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An aerial photograph of a coastal wetland. The foreground is dominated by a large, dark blue body of water with visible ripples. In the middle ground, there's a large, irregularly shaped island or peninsula covered in green marsh grasses. On the right side of this island, there's a small, rectangular building with a flat roof and several windows, possibly a research station or a small farm. The background shows a vast expanse of water meeting a hazy, distant shoreline under a clear sky.

Global Risks and Research Priorities for Coastal Subsidence

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Coastal lowlands, which rise less than 10 meters above sea level, are particularly vulnerable to the climate change effects forecast for the 21st century. Threats include inundation by accelerating sea level rise and increases in severity and frequency of tropical storm surges. These threats coincide with a world-wide surge in human population in

The ruins of Fort Beauregard (also known as Fort Proctor) are partly submerged in Lake Borgne, east of New Orleans, La. Many coastal areas are sinking even faster than sea level is rising.

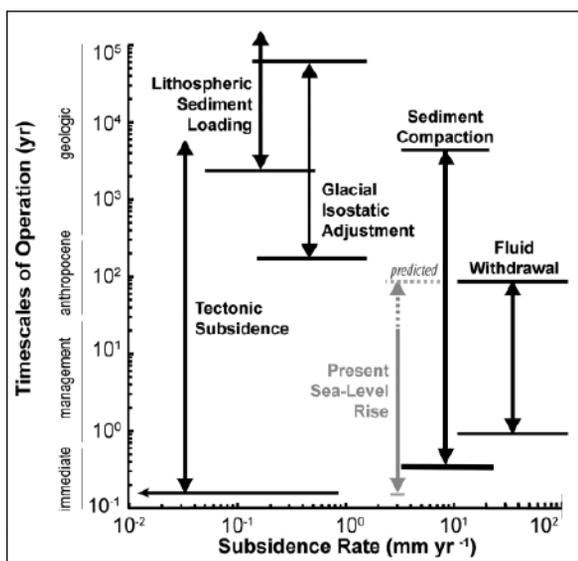


Fig. 1. Plot of major coastal subsidence mechanisms and their rates and timescales of operation. The present eustatic sea level rise and the predicted eustatic sea level rise by 2100 (possible range shown by dotted line) are also plotted, demonstrating the important contribution of subsidence to relative sea level rise in coastal areas. (Eustatic sea level changes are driven by changes in the volume of water in the ocean or changes in the shape of ocean basins rather than by land elevation changes.)

coastal areas. Coastal population centers include several megacities, whose populations exceed 10 million. Many of these coastal megacities are located on river deltas that are also major centers for agriculture, fisheries, and hydrocarbon production.

To make matters worse, many coastal areas are sinking even faster than the waters are rising: Natural and human-driven subsidence rates arising from shallow processes can be 1–2 orders of magnitude greater than the rate of climate-driven sea level rise predicted for the remainder of the 21st century (Figure 1).

The risk of rapid coastal subsidence to infrastructure and economies, as well as to the natural environment in coastal lowlands, is global and is most acute in large river deltas, which are home to about 500 million people.

Thus we have a pressing need to understand what drives coastal subsidence. We must develop better measurements and modeling, and we must link this science with its socioeconomic implications. In response to this need, an international community of researchers organized a series of workshops—one in New Orleans, La., in 2013 (see <http://bit.ly/subsidence-2013>), and another in Venice, Italy, in 2016 (see <http://bit.ly/subsidence-2016>).

As a result of this effort, a working group strategy has emerged that uses key geographic sites to design and test measurement and monitoring methods. Here we report our progress on research in the Mississippi Delta in Louisiana, and we summarize recent efforts to expand this research into other coastal areas. However, the larger goal of the coastal subsidence working group is to initiate global research and monitoring initiatives to address the critical knowledge gaps we must fill to pro-

tect coastal populations, infrastructure, and natural resources.

Subsidence Drivers

Human modifications, mainly concentrated in a zone as much as a few hundred meters below the land surface, are responsible for the largest contributions to the subsidence that appears at the ground surface, although other factors contribute as well [Syvitski *et al.*, 2009]. Compaction of high-porosity near-surface sediments often dominates land subsidence [Törnqvist *et al.*, 2008]. The risk is compounded when flood control levees and embankments prevent the deposition of sediment that could compensate for this compaction. Thus the potential exists for humans to mitigate these types of risks and effects.

Deeper, often poorly understood, processes also contribute to coastal subsidence, including thermal subsidence and fault motion. However, these deeper processes typically contribute less than a few millimeters per year (Figure 1) to the overall loss in elevation in most coastal areas, in contrast to human-caused effects like water withdrawal, which can contribute as much as a meter of subsidence annually.

