Decision Support Tools for Coastal Sea Level Change

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Executive Summary

Recent estimates based on global climate models (Wigley and Raper, 1992) suggest an increase in sea level of between 15 and 95 centimeters (cm) by 2100, with a “best guess” of 50 cm (IPCC, 1995). This is more than double the rate of sea-level rise for the past century (Douglas, 1997; Peltier and Jiang, 1997). Thus, sea-level rise will have a large sustained impact on coastal evolution in the future and will occur as both population and infrastructure in coastal regions are projected to increase.

Predicting future coastal evolution and vulnerability to change is difficult because many factors are involved. The vulnerability of a shoreline is based on the relative contributions and interactions of six variables: 1) tidal range, 2) wave height, 3) coastal slope (steepness or flatness of the coastal region), 4) shoreline erosion rates, 5) geomorphology, and 6) historical rates of relative sea-level rise. No standard method is presently in use by scientists to predict coastal change.

Two Decision Support Tools (DST) – The Wave-current Information System (WAVCIS) and the Ecological Effects of Sea Level Rise (EESLR) are considered. WAVCIS is a wave-current and surge-monitoring program for coastal Louisiana that provides information on sea state (wave height, period, direction of propagation, water level, surge, near surface current speed and direction) and meteorological conditions in real time. The data are transmittal to Louisiana State University (LSU) where the observations undergo processing and are archived in an online database. The information is then made available on the World Wide Web and is accessible to coastal managers and the public.

The EESLR program is run by NOAA and evaluates the potential impact of long-term sea level rise for the North Carolina coast, 25 to 50 years in the future. The program is designed to help coastal managers and planners prepare for coastal ecosystem challenges due to land subsidence and sea level rise. EESLR uses a quadrant approach to assess impacts of sea level rise on ecosystems in coastal North Carolina. The EESLR approach begins with a hydrodynamic tide model of the study area. Next, a high-resolution, topographic/bathymetric digital elevation model (DEM) is developed. A hydrodynamic coastal flooding model then integrates the DEM and tide models to predict and assess sea-level rise. Finally, environmental models are exercised with the coastal flooding models to demonstrate relevant landscape responses.

Pertinent NASA data streams and models were matched with these DST’s. Although the DST’s presently in use for sea level rise are yet relatively immature, there are data products that could enhance sea level rise studies.

1.0 Background

The motivation for sea level rise research is provided by the fact that, in the U.S., a majority of the population lives in 25 coastline states. It is estimated that half of this population lives within 75 km of a shoreline (NRC 1995). On a global scale, approximately 37% of the world's population lives within 100 km of the coast (Cohen et al. 1997). Such coastal regions are threatened by a range of coastal hazards (Nicholls et al. 1999). In particular, sea level rise, due to any cause, can produce significant changes in coastal zones generating both physical and ecological transformations. These facts have spurred governmental bodies to write legislation to protect endangered areas, encourage research, and provide overviews concerning sea level shifts.

1.1 Regulations and Guidance Related to Sea Level Rise

- **Coastal Wetlands Planning, Protection and Restoration Act (CWPPRA) (16 U.S.C. 3951 et seq.; 104 Stat. 4779; enacted November 29, 1990)**

CWPPRA authorizes the Director of the U.S. Fish and Wildlife Service (FWS) to participate in the development of a Louisiana coastal wetlands restoration program, to participate in the development and oversight of a coastal wetlands conservation program, and to lead in the implementation and administration of National coastal wetlands grant program. Parallel authority is granted to the U.S. Army Corps of Engineers (USACE), the Environmental Protection Agency (EPA), and the FWS to work with the State of Louisiana to develop, review, approve, and evaluate the State's Coastal Wetlands Conservation Plan. This Plan is to achieve a goal of "no net loss of wetlands" in coastal Louisiana through a combination of regulatory and non-regulatory measures. The law also requires the USACE to allocate funds among Task Force members in accordance with the priorities set forth in the Act. It also established a Federal Task Force to develop a comprehensive approach to restore and prevent the loss of coastal Louisiana wetlands.

