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Systems Approaches for Coastal Hazard Assessment and Resilience

Scott C. Hagen, Davina L. Passeri, Matthew V. Bilskie, Denise E. DeLorme, and David Yoskowitz

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Summary and Keywords

The framework presented herein supports a changing paradigm in the approaches used by coastal researchers, engineers, and social scientists to model the impacts of climate change and sea level rise (SLR) in particular along low-gradient coastal landscapes. Use of a System of Systems (SoS) approach to the coastal dynamics of SLR is encouraged to capture the nonlinear feedbacks and dynamic responses of the bio-geo-physical coastal environment to SLR, while assessing the social, economic, and ecologic impacts. The SoS approach divides the coastal environment into smaller subsystems such as morphology, ecology, and hydrodynamics. Integrated models are used to assess the dynamic responses of subsystems to SLR; these models account for complex interactions and feedbacks among individual systems, which provides a more comprehensive evaluation of the future of the coastal system as a whole. Results from the integrated models can be used to inform economic services valuations, in which economic activity is connected back to bio-geo-physical changes in the environment due to SLR by identifying changes in the coastal subsystems, linking them to the understanding of the economic system and assessing the direct and indirect impacts to the economy. These assessments can be translated from scientific data to application through various stakeholder engagement mechanisms, which provide useful feedback for accountability as well as benchmarks and diagnostic insights for future planning. This allows regional and local coastal managers to create more comprehensive policies to reduce the risks associated with future SLR and enhance coastal resilience.

Keywords: sea level rise, morphology, ecology, hydrodynamics, economic valuations, stakeholder engagement

Introduction

Worldwide, low-lying coastal land margins are becoming increasingly vulnerable to natural and manmade disasters due to the effects of climate and socioeconomic change (Barbier, 2014; IPCC, 2014). It is estimated that 1.9 billion people (27% of the world's population) live within 100 km of a shoreline and at an elevation lower than 100 m (Kummu et al., 2016). In the United States, population density in coastal counties far exceeds that of the nation as a whole (446 and 105 persons/square mile, respectively), and this trend is predicted to continue (NOAA, 2013). In addition to human communities, the coastal land margin includes ecologically and economically significant estuaries and wetlands that provide food, shelter, and nursery areas for commercially harvested fish and shellfish, and protect coastal communities by mitigating the impacts of storm surge and erosion (Barbier et al., 2011; NOAA, 2011). In 2011, 45% of the U.S. gross domestic product was produced in shoreline counties (NOAA, 2012). Global climate change and sea level rise (SLR) in particular have the potential to affect these coastal environments with more extensive tidal and storm surge inundation, increased erosion, and wetland loss. Low-gradient coastal landscapes are especially vulnerable to the effects of SLR, which could be detrimental for human communities and estuarine habitats. As populations increase, coastal areas will be susceptible to additional stresses associated with land-use and hydrologic changes (Wong et al., 2014). With more human lives at stake, along with economic output, measures to enhance coastal community resiliency are no longer an option, but a necessity.

Understanding the future of coastal environments depends on scientific evaluations of the impacts of climate change. Observations and modeling of individual coastal systems are insufficient for scientifically defensible, detailed, and credible assessments of the response of the coastal region under future conditions. Rather, synergetic studies that integrate dynamic interactions and responses among physical, ecological, and anthropogenic environments are needed for more holistic evaluations (Passeri et al., 2015c). The purpose of this chapter is to propose and encourage the use of a System of Systems (SoS) approach to assess potential ecologic and economic impacts of future coastal hazards under global climate change, and SLR in particular, herein coined "the coastal dynamics of SLR." This framework considers the integrated responses and feedbacks of multiple interdependent coastal systems to project how coastal environments will evolve under future SLR. Unique benefits of using a SoS approach include the capability to model the bio-geo-physical system, link that modeling to the historic record, and produce a dynamic response to SLR. Incorporating economic data and ecosystem services valuations into the SoS permits stakeholder groups to better understand and evaluate future coastal hazards and enhance human community coastal resiliency. Ultimately, a SoS approach supports the translation of data from science to application with transdisciplinary research results that enable coastal managers to make more informed decisions to manage human and natural communities in the future.

What Is a System of Systems?

According to Maier (1998), in the context of systems engineering, a system can be considered a SoS when:

> (1) its components fulfill valid purposes in their own right and continue to operate to fulfill those purposes if disassembled from the overall system, and (2) the components systems are managed (at least in part) for their own purposes rather than the purposes of the whole (p. 268).