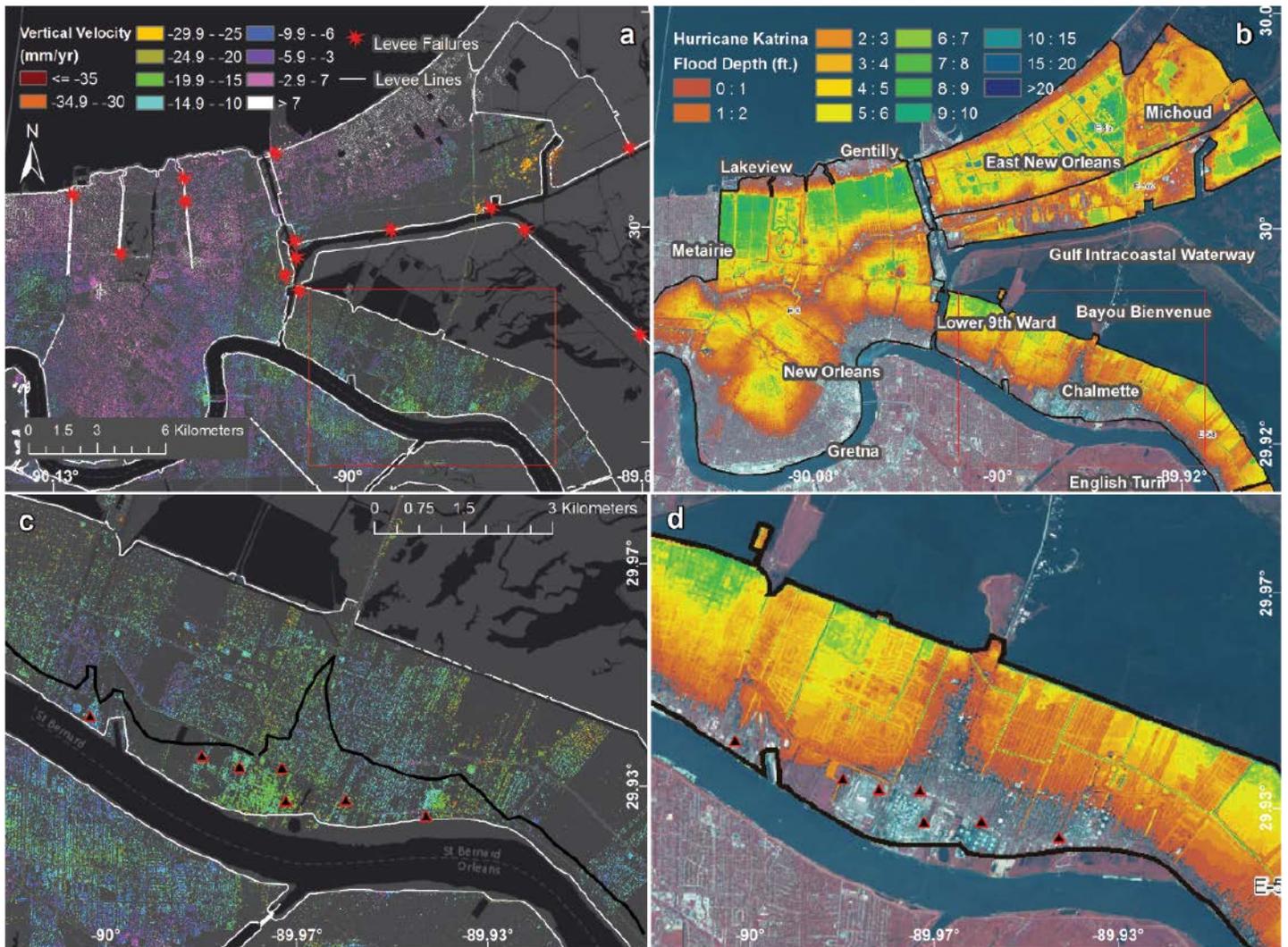
These deep processes can add to the sum of risk factors, but their contributions are commonly amplified in the deepest deposits of a sedimentary basin because of the response of Earth's lithosphere to changes in loads (isostatic adjustment), including sediment loading. For example, past ice sheets, like those that once covered large parts of North America and Europe, depressed the Earth's surface underneath, causing adjacent landmasses to rise. Now that these ice sheets have retreated, the surface underneath is gradually rebounding (isostatic adjustment). In response, the surrounding areas now experience annual subsidence rates of as much as 2 millimeters.

Humans also contribute to these deeper processes. Many deltas are major production zones for petroleum and other hydrocarbons, processes that extract fluids from deeper levels, as much as a few kilometers. Extracting these fluids can accelerate subsidence for as long as several decades afterward [Kolker *et al.*, 2011]. Burgeoning coastal lowland demand for groundwater for potable, industrial, and agriculture uses also accelerates subsidence by reducing aquifer fluid pore pressure. A dramatic example can be found in China's Huanghe Delta, where groundwater removal for coastal aquaculture has produced subsidence hot spots of 250 millimeters annually [Higgins *et al.*, 2013].

