Monitoring and measuring disaster resiliency of social and built environments in the coastal zone using remote sensing observations

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Science and Application Challenges:

The overarching goal of the Earth Surface and Interior (ESI) Program is to use NASA's unique capabilities and observational resources to better understand core, mantle and lithospheric structure and dynamics, and interactions between these processes and Earth's oceans and atmosphere. ESI studies focus on providing basic understanding and data products needed to inform the assessment, mitigation, and forecasting of natural (e.g., earthquake, tsunami, landslide, and volcanic eruption) and anthropogenic hazards (e.g., air quality and oil spills).

The *Sendai Framework for Disaster Risk Reduction 2015-2030* identified the following four priorities to prevent new and reduce existing disaster risks: (i) Understanding disaster risk; (ii) Strengthening governance to manage disaster risk; (iii) Investing in disaster reduction for resilience and; (iv) Enhancing disaster preparedness for effective response, and to "Build Back Better" in recovery, rehabilitation and reconstruction (UN, 2015). This framework aims to build resilient communities, reduce disaster risk and losses (i.e. societal – loss of lives and injury, financial – loss of livelihoods, businesses, etc., and ecological – loss of ecosystems) by implementing a multi-hazard risk assessment approach over the next 15 years.

Spaceborne observations provide synoptic and *time-critical situational awareness* to responders and decision makers during a disaster, and long-term *assessment and evaluation* of changes and impacts resulting from the disaster. The purpose of this white paper is to identify gaps in space-based opportunities and provide recommendations to facilitate the expansion of the U.S. program of Earth observations from space, which in turn will help address the following *key unresolved questions* including the five critical questions identified by the NASA Solid Earth Science Working Group report (SESWG, 2002) for ESI research and five of the seven revised primary science challenges emerging from the NASA CORE Workshop (Davis, et al., 2016): (i) What is the nature of deformation from plate boundaries and what are the implications for earthquakes, tsunamis, and other related natural hazards? (ii) How do tectonic processes and climate variability interact to shape the Earth's surface and create natural hazards? (iii) How does the solid Earth respond to climate-driven exchange of water among Earth systems and what are the implications for sea-level change? (iv) How do magmatic systems evolve, under what conditions do volcanoes erupt, and how do eruptions and volcano hazards develop? and (iv) How do human activities impact and interact with the Earth's surface and interior?

Science and Application Targets and Key Questions:

A key application target for hazard assessment is quantifying growth and vulnerability of infrastructures and megacities to multiple natural and anthropogenic hazards. Urban densification, particularly in coastal areas, is increasing global population exposure to damaging natural and anthropogenic hazards such as tropical cyclones, wildfires, earthquakes, sea level rise, and oil spills. In order to build the resiliency of communities and infrastructures to future hazards and reduce risk from hazards, the *Sendai Framework* has suggested the need to integrate geospatial and space-based technologies to study risk patterns, causes and effects of different hazards (UN, 2015). Using remote sensing technologies to observe hazards and to monitor and evaluate hazard impacts will not only contribute to the *Sendai Framework's* mission to reduce disaster risks, but also help answer the following **unresolved** questions that address topics in *Living on a Restless Planet*: (i) How can we measure, monitor and evaluate the rate of urban densification and population growth and exposure to hazards globally in order to aid disaster risk reduction and improve resiliency? (ii) How is rapid urban development changing hazard exposure globally? (iii) What are the potential impacts to global population from increasing exposure to natural hazards and the resulting economic impacts? and (iv) How can we measure the efficacy of long-term mitigation strategies to suppress vulnerabilities from continually evolving natural hazards to growing communities globally?

Scientific Objectives:

Given the rapid urbanization of coastal areas, the overall objective is to quantify the hazards and the vulnerability of infrastructure and population, and to assess the resultant damage due to actual hazardous events or even disasters. To costal communities, these include long-term hazards, such sea level rise and coastal erosion, as well as natural and anthropogenic hazards and disasters such as tsunamis and earthquakes, tropical cyclones, oil spills, etc.

Although hazards have been part of human society, hydro-meteorological events (i.e., floods and tropical cyclones) have been increasing both in severity and intensity. The 2014 National Climate Assessment report have indicated that the U.S. will experience an increase in flooding and tropical storm events due to climate change (NCA, 2014). The rising sea level in recent years due to the synergy of climate change and sinking or subsiding landmass is also posing increased threat to natural and built environments of coastal communities (USGCRP, 2009; NRC, 2010).

The U.S. coastal communities are also experiencing significant population growth. In the 254 coastal counties, population increased (from 47 million to 87 million) by about 85% during 1960 – 2008 (Wilson and Fischetti, 2010). In 2010, 39% (123.3 million) of the U.S. population was residing in coastal shoreline counties (counties adjacent to open ocean, major estuaries and Great Lakes, and susceptible to coastal hazards) (NOAA, 2013). The population density of these counties in 2010 was 446 persons/square mile as opposed to the nation's population density of 105 persons/square mile (NOAA, 2013). With continued population growth in and urbanization of coastal areas, the property exposure to coastal hazards has also increased. During 2000 and 2010, the total number of housing units in the coastal counties increased by 8%, and in 2012 coastal counties from Texas to Maine had an estimated \$10.6 trillion in insured properties - an increase of about 47% (\$7.2 trillion) since 2004 (AIRWC, 2015). Given this rising trend in coastal population and property (see Figures 1-7), understanding the exposure of built environments and megacities to coastal hazards will help plan and undertake efforts to increase resilience of social and physical systems, and adaptive capacity of coastal communities and agencies to future hazards.