- **Coastal and Estuarine Land Protection Act (CELPA) (108th CONGRESS 1st Session S. 861 [Report No. 108-158])**

This bill authorizes the acquisition of interests in undeveloped coastal areas in order to ensure their protection from development. CELPA establishes a Coastal and Estuarine Land Protection Program in cooperation with appropriate State, regional, and local units of government. The CELPA purpose is to protect the environmental integrity of coastal and estuarine areas, including wetlands and forests that have significant conservation, recreation, ecological, historical, or aesthetic values, and are threatened by conversion from their natural, undeveloped, or recreational state to other uses. The National Ocean Service (NOS) of National Oceanographic and Atmospheric Administration (NOAA) is responsible for administration of the program through the Office of Ocean and Coastal Resource Management.

- **The Ocean Observation and Coastal Systems Act (OOCSA) (Senate Bill 1400)**

The primary purposes of OOCSA is to develop a system that provides for ocean and coastal observations, to implement a research and development program to enhance security at United States ports, and to implement a data and information system required by all components of an integrated ocean observing system and related research. Specifically, in regard to sea level change, the Act recommends the establishment of a "a global ocean system to make observations in all oceans (including chemical, physical, and biological observations) for the purpose of documenting, at a minimum, long-term trends in sea level change, ocean carbon sources and sinks, and heat uptake and release by the ocean; and to monitor ocean locations for signs of abrupt or long-term changes in ocean circulation leading to changes in climate."

- **Coastal and Ocean Mapping Integration Act (COMIA) (June 2, 2004)**

This bill establishes a program within NOAA to integrate Federal coastal and ocean mapping activities. If enacted, COMIA will direct the Administrator of NOAA to establish a program to develop, in coordination with the Interagency Committee on Coastal and Ocean Mapping, a coordinated and comprehensive Federal ocean and coastal mapping program for the Great Lakes and Coastal State waters, the territorial sea, the exclusive economic zone, and the continental shelf of the United States that enhances conservation and management of marine resources, improves decision-making regarding research priorities and the siting of research and other platforms, and advances coastal and ocean science.

1.2 Climate Change Science Plan (CCSP)

The Climate Change Research Initiative (CCRI) was launched in June 2001 by the executive branch of government. A cabinet-level organization was formed in 2002 to advance government management of climate science and related technology development. In turn, two joint interagency programs were initiated. One of these interagency programs was the Climate Change Science Program (CCSP).

The following lists the five principal goals that were established to provide guidance for CCSP:

1. Improve knowledge of the Earth's past and present climate and environment, including its natural variability, and improve understanding of the causes of observed variability and change.

2. Improve quantification of the forces bringing about changes in the Earth's climate and related systems.

3. Reduce uncertainty in projections of how the Earth's climate and related systems may change in the future.

4. Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes.

5. Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change.

In particular, CCSP is interested in the promotion and widespread use of Decision Support Systems (DSS) and Decision Support Tools (DST). DDS denotes to the set of analyses and assessments, interdisciplinary research, analytical methods, model and data product development, communication, and operational services that provide timely and useful information to address questions confronting policymakers, resource managers and other stakeholders.

The connection between climate change and sea level rise is a readily apparent one. Beyond the thermal expansion of warming ocean waters, if Earth's climate continues to warm, the volume of present-day ice sheets will decrease. For instance, melting of the current Greenland ice sheet would result in a sea-level rise of about 6.5 meters. Even more, the melting of the West Antarctic ice sheet would result in a sea-level rise of about 8 meters. Table 1 displays the estimated potential maximum sea-level rise from the melting of present-day glaciers.

Table 1 - Sea level rise associated with melting of named glaciers

Location	Volume (km^3)	Potential sea-level rise (m)
East Antarctic ice sheet	26,039,200	64.80
West Antarctic ice sheet	3,262,000	8.06
Antarctic Peninsula	227,100	.46
Greenland	2,620,000	6.55
All other ice caps, ice fields, and valley glaciers	180,000	.45
Total	32,328,300	80.32

1.3 Background on Sea Level Rise

Although global warming is a contributor to changes in sea level, sea level rise is a result of a combination of factors (Nicholls and Leatherman 1996). Sea level is measured relative to datums on land, but the altitude of the land changes as well, due to natural subsidence and uplift of the Earth's crust. If the land surface is subsiding at the same time that ocean volumes are increasing, then the rate of submergence will be greater than it would be due to changes in ocean volume alone. If the land area is rising relative to the sea, apparent sea level may fall. Human changes such as ground-water extraction and fluid withdrawal from petroleum reservoirs can induce subsidence and influence relative sea-level change.