Deltas often contain extensive Holocene peat beds that are exposed to oxidation and rapid collapse as shallow aquifers are deflated. In Southeast Asia, deforestation and drainage for agriculture may reduce these peatlands from 90% to 20% intact between 1990 and 2020, resulting in annual subsidence rates of as much as 30–60 millimeters [Hooijer *et al.*, 2012].

Measurements and Monitoring Strategies

Developing subsidence mitigation plans requires a combination of measurement and monitoring strategies. The spatial and temporal changes in elevation associated with subsidence must be measured accurately. Also, the contributions from various driving factors must be separated out,



Jones et al. (2016)

and their respective contributions to the total subsidence rate expressed at the land surface must be quantified.

Measurement strategies must be tailored for individual settings and availability of funds, but any unified, international effort must focus on deltaic areas and coastal megacity “supersites.” These areas are characterized by extreme subsidence rates, and large human populations and supporting infrastructure are at risk.

New Orleans, La., is not a megacity in population, but it is a suitable supersite for concentrating mapping and monitoring of total subsidence because it lies within the subsiding Mississippi Delta. Subsidence in this delta has been identified as a major cause of rapid wetland loss and barrier island degradation, which threaten the viability of the coastal ecosystem [Louisiana Coastal Protection and Restoration Authority (LACPR), 2012]. This region also experiences subsidence issues related to groundwater extraction and drainage of peat-rich soils [Dixon et al., 2006].

The integrated strategy implemented in metropolitan New Orleans combines a terrestrial network of site-specific measurement stations with remote sensing. We believe that this strategy can be used as a guide for other high-risk coastal cities and deltas.

New Orleans, La., is the site of coastal subsidence and hurricane-induced flooding. (a) Red asterisks indicate the locations of levee failures during Hurricane Katrina in 2005. Pinkish and white shades on the map indicate the highest subsidence rates, as millimeters per year of vertical velocity. (b) Flood depths (in feet; 1 foot = ~0.3 meter) are shown for 3 September 2005, shortly after Hurricane Katrina dissipated. Green indicates the deepest flooding. (c) Thick peat layers near Bayou Bienvenue are associated with high subsidence rates at nearby Chalmette, La. There is little to no peat under several industrial areas (red triangles). (d) Chalmette flood depths for 3 September 2005.

Our group is addressing the measurement challenge using data from the interferometric synthetic aperture radar (InSAR; <http://go.nasa.gov/2bwYkro>) instrument aboard NASA Jet Propulsion Laboratory’s Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR; <http://go.nasa.gov/2bMsvMr>) aircraft to produce spatially continuous total subsidence maps of metropolitan New Orleans [Jones et al., 2016]. This aircraft has gathered L band (1–2 gigahertz) SAR data during semiannual overflights since June 2009. Continuously operating GPS reference stations (CORS) fix these remotely sensed, relative dis-

placement measurements within a global reference frame. Additional CORS stations are being installed at strategic locations in 2016, which will enable more frequent and precise point monitoring of total subsidence.

The second main challenge is to separate out, or deconvolve, the processes that contribute to total subsidence over large urban and deltaic areas. Our strategy is to develop a network of “superstations” in critical, rapidly subsiding areas where multiple subsidence measurement methods can be applied at a single site to examine past and present subsidence. The superstation methodology is motivated by the fact that previous studies, commonly relying on just one method, have often produced conflicting results.

One such superstation, funded by the U.S. Army Corps of Engineers and the first of a planned network, has been installed at a wetland site in the Mississippi Delta. Work began in January 2016. The superstation came online in August 2016, and the instruments are sending data through the uplink. A continuous sediment drill core extends throughout the Holocene succession into the top of the Pleistocene, enabling us to reconstruct the subsidence history at the site. The superstation is located at a site operated by the Coastwide Reference Monitoring System (CRMS; <http://bit.ly/USGS-CRMS>) network, which monitors, among other things, surface elevation change and vertical accretion (deposit accumulation on the delta plain) by means of the rod surface elevation table-marker horizon (RSET-MH) technique [Webb *et al.*, 2013].

The superstation (colocated with the CRMS0276 site) is being equipped with recently developed low-power interferometric optical fiber strainmeters in multiple wells, which are capable of continuous, micrometer-resolution strain monitoring [DeWolf *et al.*, 2013]. Strainmeters will be installed at three depths (about 39, 26, and 10 meters). The deepest of these will penetrate into the Pleistocene basement, allowing us to monitor vertical motions over different depth-integrated strata. GPS antennas will be attached to either the base or the top of the strainmeters and tied in to the CORS network (see <http://bit.ly/NOAA-CORS>) that is operated by the National Geodetic Survey.