Since 1970s, resilience has been discussed in the ecological, environmental and social sciences as a measure characterizing the primary performance of a community and its supporting infrastructure systems subjected to hazards and disasters. This measure defines the ability of a community (and its infrastructure supporting system) to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events (Cutter et al. 2010). In fact, building community resilience has been advocated as a national imperative by the National Research Council (2012) -- if the current status-quo non-resilience approach were not diverted, deadly injuries, loss of lives, and costly losses of infrastructure, homes, business interruption, and all other damage to the society would likely remain unchanged (NRC, 2012).

Building resilience starts with reducing vulnerabilities. Although technological advancements, such as using novel materials, design and construction technologies, have played a role in resilience building, the two key dimensions to building resilience are: (i) preparing for, and responding to multiple hazards and disasters in a timely manner so as to enable faster recovery, and (ii) accounting for and addressing the temporal and spatial uncertainties associated with hazard activities, urban growth, human activities, and climate changes etc. While resilience refers to the capacity of a system to get back to original condition by absorbing and recovering from the impacts of a disturbance, adaptation refers to making changes to the social and physical systems in response to environmental changes (Nelson et al., 2007). Therefore, increasing resilience requires undertaking adaptation activities, such as continuous monitoring and measuring of spatial and temporal distribution of hazard events, and potential risk, vulnerability and exposure of natural and built environments to these events.

One of the recommendations of the National Research Council (2012) was to establish a natural resource of disaster-related data documenting injuries, loss of life, property loss, and impacts on economic activity, which can be used to develop quantitative risk models and to better understand structural and social vulnerability to disasters. Although field based methods can be used for data collection, this approach is time and cost intensive. An alternative is to use remote sensing technologies, such as space- or airborne systems to obtain data at varying geospatial and temporal resolutions. Numerous studies have indicated that remote sensing technologies uniquely provide data support for hazard mapping and monitoring that will help build resilient communities and infrastructures, and aid with different phases of emergency management - preparedness, mitigation, response and recovery (Tralli et al., 2005; Gillespie et al., 2007; Joyce et al., 2009). Although space- and airborne radar and optical imaging provide timely and ground-truth observation data, some of the limitations of using these data are – lack of availability of remote sensing images at high spatial and temporal resolutions, and presence of erroneous information due to varying resolution to be useful in near real-time during emergency management (Gao, Wang, Barbier & Liu, 2011; Pu & Kitsuregawa, 2014).

Measuring Key Geophysical Variables to Achieve Science and Application Targets:

Space-based observations have been fundamental to hazard research and disaster response for decades. These observations enable long-term monitoring of evolving geophysical and meteorological processes, such as seismic faulting, climate changes, sea level rise, and offer short-term or rapid coverage of emergent or cascading geological or climatic hazards, such as earthquakes, tsunami, tropical cyclones, storm surges, land sliding, and coastal erosion. Earth observation data have also been extensively used to identify and assess environmental and infrastructure damage, and monitor post-disaster recovery efforts for extreme events such as earthquakes and tsunamis, floods, wildfires, storms and tornados, oil spills, droughts, etc.

The rapid urbanization and densification of the landmass is significantly increasing the exposure and hence the vulnerability of global population and urban habitats, especially those in the coastal regions (see Figure 8, for example). The science target of this white paper is the measurement and observation of natural hazards and disaster events, while the application target will focus on urban growth, vulnerability, and ultimiately building resiliency into coastal cummunities. The specific measurements for which space-based observations and technological advancements are required include: rate of change of urban growth and land cover (090), sea level rise (059 – wave height and 060 – wave direction) and coastal change (075 – 078), ocean temperature (056) and storms, tsunamis and earthquakes (095 and 096 – crustal movement), structures (exposure, risk), and oil spills (055).

Key Requirements – Quality and Coverage of Measurements to Achieve Science and Application Targets

Undertaking multi-hazard analysis will require observations from multiple sensors that could be merged to determine the vulnerability and exposure of urban areas across space and time (see Figure 9). Such analysis will provide compounded benefit for both predictive vulnerability and risk evaluation as well as post-disaster damage assessment. However, with regard to current available remote sensing technologies, undertaking such analysis will require future targeted observations to provide low latency, accurate, and geographically detailed images so that algorithms and techniques can be implemented to accurately measure and model growth, assess community and infrastructure resilience, and estimate damage and exposure. For example, earth observation images that are typically used for an earthquake-tsunami and aftershock scenario (e.g. the 2011 Japan Earthquake and Tsunami) include: (1) high-resolution optical images; (2) low to moderate resolution multispectral/hyperspectral images; and (3) radar and derived InSAR images. The pre-/post-event high-resolution optical images could be used for high-fidelity and object-based damage assessment of coastal infrastructure. The moderate- and low resolution multi- or hyperspectral images are much efficient for characterizing large-scale disaster impacts and generate impact zones. Being all-weather images, radar and InSAR images can also be used to measure ground movement and seismic damage to the built environment.