Monitoring altitudinal changes in the Earth's crust is a difficult task, although satellite measurement and global positioning systems (GPS) promise to furnish more accurate results than were formerly possible. Further, changes in ocean volumes due to natural or man-induced climate changes can cause short-term fluctuations in sea level, by simply changing the thermal expansion of the global ocean. The lack of a single predictor for sea level change creates difficulties in obtaining accurate estimates of the phenomenon.

Eustatic processes are variations in sea level resulting from alterations in the volume of the world's oceans. Global climate drives eustatic processes. *Isostatic* processes are sea level changes that result from variations in land level. These changes can be on a regional or local scale. See Table 1.

Table 2 - Types of eustatic and isostatic processes that impact sea level rise

Eustatic	**Isostatic**
Thermal expansion of seawater	Tectonic activity
Melting of land ice. (e.g., Antarctica, Greenland)	Post-Glacial Rebound
Changes in ocean depth. (e.g., sedimentation, tectonic and volcanic activity)	Subsidence due to sediment loading
Changes in ocean currents and wind fields	Human-induced subsidence from extraction of groundwater, minerals, and hydrocarbons
Changes in the hydrologic cycle. (e.g., water storage in reservoirs)	Milankovich cycles – Tilt (40kyr), Wobble (21kyr), Eccentricity (100kyr)

Relative sea level is rising in most coastal regions and causing major problems at a time of coincident increase in coastal developments (Nicholls, 1995). Recent analyses indicate that eustatic sea level has risen approximately 2 mm per year during the last century. This rate is projected to increase during the next century partly because of global warming (Warrick and Oerlemans, 1990). Figure 1 shows the potential inundation of the east coast of the United States for future sea level shifts, while Table 2 provides a look at projected sea level rise for selected US locations.