While the individual constituents of a SoS can differ and function autonomously, new properties and patterns may emerge from their interconnectivity. These properties/patterns cannot be realized *a priori* and cannot be inferred from the systems' individual constituents or their individual properties alone (Keating, 2008). In the context of coastal hazards, a SoS approach allows nonlinear and dynamic effects of SLR to emerge among individual coastal systems that would otherwise be unobserved using simplified models. In doing so, more complex interactions and feedbacks among individual systems are accounted for, which provides a more holistic understanding of how the larger system may evolve over time.

The SoS for the coastal dynamics of SLR contains smaller subsystems such as hydrodynamics, morphology, ecology, and land use that are tied to political and social system implications (Figure 1). Each of these subsystems contains components that can reach higher levels of complexity and refinement. For example, hydrodynamics are comprised of tides, waves, and storm surge. Likewise, coastal morphology includes features such as barrier islands, beaches, and dunes. Each subsystem interacts dynamically on different spatial, temporal, and energy scales. To capture the function, interactions, and dynamic responses of subsystems to drivers such as global climate change, integrated models are needed that link SLR to carbon emission scenarios so that the full climate change impact is considered. This scenario-based approach produces projections of potential dynamic responses rather than deterministic predictions. Modeled projections can then inform economic impact assessments and ecosystem services valuations, which can be used with projections of how the system will evolve to produce management tools though stakeholder engagement. These tools, along with judgement, allow coastal managers to make more informed decisions on coastal hazards, which can be fed back into the suite of integrated models for evaluation of the impacts of potential management actions. This distinguishes the SoS approach from existing methods to assess coastal hazards such as the Source–Pathway–Receptor–Consequences (Gouldby and Samuels, 2005) approach, in which a hazard (e.g., SLR) is connected linearly to a risk (e.g., loss of ecosystems), but integrated responses and feedbacks of other risks (e.g., loss of shorelines), and the effects of coastal management decision making are not accounted for. The following sections detail the various subsystems and components that comprise the SoS approach to the coastal dynamics of SLR.

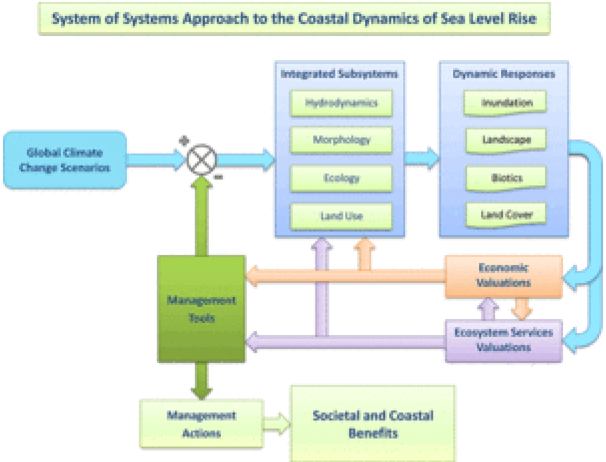

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Figure 1. A system of systems (SoS) approach to the coastal dynamics of sea level rise. Global climate change scenarios (particularly SLR) drive changes in integrated coastal systems such as hydrodynamics, morphology, ecology, and land use. The response of these systems to SLR is dynamic and may include inundation of land, changes to the coastal landscape (e.g., dune and shoreline erosion), changes in biologic species (e.g., marsh loss or migration), and changes in land cover. Projecting the response of each subsystem is necessary for ecologic and economic valuations. Through stakeholder engagement, results from these assessments can be translated from science to application via management tools that can be used to make more informed decisions about mitigating risks such as SLR. The results of the valuations can also be fed back into the analysis of the coastal systems to re-evaluate potential impacts. Likewise, actions based on management tools can induce further changes in the coastal systems.