Towards the goal of community resilience that relies on rapid and scientific decision making, greater accuracy in material-level and 3-dimensional characterization of disaster impacts will be ever demanded. As such we recommend the following game-changing sensors that will provide data with such details: (i) High spatial-resolution multispectral/hyperspectral sensors (e.g. the HyspIRI sensor) to provide spectral reflectance of earth surface features at meter to sub-meter resolution similar to IKONOS and ORBVIEW to help study changes in demographics, urban infrastructure, land use, and utilities, etc.; (ii) Space-based gazing imagers providing 3D imaging capability in the space to help identify and assess elevational and 3D features of ground objects; (iii) High temporal resolution (24 hour or less) sensors to help with emergency response and recovery efforts after a hazard event of any kind; (iv) Higher spatial and temporal resolution radar images to help with hydro-meteorological hazards because of their cloud and haze penetrating ability; and (v) Citizen scientists or crowd-based UAV (e.g. small drones) sensors providing regional sub-meter resolution and potentially real-time 3D imaging models. Figure 10 illustrates a drone image of vertical collapse of the Pacifica's coastal cliff and a 3D image of landslide based on a drone video captured from the 2016 Kyushu (Japan) Earthquake.

Observational measurements that will be crucial to addressing the questions identified in this white paper would include: (i) High resolution airborne or satellite surveys of urban areas and critical infrastructure for optical pixel correlation-type and rapid rupture mapping; (ii) High resolution radar mapping of infrastructure for structural identification and exposure analysis; (iii) Hyperspectral analysis of urban land-cover change, storm tracking, and sea level rise; (iv) Additional GNSS GPS stations near seismic faults. Aim for fault depth over two 2D spacing to enable strain monitoring (eg 5 km where depth is 10 km); (v) More GPS reference frame stations in the southern hemisphere; (vi) Deploying UAVSAR for global service and to take coincident video of sky and ground to help users identify compromised data; (vii) Developing open database of objects and regions that yield non tectonic measurements in repeat pass InSAR; and (viii) developing nominal geodetic time dependent velocity model including plate motion, postseismic, postglacial, aquifers, etc., which will enable fast comparison with InSAR like NISAR to identify anomalies.

Data accessibility:

Availability of remote sensing images is essential to undertaking the studies we have identified in this white paper. This does not only mean the launching of new satellite/sensors as part of NASA's mission, but also establishing a central data repository similar to the USGS' Earthquake Hazards program. The repository will provide access to all types of imageries available not only from NASA, but also from other agencies at varying resolutions for all kinds of hazards. In essence, this will be a repository of images that are available at a given time for a given location on the earth. This site should also provide access to crowd sourced images obtained via UAV/UAS and drones. The repository should also provide access to new algorithms and tools that are being developed to enable faster processing of images for feature/information extraction, change detection, etc. to allow usage of these tools by different stakeholder groups.

Distributed computing and automation:

The availability of high volume of imageries requires large storage space and availability of distributed computing to increase processing power of advanced algorithms and tools. As part of its investment to raise Technology Readiness Level of enabling technologies, NASA's future mission should also look into the possibility of providing such computing power to local stakeholders and academic researchers who lack financial resources and skill set to implement image processing algorithms. NASA should also consider the establishment of a "Data as a Service" programmable platform using best practices of academic and commercial approaches to data centric computing. Such a platform should allow, for example, scientists to explore, combine, and analyze NASA data products, integrate NASA and non-NASA data sets (such as user-supplied and third party data), for simulation and modeling.

Despite wide usability of remote sensing data for hazard and disaster applications, significant challenges yet exist with regard to automating the computing process, for example, disaster assessment using a variety of images available at varying spatio-temporal scales. For instance, the nadir or off-nadir views of earth observation data from conventional space sensors are limited in capturing and characterizing hazardous and disaster impacts. To enable near real-time response, efficient machine learning and artificial intelligence-supported disaster scene computing algorithms, standardized robust change detection and damage classification algorithms, etc. are needed. Likewise, libraries of damage features to be used as training data for these activities also need to be developed. Given that crowdsourcing- and citizen science-based visual interpretation has been widely attempted for damage assessment, disaster damage data libraries should also include standardized features that can be used with crowdsourced data.

Likelihood of affordably achieving the required measurements in the decadal timeframe

There is a high likelihood of achieving these measurements within the decadal timeframe. Existing regional GPS measurements capture crustal motion with good spatial and high temporal coverage; existing SAR (L- and X-band) provide synoptic, all-weather observations of natural and anthropogenic hazards and post-disaster damage; moderate and high resolution optical sensors provide detailed coverage of change and damage and can help characterize building types in urban areas. However, dedicated observations for these hazards and urban growth and vulnerability need to be addressed. Current sensors such as ASTER have been used to map urban change, and night lights have been mapped using the Visible Infrared Imaging Radiometer Suite (VIIRS) (See Figure 11). However, the increasing accuracy and quality of existing measurements as well as ensuring continuous, global coverage is necessary to capture important attributes of cities, their infrastructure, and population distribution in order to characterize risk and vulnerability and increase resiliency.