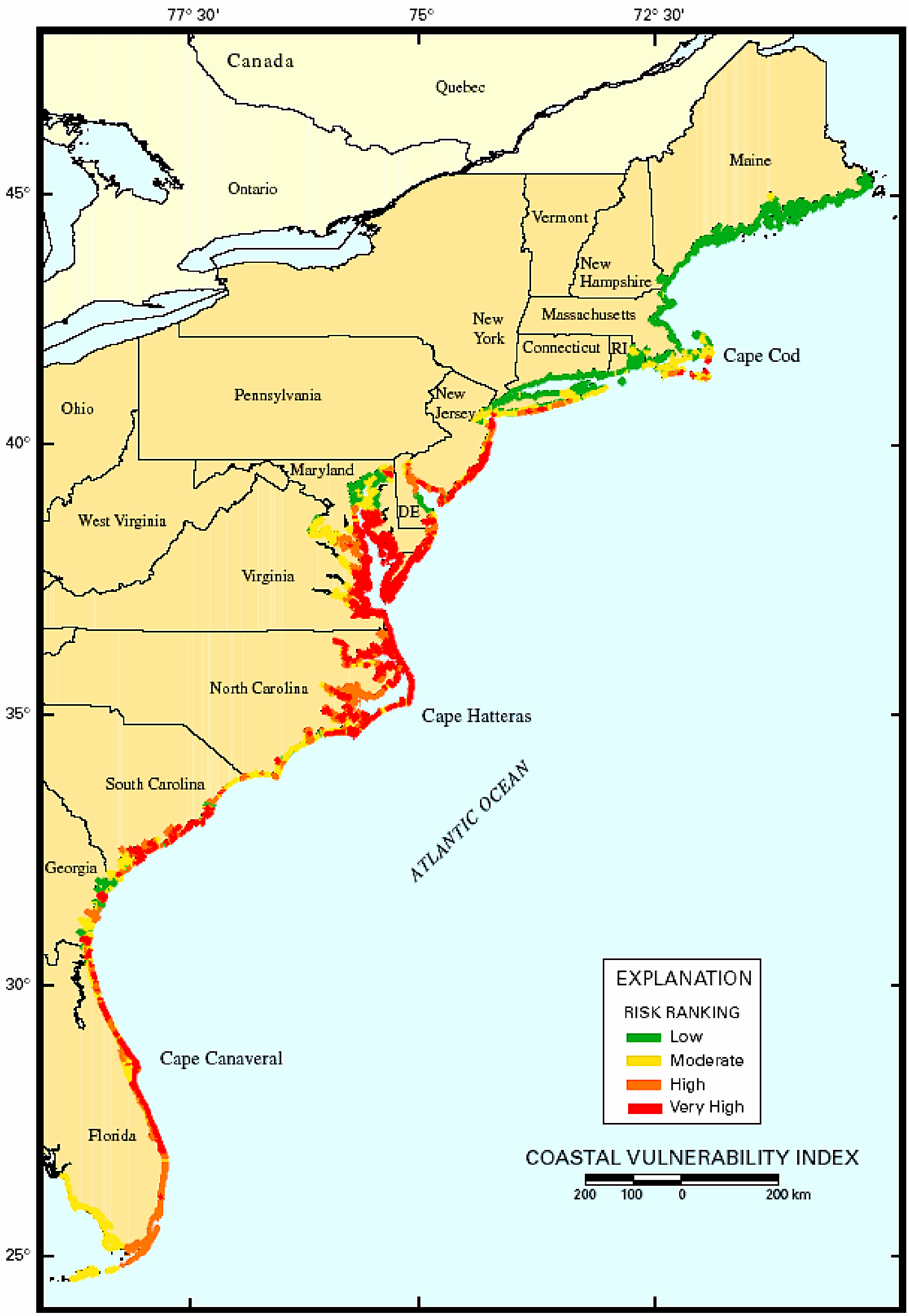

Figure 1 - Map of the Coastal Vulnerability Index (CVI) for the U.S. East Coast showing the relative vulnerability of the coast to changes due to future rises in sea level.

Table 3 - Historic rate of sea level rise at various locations in the United States (mm/year)

Location	State	Sea Level Change (mm/yr)	Region
New London	CT	2.1	East Coast
Lewes	DE	3.1	East Coast
Fernandina	FL	1.9	East Coast
Mayport	FL	2.2	East Coast
Miami Beach	FL	2.3	East Coast
Ft. Pulaski	GA	3.0	East Coast
Boston	MA	2.9	East Coast
Woods Hole	MA	2.7	East Coast
Annapolis	MD	3.6	East Coast
Solomons, Is.	MD	3.3	East Coast
Eastport	ME	2.7	East Coast
Portland	ME	2.2	East Coast
Wilmington	NC	1.8	East Coast
Atlantic City	NJ	3.9	East Coast
Sandy Hook	NJ	4.1	East Coast
Montauk	NY	1.9	East Coast
New York	NY	2.7	East Coast
Philadelphia	PA	2.6	East Coast
Newport	RI	2.7	East Coast
Charleston	SC	3.4	East Coast
Hampton Roads	VA	4.3	East Coast
Portsmouth	VA	3.7	East Coast
Washington	VA	3.2	East Coast
Key West	FL	2.2	Gulf of Mexico
Pensacola	FL	2.4	Gulf of Mexico
St. Petersburg	FL	2.3	Gulf of Mexico
Eugene Island	LA	9.7	Gulf of Mexico
Grand Isle	LA	10.5	Gulf of Mexico
Freeport	TX	14.0	Gulf of Mexico
Galveston	TX	6.4	Gulf of Mexico
Padre Island	TX	5.1	Gulf of Mexico
Sabine Pass	TX	13.2	Gulf of Mexico
Juneau	AK	-12.4	Pacific Northwest
Sitka	AK	-2.2	Pacific Northwest
Alameda	CA	1.0	Pacific Northwest

Crescent City	CA	-0.6	Pacific Northwest
La Jolla	CA	2.0	Pacific Northwest
Los Angeles	CA	0.8	Pacific Northwest
Newport	CA	1.9	Pacific Northwest
San Diego	CA	2.1	Pacific Northwest
San Francisco	CA	1.3	Pacific Northwest
Santa Monica	CA	1.8	Pacific Northwest
Hilo	HI	3.6	Pacific Northwest
Honolulu	HI	1.6	Pacific Northwest
Astoria	OR	-0.3	Pacific Northwest
Neah Bay	WA	-1.1	Pacific Northwest
Seattle	WA	2.0	Pacific Northwest

Understanding and predicting sea-level rise and its effects on erosion, flooding, and storm related damage is critical to planning future coastal zone management strategies and assessing impacts on coastal ecosystems.