Sea Level Rise

The first component to consider in the SoS for the coastal dynamics of SLR is global climate change and SLR in particular, which drives dynamic changes in each subsystem. The main factors contributing to global mean SLR include thermal expansion of sea waters, land ice loss, and changes in land water storage. Spatially, SLR is nonuniform, primarily as a result of changes in ocean density structure caused by temperature and salinity variations (i.e., steric effects) (Bindoff et al., 2007), as well as effects related to the response of the Earth to present-day land ice melt and the last deglaciation. Additionally, localized vertical land movement such as subsidence or uplift (due to natural causes or human activities) can amplify or reduce the effects of SLR. These three components can cause large deviations in local relative sea level rise (RSLR) measurements compared to global SLR observations (Cazenave & Le Cozannet, 2013). Historic tide gauge records indicate a global mean SLR between 1.6 mm/year and 1.8 mm/year over the 20th century (Church & White, 2006; Jevrejeva, Grinsted, Moore, & Holgate, 2006; Jevrejeva, Moore, Grinsted, & Woodworth, 2008; Church & White, 2011). According to high-precision satellite altimetry data, global mean SLR has accelerated with global rates as high as 3.4 mm/yr between 1993 and 2009 (Nerem, Chambers, Choe, & Mitchum, 2010; Hay, Morrow, Kopp, & Mitrovica, 2015). Climate change modeling indicates that sea levels will continue to rise in the upcoming decades and even centuries (IPCC, 2013; Levermann et al., 2013). Therefore, projecting future global mean sea level is critical for assessing vulnerabilities to built and natural environments. Projecting future rates of SLR can be challenging due to the complexities in contributory processes such as glacier melt, air temperature, CO_2 levels, thermal expansion, and volcanic, solar, and greenhouse gases (Church & White, 2006; Jevrejeva et al., 2006). Although historic rates of SLR can be used to assess future impacts, they cannot account for predicted changes and associated uncertainty in future SLR. Projections of future global mean SLR can be used to consider multiple future conditions and develop response options, given the range of uncertainty (Parris et al., 2012). For example, the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report projects that global mean sea level will rise between 52 and 98 cm by the year 2100 under the highest emissions scenario, and 28–61 cm under the lowest emissions scenario (Church et al., 2013). Similarly, Parris et al. (2012) identified four scenarios of global mean SLR by 2100: the lowest (0.2 m) is derived from a linear extrapolation of historical mean sea level using tide gauge records dating back to 1900; the intermediate-low (0.5 m) is determined using the upper end of the IPCC Fourth Assessment Report (AR4) global SLR projections from climate models employing the B1 emissions scenario; the intermediate-high (1.2 m) is derived from the average of the high end of semiempirical global SLR projections that use statistical relationships between observed global sea level change, including recent ice sheet loss and air temperature; and the highest (2.0 m) projection is determined using the IPCC AR4 global SLR projection with estimates of maximum possible glacier and ice sheet loss by the end of the century.

Coastal Dynamics of Sea Level Rise

In this section, three dynamic subsystems—namely coastal morphology, ecology, and hydrodynamics—are selected to illustrate how individual subsystems integrate to form the larger coastal system. Although each subsystem responds to the effects of SLR on different spatial, temporal, and energy scales, the responses are dynamic and interrelated.

Coastal Morphology

Coasts are dynamic systems that continuously transform as a result of integrated geomorphic and oceanographic processes that occur over different temporal and spatial scales (Cowell et al., 2003A, 2003B). The impacts of short-term processes (such as storms) on barrier islands and beaches are regulated largely by dune elevations (Sallenger, 2000; Stockdon, Sallenger, Holman, & Howd, 2007; Long, de Bakker, & Plant, 2014), and can result in erosion, overwash, or breaching, depending on the island's characteristics (Sallenger, 2000; Plant & Stockdon, 2012). Over longer timescales (decades to centuries), the combination of storms and SLR will evolve barrier island morphology (Fitzgerald, Fenster, Argow, & Buynevich, 2008; Gutierrez, Williams, & Thieler, 2009; Wahl & Plant, 2015). This can produce rapid shoreline erosion as a function of high rates of relative SLR (Morton, Miller, & Moore, 2004) and storm impacts (Fearnley, Miner, Kulp, Bohling, & Penland, 2009; Stockdon et al., 2012). Additionally, the local sediment budget and sediment texture affects long-term barrier island evolution; barrier islands with limited or finer sediment will erode more quickly than barriers with abundant or coarse sediment (Twichell, Pendleton, Baldwin, & Flocks, 2009; Twichell, Flocks, Pendleton, & Baldwin, 2013).

The most straightforward approach to assess the long-term shoreline response to SLR is to consider inundation under a static, or "bathtub" approach based on the elevation of the land and the amount of SLR. Coasts with mild slopes will experience more inundation for a given SLR than coasts with steep slopes (Zhang et al., 2004). This approach can be problematic due to large uncertainties in the topographic data (Gesch, 2009; Gesch, Gutierrez, & Gill, 2009) as well as neglecting hydrodynamic processes that may cause shoreline erosion (Passeri et al., 2015C). While numerical models are capable of predicting barrier island response to specific storm events with high skill (Roelvink et al., 2009; McCall et al., 2010), they are often too complex and inefficient to make long-term projections in response to multiple storms and SLR. Instead, simplified morphodynamic models based on empirical rules and analyses (Cowell, Roy, & Jones, 1995; Storms, Weltje, van Dijke, Geel, & Kroonenberg, 2002; Stolper, List, & Thieler, 2005; Lorenzo-Trueba & Ashton, 2014), as well as statistical approaches (Hapke & Plant, 2010; Gutierrez, Plant, & Thieler, 2011; Yates & Le Cozannet, 2012; Gutierrez, Plant, Thieler, & Turecek, 2015; Plant, Thieler, & Passeri, 2016) can be more effective for examining long-term barrier island evolution. These models rely on capturing joint correlations between morphological parameters and their drivers, as well as feedback mechanisms (Plant et al., 2016). Probabilistic models have indicated that as SLR continues to accelerate along low-gradient coastlines, long-term shoreline erosion rates will increase (Gutierrez et al., 2011; Plant et al., 2016), while dune elevations will decrease as a result of frequent overwash or rapid evolution in which a low coastal elevation is maintained (Plant et al., 2016).