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Figures

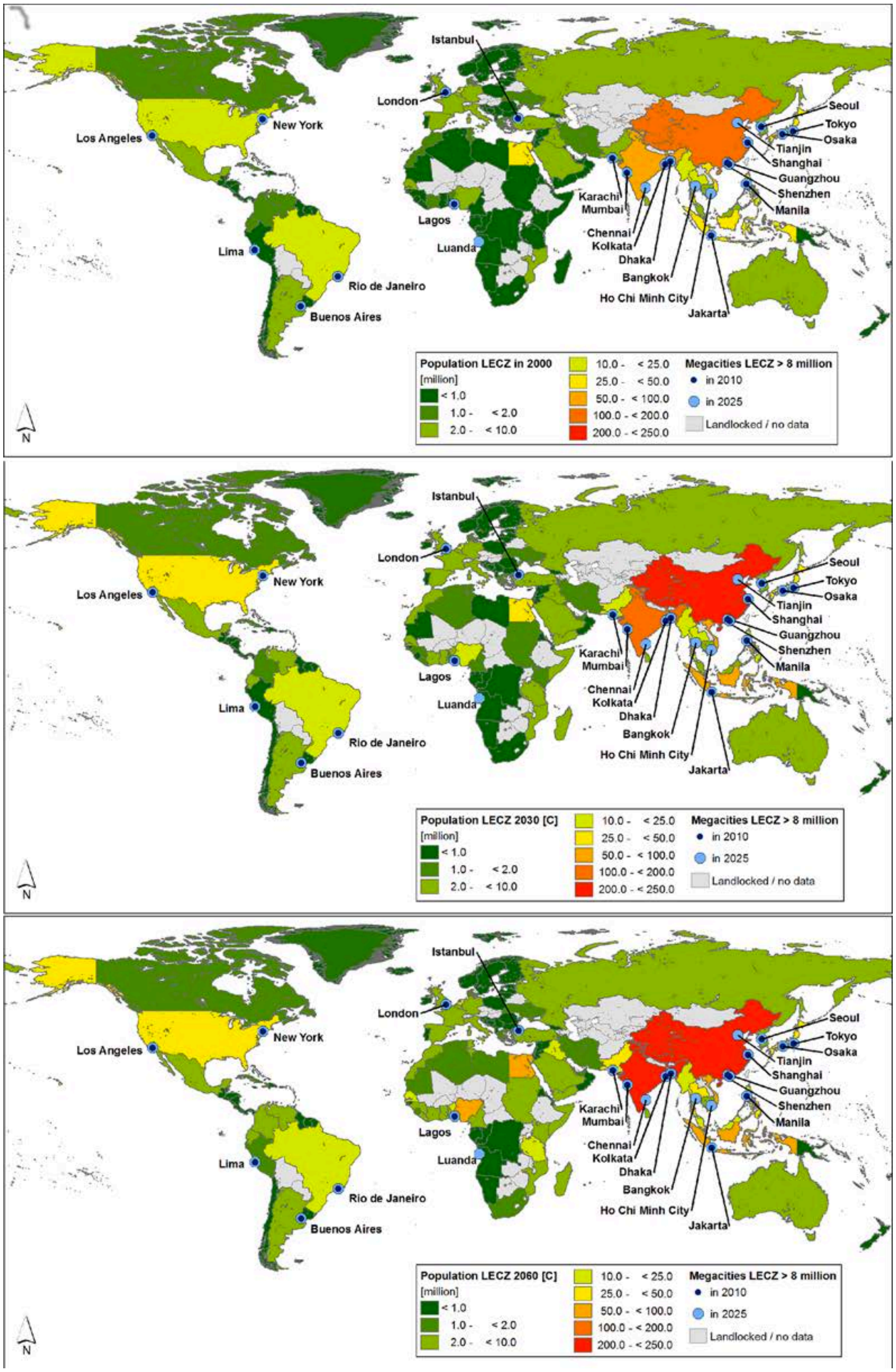

Figure 1. By using the UN World Urbanizations Prospects, population estimates for the year 2010 and projections for the year 2025 are mapped for selected megacities (>8 million people) located in the Low Elevation Coastal Zone (LECZ) (from Neumann, et al., 2015).

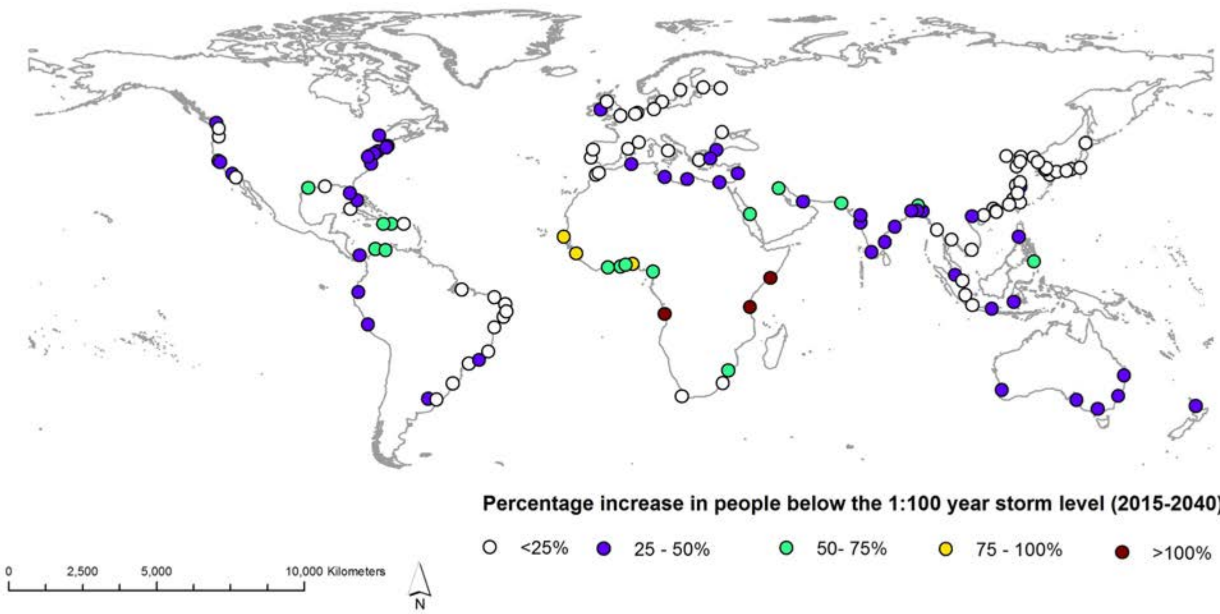

Figure 2. Map showing port cities where population increases are expected by 2045 in areas where they lie below the 1:100 year storm level and will be affected by the time a 2°C global temperature has occurred (https://www.atlas.impact2c.eu/en/coastal-themes/planning-for-coastal-floods-in-port-cities/?parent_id=340)