The site will be outfitted with enhanced backscatter hardware, including transponders or corner reflectors [Fujita, 2003; Strozzi *et al.*, 2013] to test various radar reflector designs to optimize use with L band SAR. We will use SAR to derive the regional pattern of total elevation change in deltaic wetland areas, using radar scattering benchmarks as a reference. Subsidence rates can also vary substantially over time, so we anticipate that we will monitor at this and future Mississippi Delta superstations for many years.

Beyond the Mississippi

Team members have allied efforts in other systems, using multiple measurement methodologies to examine the diverse causes of coastal subsidence. For example, in the Ganges-Brahmaputra Delta in Bangladesh, L band InSAR

instruments, calibrated with CORS, are measuring land subsidence rates of as much as 18 millimeters per year, with the lowest rates appearing primarily in exposed Pleistocene terraces and the highest rates in Holocene organic-rich muds [Higgins *et al.*, 2014].

Although regional subsidence in this delta is primarily controlled by local stratigraphy, with rates varying by more than an order of magnitude depending on lithology, dewatering and tidal sediment exclusion induced by coastal poldering in the 1960s have generated 1–1.5 meters of elevation loss relative to surrounding natural mangrove forest [Auerbach *et al.*, 2015].

In the Venice Lagoon (Italy), a comprehensive monitoring program has been ongoing since 2007, using SAR and an innovative network of more than 50 artificial corner reflectors placed in marshes and tidal flats [Strozzi *et al.*, 2013]. Subsidence rates have declined lagoon-wide since

the cessation of groundwater pumping in the 1970s. However, ongoing monitoring with a new generation of SAR satellites (e.g., ALOS PALSAR, COSMOS-SkyMed, Sentinel-1) has recently identified rapid (up to 40 millimeters per year) local subsidence associated with renovation of historical structures and the construc-

tion of structures for the Modulo Sperimentale Elettromeccanico (or Experimental Electromechanical Module, MoSE) tidal barrier to protect the lagoon from high-water (acqua alta) events [Tosi *et al.*, 2016].

From Measurements to Modeling

The frontier in subsidence modeling is finding a way to couple individual drivers to provide an integrated simulation of ground motion within a study area that accounts for their interaction. To date, data availability has been a major obstacle in creating such coupled models. Hence our proposed supersite/superstation network methodology will provide direct observational control on active subsidence drivers in key localities and should be part of an international effort that will also catalog, manage, and disseminate the data to the modeling community.

Predicting future elevation loss in coastal lowlands will ultimately require the use of multiple modeling strategies. Future coupled model advances are necessary to address the complexity induced by multidriver subsidence and interactions between drivers.

Researchers have developed numerical models to simulate a variety of independent subsidence drivers. These include deep natural processes such as isostatic subsidence [Wolstencroft *et al.*, 2014], geomechanical subsidence at the regional scale due to fluid withdrawal [Gambolati and Teatini, 2015], and local-scale processes such as peat oxidation or shallow consolidation caused by surface loading in newly urbanized zones or recently formed deltaic areas [Meckel *et al.*, 2006].

The world of complex research models that simulate underlying subsidence processes is distinct from the need for simple kinematic, planning-level models of

The master plan to restore the Mississippi Delta and adjacent coastal Louisiana is the most expensive restoration plan conceived to date globally.

reduced complexity that can be used by policy makers. What we need, in addition to the research models, are simple models that simulate ground motion over timescales (years to decades) and spatial areas (tens to hundreds of square kilometers) that are relevant to decision makers. To assess coastal subsidence as part of a larger risk assessment analysis, these models will need to be used in conjunction with other models that predict coastal hazards associated with such phenomena as storm surges, climate-driven sea level rise, and river flooding.

In the Mississippi Delta, where Louisiana's modeling team is using reduced complexity models to guide project selection and the overall coastal restoration effort, coupling various reduced complexity subsidence models would be a major advance.

Implications for the Mississippi Delta

The master plan to restore the Mississippi Delta and adjacent coastal Louisiana [LACPRO, 2012], the most expensive restoration plan conceived to date globally, presently uses a map, differentiated into 17 geographical regions derived by an expert team, of plausible subsidence rates (0 to 35 millimeters per year). These rates play a much larger role than predicted eustatic sea level rise rates in acreages of wetlands built and preserved and the sustainability of these wetlands over 50-year model simulations for proposed projects [Couvillion *et al.*, 2013].

The integrated program under way by our expert team and others combines satellite and aerial SAR, point ground measurements (CORS, leveling), and subsurface monitoring instrumentation (strainmeters) to better understand the rates and drivers of coastal subsidence. This program will dramatically improve decision makers' ability to gauge the cost-benefit ratio of individual restoration and protection projects, particularly with regard to their postconstruction evolution.

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