Ecology

Another subsystem to consider in the coastal dynamics of SLR is ecology. Ecosystems are unique compared to the other coastal subsystems because they are self-organized, adaptive, and contain many feedback mechanisms (Jorgensen & Fath, 2011). For example, coastal salt marshes that are found at the coastal land margin sequester carbon, improve water quality, provide habitats for commercially harvested species, and dampen wave energy, thereby protecting nearby shorelines from erosion during storm events (Moller, Spencer, French, Leggett, & Dixon, 1999; NOAA, 2011; Ouyang & Lee, 2014). These ecological subsystems are governed by their own physical processes and influenced by changes in other subsystem's physical processes (Silliman & Bertness, 2002). Salt marsh growth is governed by elevation, tidal inundation, hydroperiod, sediment supply, and biological dynamics (Morris, Sundareshwar, Nietch, Kjerfve, & Cahoon, 2002; Stralberg et al., 2011). The elevation of a marsh platform can increase through particle capture during tidal inundation (Mudd, D'Alpaos, & Morris, 2010). Proximity to tidal creeks is crucial for deposition; areas near the banks of the creeks tend to accrete faster than the inner marsh (Townend, Fletcher, Knappen, & Rossington, 2011). If currents in tidal creeks are flood-dominant, there is likely a higher suspended sediment concentration at the marsh boundary, which supplies more marine sediment to the marsh. If currents are ebb-dominant, sediment supplies are likely reduced as sediment is transported seaward (Friedrichs & Perry, 2001). Hydroperiod (i.e., the period of time a marsh is inundated), which is dependent on the local tidal range, dictates sediment transport across the marsh surface (Reed, 1990). An increase in hydroperiod allows for inorganic sediment accretion until the hydroperiod eventually decreases; at this point, stress on the vegetation decreases accretion, once again increasing the hydroperiod (Friedrichs & Perry, 2001). Additional factors contributing to platform accretion include deposition of organic matter from root growth (Mudd et al., 2010) and inorganic matter from mineral sediment (Morris et al., 2016) and nearby eroded shorelines, especially during storm events (Phillips, 1986; Cahoon et al., 1995; McKee & Cherry, 2009; Baustian & Mendelssohn, 2015).

The spatial extent of salt marshes in the future relies on their ability to grow vertically at rates greater than relative SLR or to migrate inland before their seaward boundary is eroded (Kirwan, Temmerman, Skeehan, Guntenspergen, & Fagherazzi, 2016). The marsh platform elevation must continuously adapt through sedimentation towards an equilibrium that keeps pace with changes in mean sea level (Morris et al., 2002). A small increase in sea level relative to the platform elevation can increase accretion and therefore productivity (Reed, 1990; Nyman, Walters, Delaune, & Patrick, 2006; Alizad et al., 2016). Relatively low rates of SLR can also reduce depths on adjacent tidal flats, which increases wave dissipation and sediment deposition, and allows the marsh boundary to prograde (Mariotti & Fagherazzi, 2010). However, if the rate of SLR is too high and exceeds the rate of accretion, the marsh will drown (Reed, 1990; Mariotti & Fagherazzi, 2010; Alizad et al., 2016; Sampath & Boski, 2016). Salt marshes may also attempt to migrate landward under SLR, which may be constrained by anthropogenic infrastructure such as roads or buildings (Friedrichs & Perry, 2001; Alizad et al., 2016; Sampath & Boski, 2016). Studying the integrated processes of salt marshes requires the coupling of dynamic models that capture biophysical feedback mechanisms (Reed, 1990). However, developing models that combine realistic subsystem marsh processes with the dynamics of larger-scale system processes can be challenging (Stralberg et al., 2011). Models that neglect bio-geo-physical feedback processes or don't account for marsh migration tend to underestimate resilience (Kirwan et al., 2016).