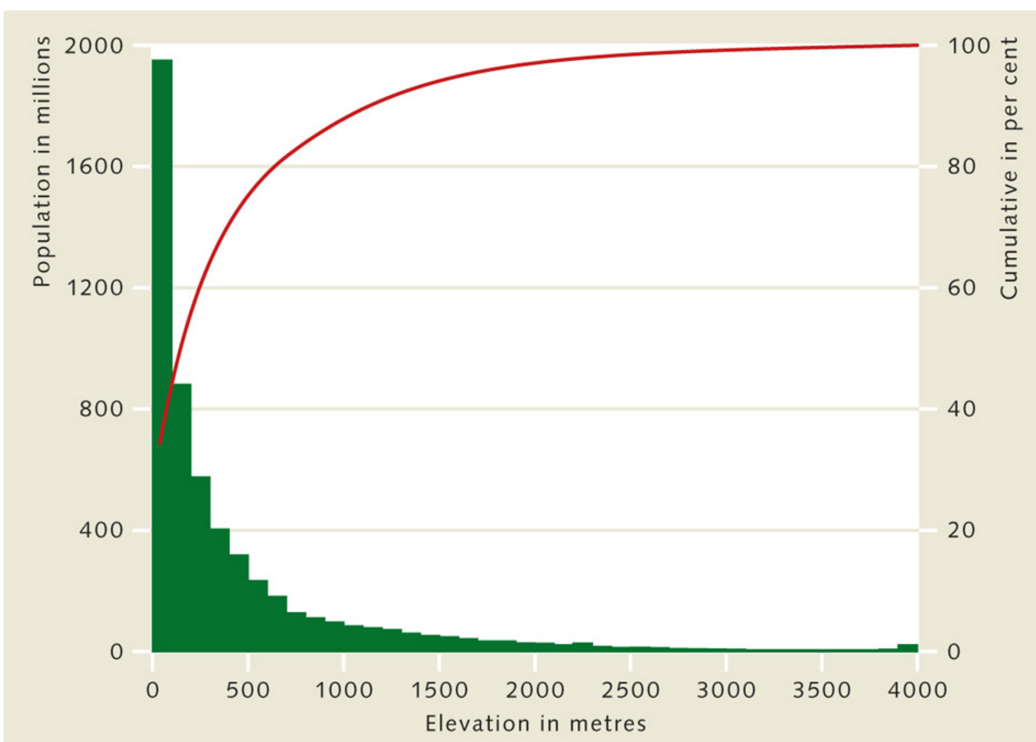

Figure 3. Population distribution by elevation. © maribus (after Cohen and Small, 1998 http://worldoceanreview.com/en/wor-1/coasts/altering-the-coasts/)

