials and the general public and will guide the progressive evolution of the Consortium. An important initial metric may be to quantify the degree to which a consensus is achieved among participating scientists and stakeholders with regard to strategies for moving forward on the decadal time scale and how best to integrate across disciplines. Measures of effective collaboration may include the production of interdisciplinary, multi-authored white papers, publications, proposals and disaster response plans. The extent to which the collaborative products are adopted by, or influence, operational agencies is another important metric as are improvements in the ability of the scientific community to gain the trust of politicians and officials. As the Consortium matures and supports innovative modeling and testbed activities, skill assessments of new integrative complexity and social science models may be added to the list of metrics.

13. Conclusions

Impermanence and dynamic change have always characterized coastal environments and efforts by engineers, managers or officials to enforce stasis are destined to fail over the long term. Adaptive strategies that consider all pertinent facets, socioeconomic and natural, of the coastal system are preferable but involve far more non-linear complexity and modeling challenges than do static technological solutions that are intended to "resist" rather than adapt. Developing such adaptive strategies is not a trivial exercise and must involve an interdisciplinary group of individuals who are able to embrace the greater value of community advances over personal ego. Climate change, sea level rise, ecosystem evolution, hydrologic changes in river discharge to the coasts and changes in the intensity and duration of storms and attendant coastal erosion are likely to accelerate the alteration of natural coastal realms over the decades ahead. In concert with these natural changes, the socioeconomic environment that underpins human coastal communities is also impermanent and dynamic. The interdependence of natural and socioeconomic processes in the Anthropocene (Certini and Scalenghe, 2015) is already giving rise to suites of highly complex and non-linear feedbacks, many of which are counter intuitive. In some cases, the outcomes of these feedbacks may be beneficial, but, for the most part, they are detrimental and, sometimes, have the potential for catastrophe as we saw in New Orleans when hurricane Katrina made landfall.

Improved abilities to predict, communicate, mitigate and respond to the outcomes of future coastal processes, gradual as well as abrupt, on both long-term and event time scales are essential to the welfare of coastal communities and to the sustainability of coastal ecosystems and built infrastructures. As noted in Section 9, "big data" provides humans, organizations, and communities substantial new capacities for innovation and change (McKinsey Global Institute, 2011; National Research Council, 2013). We may assume that this new "big data" capacity will be a major force in human adaptation to changing climate and other environmental conditions. Research that understands this process and links it to our knowledge and understanding of physical and biological phenomena is an exciting and potentially fruitful area of research. The distributed virtual world of "big data" and HPC resources offers the potential for the scientific community to make giant strides in developing these essential abilities. But only as a community that embraces the extended brain trust of all relevant disciplines and draws from many universities, federal agencies, NGOs and industry. Ideally, this distributed "*Collaboratorium"* should not be confined to U.S. institutions but may include international talent willing to participate in an "open source" and "open access" activity governed by a rigorous set of data and coding standards and rules of engagement. No single agency, university or organization will ever have the breadth or depth of capability that exists within the globally distributed scientific community at large. Similarly, no single agency, foundation or industry should be expected to fund the consortium. Instead, a competitive, multi-agency model, such as the National Ocean Partnership Program (NOPP) should be explored initially but with the hope of growing the effort over time through foundation and private sector support. The future must involve the broadest and most extensive collaboration possible. The consortium envisioned here should enable, encourage and guide the needed collaboration. And, like the resilient adaptive solutions it is intended to facilitate, the program that emerges must be adaptive, fluid and non-rigid.

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