Hydrodynamics

The last subsystem presented is hydrodynamics, namely astronomic tides and storm surge (tropical or extratropical), which is the backbone of the SoS approach to the coastal dynamics of SLR. Hydrodynamic models governed by forms of the Navier–Stokes equations provide an opportunity to examine the nonlinear feedback mechanisms of coastal flooding and allow for more accurate assessments of tides and storm surge inundation under SLR than static (i.e., "bathtub") models (Atkinson, Smith, & Bender, 2013; Bilskie, Hagen, Medeiros, & Passeri, 2014; Bilskie et al., 2016A). Static models typically assume a spatially constant and linear increase in flood depths and do not account for physics-based methods to inundate new land. In addition, static models are not always straightforward and can, counterintuitively, be complicated to apply (Hagen & Bacopoulos, 2012; Zhang, Li, Liu, Xu, & Shen, 2013). This is especially true along low-gradient coastal landscapes where minor increases in SLR and flood depths result in vast areas of new inundation (Passeri et al., 2015C).

Astronomic tidal amplitudes and tidal velocities have been shown to increase under SLR. As mean sea level increases, tidal inlets grow and enhance tidal flow volume through inlet–bay systems. Additionally, changes to tidal velocities may contribute to further erosion or deposition of sediments as tidal regimes can become more ebb or flood dominant. These changes have potential to alter salt marsh and seagrass productivity and oyster recruitment through availability of sediment and nutrients within the water column (Passeri, Hagen, Medeiros, & Bilskie, 2015B; Passeri et al., 2015C, 2016). SLR is also projected to modify flooding patterns during tropical cyclone events and can increase peak surge. Many regions along low-gradient coasts such as the northern Gulf of Mexico are susceptible to larger peak surges (up to 1.0 m higher than the rise in SLR), earlier arrival of the peak surge, lengthier inundation times, and additional inundated land (Bilskie et al., 2016A).

Linkages

The SoS approach to the coastal dynamics of SLR advocates the use of integrated dynamic models to capture subsystem responses and feedback mechanisms to provide more comprehensive evaluations of how the coastal system may evolve under different scenarios. A physics-based numerical hydrodynamic model provides the means to simulate the coastal dynamics of SLR as governed by shallow water equations (Bilskie et al., 2016B). Although hydrodynamics can be computed stand-alone, it is imperative that the various subsystems are linked to hydrodynamics (and vice versa) using a SoS approach. Information about future morphology, such as shoreline and barrier island configuration and dune elevations can be implemented into a hydrodynamic model to represent potential coastal landscape changes and their effect on hydrodynamics. For example, future oceanic shoreline recession and eroded dunes can modify the path and pattern, and increase magnitude of tide and storm-induced inundation, especially along barrier islands (Passeri, Hagen, Bilskie, & Medeiros, 2015A; Passeri et al., 2015B; Bilskie et al., 2016A; Passeri et al., 2016). This can change the depth of the water table, inducing saltwater intrusion into groundwater, which can negatively affect interdependent ecosystems including marshes, shrub thickets, and maritime forests (Masterson et al., 2013). Additionally, coastal landscape changes can reduce dune vegetation growth (Feagin, Sherman, & Grant, 2005) and alter habitats for nesting species such as sea turtles (Reece et al., 2013), shore birds (Gieder et al., 2014), and beach mice (Chen, Wang, Wang, Tawes, & Rollman, 2014).

Changes in land use can be incorporated into the hydrodynamic model to represent future land roughness (Bilskie et al., 2016A). For example, urbanization results in newly developed areas, which may reduce the area of coastal forests, thereby altering the propagation of overland inundation (i.e., there is less resistance and wind momentum is more directly transferred as water flows across a paved surface than through a dense forest). Additionally, projections of salt marsh evolution can be incorporated into the hydrodynamic model. Salt marshes attenuate surge and dissipate wave energy through their vast expanse and relatively high bottom friction (Smith, Cialone, Wamsley, & McAlpin, 2010; Moller et al., 2014), which can have a substantial impact in terms of tide and tropical cyclone-induced overland inundation (Bilskie et al., 2014, 2016A; Passeri et al., 2016).

The SoS approach requires the use of high-resolution models to describe small-scale processes, which limits the spatial scale at which it can be applied; however, this allows decision-making to occur on a local scale to address the needs of individual communities and implement specific strategies to mitigate future coastal hazards. Overall, the SoS approach permits more realistic scientifically-based assessments that can better guide stakeholders, coastal managers, and decision makers to prepare, mitigate and adapt coastal communities and ecosystems to a changing landscape and future SLR (Tribbia & Moser, 2008; Passeri et al., 2015C).