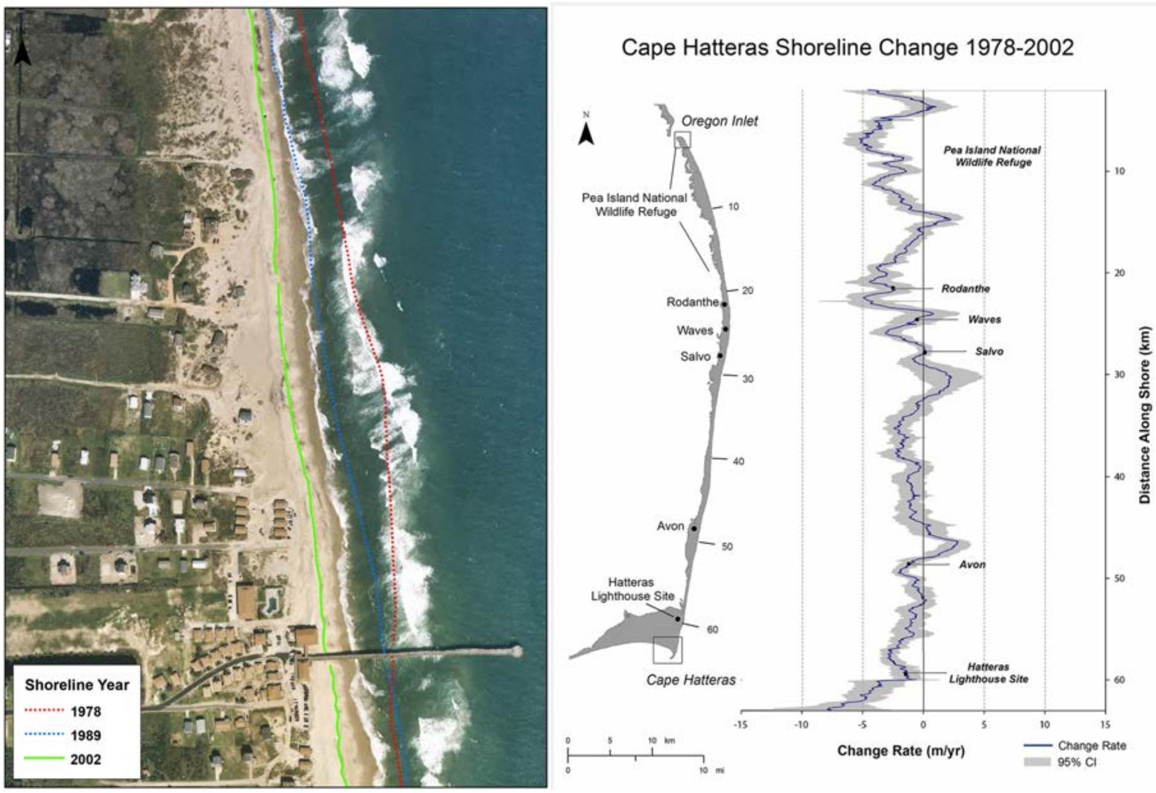

Figure 4. Left: Long term erosion from 1978-2002 is shown in an orthophotograph from 2002 of Rodanthe in the Outer Banks of NC. Right: Using fourteen shorelines spanning twenty-four years for Hatteras Island, NC, rates of shoreline change have been calculated using a linear regression methodology. The gray band around the plot is the uncertainty (95% confidence interval). (http://marine.usgs.gov/coastalchangehazards/research/long-term-change.html)

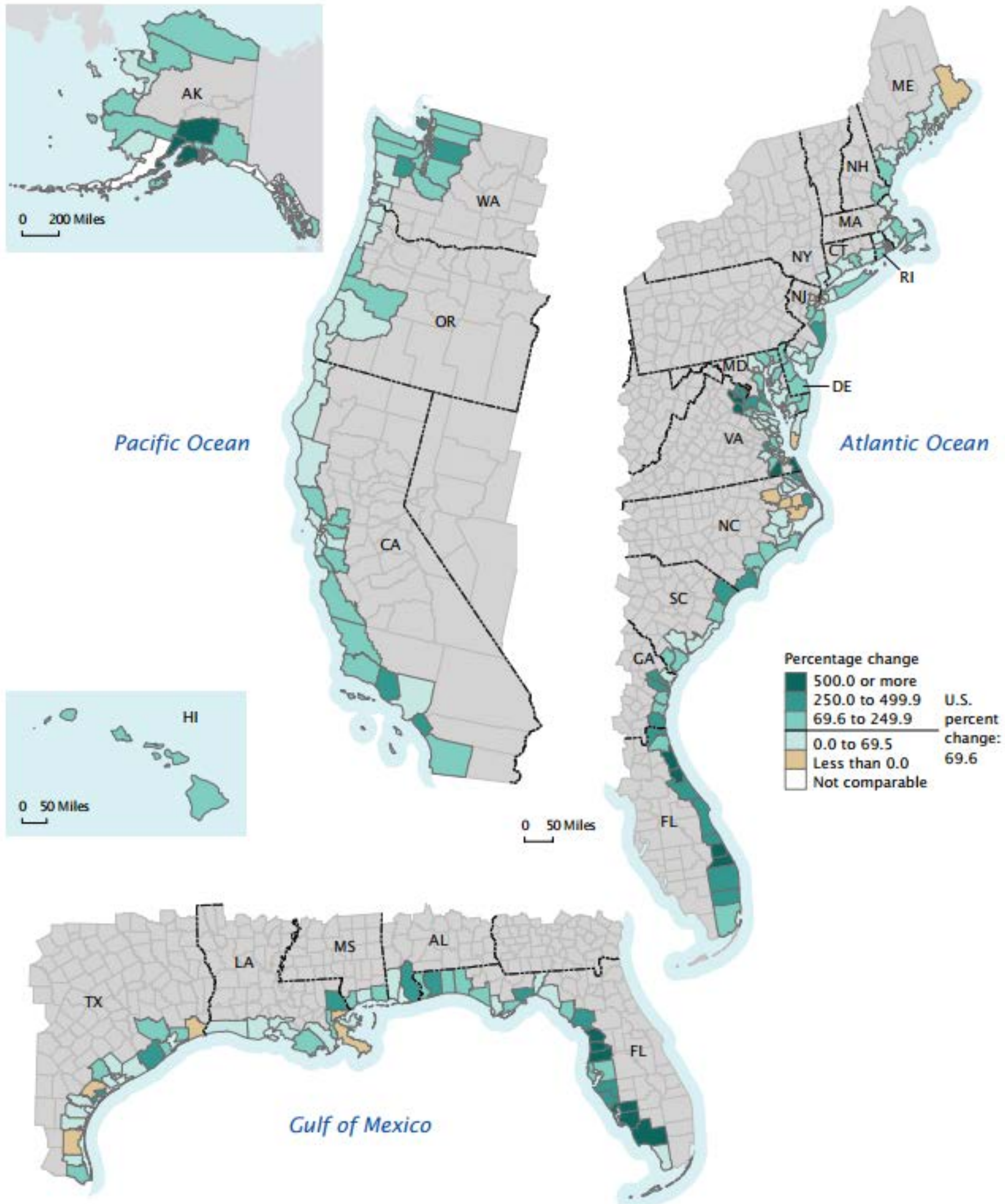

Figure 5. Change in Coastline Population by County: 1960 to 2008. (Figure 2 from Wilson, S. G., and Fishetti, T. R., 2010. *Coastline population trends in the United States: 1960 to 2008. U. S. Census*)