Economic and Ecosystem Valuations

As the coast evolves, natural resource management plans will strive to achieve long-term sustainability of ecological habitats. However, these efforts may conflict with future land-use decisions since anthropogenic development tends to be favored along stable areas of barrier islands (Masterson et al., 2013). Output from the integrated coastal subsystem models is used to quantify economic and ecologic impacts through valuation assessments. The results of both types of valuations—economic impact and ecosystem services—whether measured in monetary or nonmonetary terms, are critical for resource management and adaptation strategies.

Recognition of the economic importance of the environment and impact on human well-being beyond traditional measures (e.g., income, jobs, taxes) continues to grow as federal and state agencies look for opportunities to make the case for natural resource protection and enhancement (Yoskowitz & Russell, 2015). Ecosystem services assessment and valuation has increased in use to connote importance of natural resources, especially in coastal and marine environments (Barbier, 2012; Yoskowitz et al., 2016). Applying ecosystem service assessments to benefits specifically derived by Natural and Nature-Based Features (NNBFs), or coastal green infrastructure (e.g., living shorelines), has been lacking (OSTP, 2015). Yet the need is great, given damage that tropical storms and persistent nuisance flooding can inflict and the role that NNBFs can play in reducing impacts. For example, the estimated impact of hurricanes Sandy and Katrina was $67 billion and $151 billion, respectively (NOAA, 2015). Additionally, studies have calculated the traditional economic impact of storm surge and the benefits that enhanced “natural” protection would provide (Costanza et al., 2008; Barbier, Georgiou, Enchelmeyer, & Reed, 2013) but have failed to connect it specifically to SLR scenarios and NNBF enhancement. In a meta-analysis, Geden, Kirwan, Wolanski, Barbier, and Silliman (2011) stress the need to close the gaps on “… the mechanistic and context-dependent aspects of shoreline protection” (p. 8) and connecting to the economic impact of surge and nuisance flooding.

U.S. Federal policy regarding valuation of ecosystem services and coastal green infrastructure has undergone major advancements during 2015. The White House recently issued two important directives. The first is the *Ecosystem-Service Assessment: Research Needs for Coastal Green Infrastructure* (OSTP, 2015), which identifies significant opportunities for advancing use of NNBFs as well as filling science gaps, including explicit linkages between biophysical structure, function, and processes and the value of ecosystem services. The second was a directional memo (*Incorporating Ecosystem Services into Federal Decision Making*, p. 1) in October of 2015, which “… provides direction to agencies on incorporating ecosystem services into Federal planning and decision making.” These new policies provide viable avenues to initiate connecting NNBFs with ecosystem services and examining impacts on community resilience.

Ecosystem service assessment should be highly interdisciplinary, involving ecologists, physical scientists, modelers, economists, and social scientists, and ideally, transdisciplinary with the input from nonacademic stakeholders. To be successful, extensive research and data in these disciplines as well as input from communities of stakeholders are required (Yoskowitz & Russell, 2015). Looking at the societal impact of SLR through an “ecosystem services lens” is limited. The biophysical science, a necessary input for an ecosystem services assessment, is relatively well developed (Morris et al., 2002; Akumu, Pathirana, Baban, & Bucher, 2011; Hagen, Morris, Bacopoulis, & Weishampel, 2013) but the connection to human well-being is lacking (NRC, 2012) along with the consideration of NNBF (coastal green infrastructure) (OSTP, 2015).

Economic impact and ecosystem valuations fit into the SoS for the coastal dynamics of SLR first through the explicit recognition that humans and their activities are part of the natural environment and not separated from it, and that “environmental” problems are created, and hopefully solved, by humans. For example, nuisance flooding increases in Houston, Texas as a result of SLR, cutting off roads to a factory that cannot ship its product out on those days. Two things can happen. One, the factory adapts and raises the road. This has associated impact on jobs, income, and taxes. Or two, the factory does not adapt and sales are diminished and there are once again associated impacts. Assessment of “traditional” economic impact from commercial and noncommercial activities can be measured in a relatively straightforward manner using economic input–output models. Economic impact analysis—based upon input–output models—traces spending by a program or policy through the economy. The cumulative effects are measured monetarily. Results show direct effects, secondary effects including indirect and induced effects, and total output effects. Direct effects show the initial change in the economic activity associated with the final demand value, or how the industry is experiencing the change. Indirect effects include all the other supply chain responses and local employment indirectly affected by backward linkages. Induced effects refer more to household spending and are the result of spending of wages by the workers responsible for the direct and indirect effects. Indirect and induced effects are commonly referred to as secondary effects or spillover effects (IMPLAN Group, 2013). Here the economic activity must be connected back to biophysical changes in the environment due to SLR. Therefore, the understanding of the economic system (traditional) is used to identify changes in the biophysical system and assess the impact to the economy.

Valuing ecosystem services—the benefits that we enjoy from our natural environment—that aren’t captured in market transactions can be challenging. These services can range from carbon sequestration to recreational fishing opportunities and aesthetic values (Farber et al., 2006). All of these services could be impacted by SLR as it changes the biophysical makeup of a system if we were to look at the provisioning of these services emanating from a particular biophysical feature (marsh, oyster reef, and seagrass). This is traditionally how ecosystem service assessments are conducted (NRC, 2012). However, the services should be thought of as being supplied by a “system.” For example, if one were to only look at the connection between SLR, marsh, and recreational fishing and conclude that recreational fishing would be negatively impacted, this could be incorrect in systems that have multiple biophysical features that recreational species have fidelity to (mangrove, seagrass, and oyster reefs). As areal extent of marsh diminishes other habitats may expand their range.

Translating Science to Application for Societal and Coastal Benefits

There is significant concern and discussion among practitioners, scholars, politicians, and the public about the gap between what scientists and decision makers consider to be useful climate change-related knowledge (Lemos, Kirchoff, & Ramprasad, 2012). It has been argued that this complex and pressing issue calls for research approaches that are “transdisciplinary” (Allen, Kruger, Leung, & Stephens, 2013). According to the emerging body of literature on this subject, the key distinctive characteristics of transdisciplinary research are that it focuses on a real-world problem, has an evolving and iterative methodology that integrates different scholarly fields, and actively engages nonacademic stakeholders throughout the project duration (Wickson, Carew, & Russell, 2006; Levy, 2011; Allen et al., 2013). The term “stakeholder” has been defined in many ways but it is generally used to describe groups or individuals with a vested interest (e.g., monetary, professional, personal) in a particular research project or who will be impacted by a decision outcome (McNie, 2007; Phillipson, Lowe, Proctor, & Ruto, 2012; NOAA Office for Coastal Management, 2015). Identifying, analyzing, and understanding the stakeholders in a particular issue is vital and there are various approaches (Meffe, Nielsen, Knight, & Schenborn, 2002; Carney, Whitmarsh, Nicholson-Cole, & Shackley, 2009; NOAA Office for Coastal Management, 2015). Meffe et al. (2002) propose five major categories of stakeholders: (1) “people who live, work, play or worship at or near a resource”; (2) “people interested in the resource, its users, its use, or its non-use”; (3) “people interested in the processes used to make decisions”; (4) “people who pay the bills”; and (5) “people who represent citizens or are legally responsible for public resources.” Though not mutually exclusive, these different categories of stakeholders may require different forms of engagement and communication within the context of a transdisciplinary project.

Stakeholder engagement (sometimes called participatory processes, participatory management, or participatory programs) acknowledges the important effect of public perceptions, beliefs, and knowledge on issues such as resource management and incorporates processes, strategies, and mechanisms that proactively involve these nonexpert groups in projects and decision-making (NOAA Office for Coastal Management, 2015). The value of stakeholder engagement has become increasingly recognized over the past several decades, and stakeholder engagement is now a fundamental component of many agency operations in the 21st century (DiStaso, 2015; NOAA Office for Coastal

Management, 2015). As discussed and reported across a range of projects, there are numerous benefits of stakeholder engagement, including providing local knowledge about a natural resource or a system and verifying researcher assumptions; improving scientific data quality and credibility; generating better decisions or outcomes and fostering support; building and maintaining trust; increasing understanding, acceptance, dissemination, and effective application of project results; and cultivating relationships and future collaborative opportunities (Jakeman, Letcher, & Norton, 2006; Roux, Rogers, Biggs, Ashton, & Sergeant, 2006; McNie, 2007; Liu, Gupta, Sprinter, & Wagener, 2008; Frazier, Wood, & Yarnal, 2010; Hage, Leroy, & Petersen, 2010; Voinov & Bousquet, 2010; Phillipson et al., 2012; Bartels et al., 2013; Podesta, Natenzon, Hidalgo, & Toranzo, 2013; NOAA Office for Coastal Management, 2015; Stephens DeLorme, & Hagen, 2015; Thompson, Lemieux, & Davis, 2015). There are also potential challenges with stakeholder engagement that should be considered, such as being laborious, communication-intensive, time-consuming, and costly (NOAA Office for Coastal Management, 2015).