Figure 6. Population and construction growth near Mt Pleasant, SC. Top images taken 02/1994, bottom image taken 02/2016. (Source Google Earth)

Figure 7. Population and construction growth near North Naples, FL. Top images taken 01/1995, bottom image taken 02/2016. (Source Google Earth)

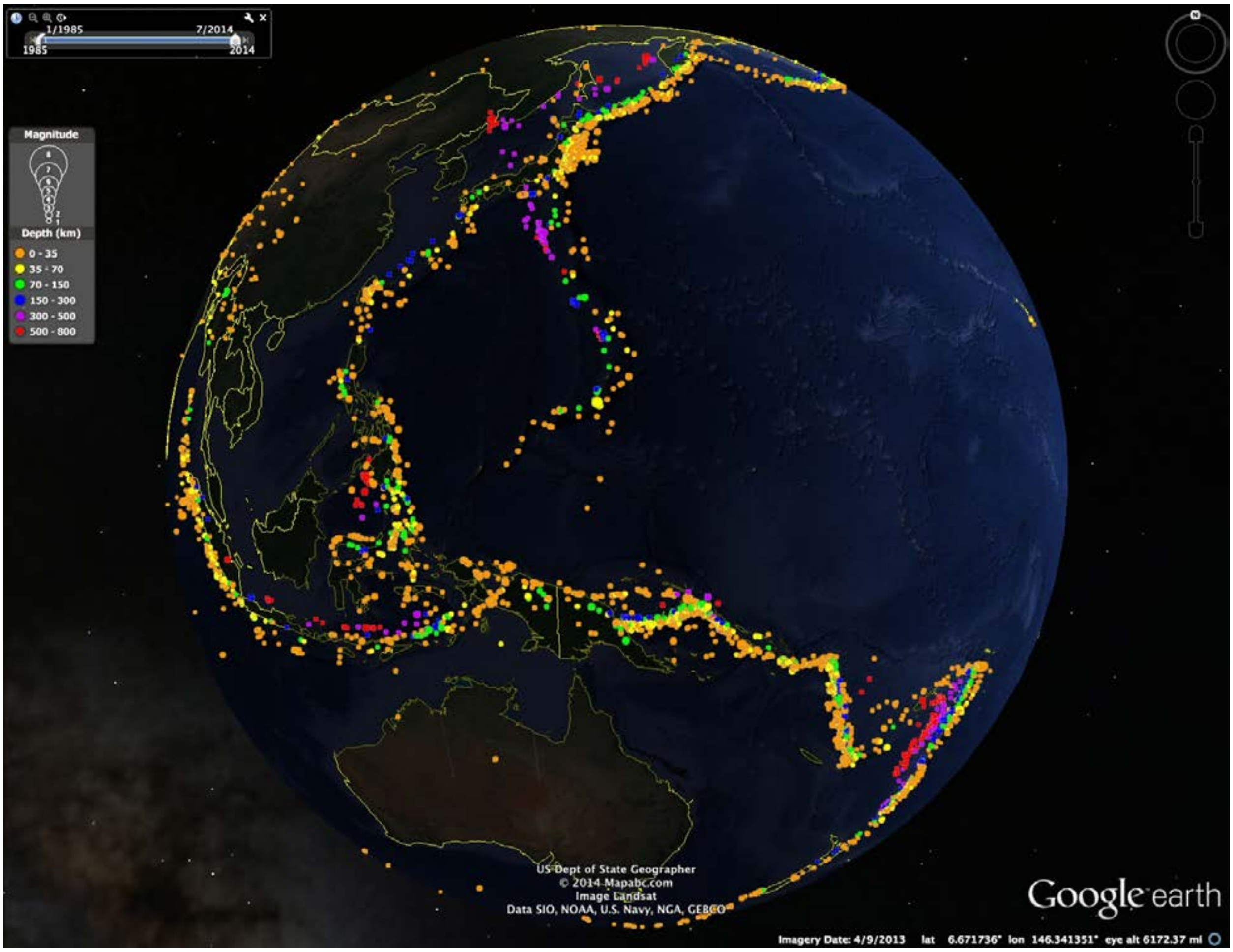

Figure 8. Damaging earthquakes are concentrated near coastal areas. Here two decades of potentially damaging earthquakes are displayed over East Asia and the Pacific, colored by depth. (Data are from the Advanced National Seismic System).