A plethora of stakeholder engagement mechanisms, techniques, methods, and activities have been presented and reported in multiple disciplinary literature streams and in an array of technical reports (Lynam, de Jong, Sheil, Kusumanto, & Evans, 2007; Lauber, Decker, & Knuth, 2008; Reed et al., 2008;Reed, Graves, Dandy, & Posthumus, 2009; Hage et al., 2010; Allen et al., 2013). Selecting appropriate (i.e., efficient and effective) engagement mechanisms depends on the issue, situation, and stakeholders (NOAA Office for Coastal Management, 2015). To enhance accessibility and inclusion, projects often incorporate a combination of different engagement activities as each can offer particular strengths for different situations (Jacobs, Garfin, & Lenart, 2005). While there is no universal best approach, there is general consensus among practitioners and scholars that effective stakeholder engagement entails: identifying the appropriate stakeholders; communicating expectations clearly; proactively facilitating early, fair, and frequent multi-directional interaction throughout the life of the project from initiation to completion; and developing a positive and constructive “science-management” collaborative and inclusive learning partnership in which various perspectives and iterative feedback are encouraged and considered (Dalton, 2005; Jacobs et al., 2005; Jakeman et al., 2006; Roux et al., 2006; Liu et al., 2008; Reed et al., 2008; Phillipson et al., 2012; Bartels et al., 2013; Podesta et al., 2013; NOAA Office for Coastal Management, 2015; Thompson et al., 2015; DeLorme, Kidwell, Hagen, & Stephens, 2016).

Four types of stakeholder engagement mechanisms deemed especially appropriate and effective for transdisciplinary research and climate change-related projects include advisory committees, workshops, focus groups, and webinars (Hossain & Wigand, 2004; Jacobs et al., 2005; Liu et al., 2008; Voinov & Bousquet, 2010; Moser & Ekstrom, 2011; Halofsky et al., 2012; Allen et al., 2013; Ernst & van Riemsdijk, 2013; Kragt, Robson, & Macleod, 2013; Podesta et al., 2013; Thompson et al., 2015; DeLorme et al., 2016). Advisory committees are small groups of stakeholders representing various interests that are selected and established for a specified period of time to provide input, feedback, and guidance on certain aspects of a project or on certain decisions (NOAA Office for Coastal Management, 2015). Advisory committees can operate in a range of capacities and offer particular strengths of local knowledge and technical expertise, as well as boost project credibility. Workshops are small (i.e., fewer than 25 people) gatherings of selected stakeholders that are designed to complete a specific objective in a relatively short period of time (NOAA Office for Coastal Management, 2015). As a standard yet flexible form of engagement, workshops have been convened and conducted successfully for a spectrum of purposes. According to the literature, the strengths of this technique include a familiar process and a setting for forming relationships, facilitating dialogue, and encouraging learning about a project or issue (Jacobs et al., 2005; Moser & Ekstrom, 2011; Halofsky et al., 2012; Picketts et al., 2012; Allen et al., 2013; Thompson et al., 2015). Focus groups are a longstanding qualitative social science interviewing method that offers strengths in capturing spontaneous remarks, detailed firsthand descriptions, and contextual nuances (Krueger & Casey, 2000; Berg & Lune, 2012; Stewart & Shamdasani, 2015). Focus groups have been conducted successfully as a form of stakeholder engagement in transdisciplinary research and other projects addressing various environmental issues (Eisenhauer & Nicholson, 2006; Frazier et al., 2010). Webinars are conference calls that are enhanced by virtual presentation through software (Hossain & Wigand, 2004; Ernst & van Riemsdijk, 2013). With strengths of advanced technology, webinars can support stakeholder engagement by enabling synchronous communication, building trust, and preparing participants for related face-to-face project activities and meetings (Hossain & Wigand, 2004; Ernst & van Riemsdijk, 2013).

Evaluation of stakeholder engagement is advised as it can provide useful feedback for accountability as well as benchmarks and diagnostic insights for future planning. Due to the diversity of stakeholder engagement situations, however, there are no universal procedures to follow for evaluating success. Two common and broad criteria to consider for evaluation are process criteria (e.g., a workshop satisfaction survey that measures opportunity to provide input) and short- or long-term outcome criteria (e.g., helping to achieve overall project objectives such as development of a dynamic SLR impact model) (NOAA Office for Coastal Management, 2015). Like evaluation of other components of transdisciplinary projects, evaluation of stakeholder engagement is best considered an ongoing process and requires proper planning and preparation for optimal data collection and accurate results.

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Scott C. Hagen

Louisiana State University, Center for Coastal Resiliency

Davina L. Passeri

U.S. Geological Survey, St. Petersburg Coastal and Marine Science Center

Matthew V. Bilskie

Louisiana State University, Center for Coastal Resiliency

Denise E. DeLorme

Louisiana State University, Center for Coastal Resiliency

David Yoskowitz

Harte Research Institute, Texas A&M University-Corpus Christi