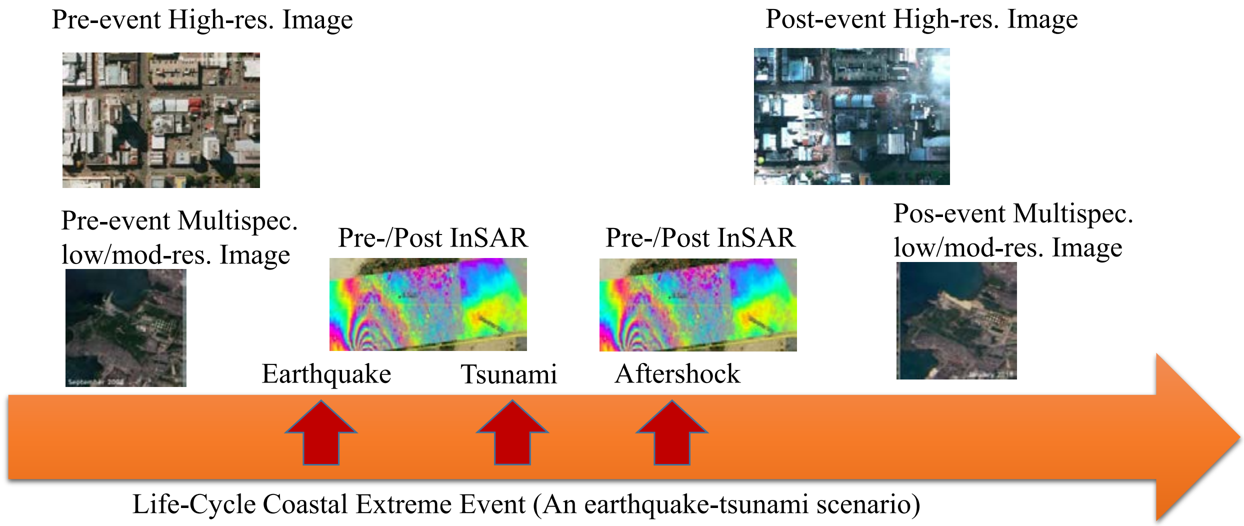

Figure 9. Multi-hazard analysis will require observations from multiple sensors that could be merged to determine the vulnerability and exposure of urban areas across space and time.

Figure 10. Left: Drone image of vertical collapse of the Pacifica's coastal cliff. Right: 3D image of landslide based on a drone video captured from the 2016 Kyushu (Japan) Earthquake.

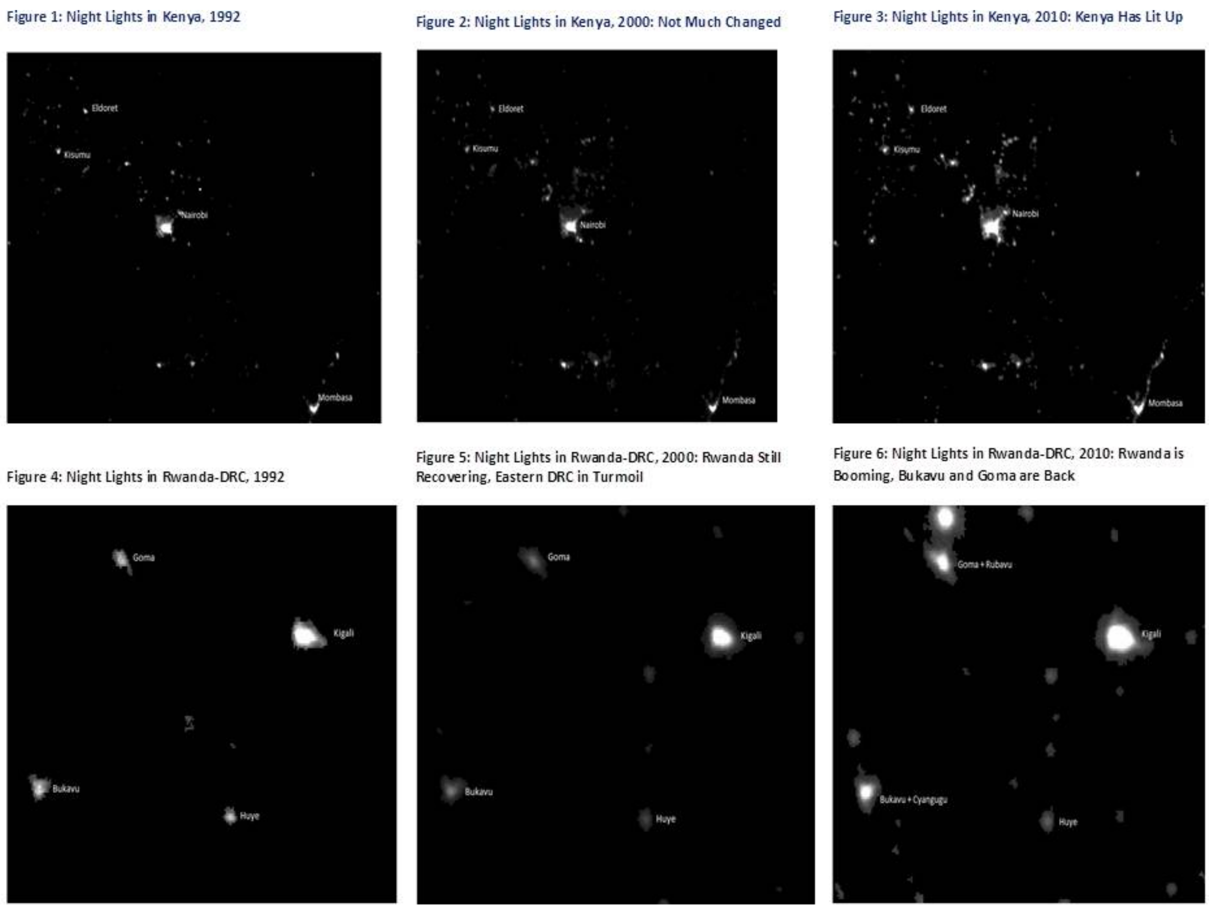

Figure 11. Change in night lights in Africa over time (1992-2010). Night light data has been used as a key measurement for population indicator, but additional observations from radar and multispectral sensors could greatly improve characterization of population growth, risk and vulnerability to hazards, and improve resiliency (from http://blogs.worldbank.org/futuredevelopment/can-outer-space-tell-us-something-useful-about-growth-and-poverty-africa).