Negative effects of sea level rise would include the following: 1) Loss of wetlands, 2) Erosion of beaches and bluffs, 3) Increased flooding and storm damage, 4) Inundation of low-lying areas, 5) Salt intrusion into aquifers and surface waters, 6) Higher water tables, and 7) Reduction/loss of habitat of affected flora and fauna (extinction of species).

Coastal areas with adequate elevation above sea level to escape inundation would be threatened by a different cause of shoreline retreat: erosion. In fact, recent sea level rise may be to blame for erosion occurring in many coastal resorts. Strong waves force beaches to take a certain profile, which fluctuates seasonally. Winter storms erode the upper beach and deposit sand offshore, and calmer warmer weather waves redeposit the sand and restore the beach.

In contradistinction, an increase in sea level shifts the nature of the beach profile relative to the water level. Since deeper water exists near the beach now, additional energy is necessary to shift offshore sand back to the beach. Therefore, material deposited offshore by winter storm waves stays offshore, and some portion beach is forever gone (Bruun, 1962).

Figure 2 tabulates six significant variables that relate their possible impact on coastal areas as sea level rises. The geomorphology variable expresses the potential for erosion of diverse landform types. These data were originally derived from state geologic maps and USGS 1:250,000 scale topographic maps.

Table 4 - Comparison of CVI variables

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> .2	.2 – .07	.07 – .04	.04 – .025	< .025
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0	-1.0 – +1.0 Stable	-1.1 – -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<.55	.55 – .85	.85 – 1.05	1.05 – 1.25	>1.25

Sea level rise may cause the saline content of estuaries and aquifers to increment landward. Since the specific gravity of salt water is greater than fresh water, freshwater will float on top of saltwater. The intruding saltwater tends to form a wedge-shaped gradient such that the layering between fresh and salt water moves inland. The level of the water table is itself determined by sea level; hence, a rise in sea level causes the freshwater-saltwater interface to move upward causing some freshwater wells to become saline.

Sea level rise would boost the salt content of rivers and estuaries. Given an increase in the volume of seawater coming into estuaries, salt would move upstream. A sea level increment of only thirteen centimeters could produce Delaware River salt concentrations to migrate two to four kilometers upstream (Hull and Tortoriello, 1979). Postulating a one-meter rise would cause the migration of salt concentrations a distance of approximately twenty kilometers. This would be sufficient to possibly contaminate Philadelphia's drier season water supply. Since rivers serve to recharge aquifers in some areas, local aquifers might also become contaminated.

1.4 Determination of Sea Level Rise

Tide gauges provide one of the most direct measurements of sea level. The Permanent Service for Mean Sea Level (PSMSL) was established in 1933, and is the global data bank for long-term sea level change information from tide gauges. As of August 2002, the database of the PSMSL contains almost 49000 station-years of monthly and annual mean values of sea level from over 1800 tide gauge stations around the world received from almost 200 national authorities. On average, approximately 2000 station-years of data are entered into the database each year.

Estimates of the rate of global sea level rise determined from tide gauge records have been summarized by Gornitz (1994). Usually installed on piers, these instruments are used to measure sea level height relative to local geodetic benchmarks. However, the determination of a global rate of sea level change from tide gauge data is complicated by regional subsidence or emergence. The technology required for the detection of vertical shifts of the earth’s crust uses the Very Long Baseline Interferometer (VLBI) (Carter et al., 1986) as a monitoring system. Such a system could be used to provide a global absolute geodetic reference system to which tide gauge sites could be referenced.

Also, tide gauge sites movement can be monitored with respect to the absolute global geodetic datum using Global Positioning System (GPS) receivers. The elements of this system are in place, and accuracy in the vertical direction of about 1 cm has been demonstrated (Carter et al., 1988).

Coastal wetlands, which comprise salt marshes, mangroves and intertidal areas, are sensitive indicators of sea level change, since their location is closely associated with the local extant sea level. Various shifts in water levels may overwhelm coastal wetlands or create wave impact erosion. Therefore, apprehending the coupling between physical and ecological processes is critical to gauging the effects of sea level rise. For instance, intertidal areas should steadily submerge during a tidal cycle. With a rise in sea level, however, the tidal cycle will endure for progressively longer periods. This will cause native flora to perish -- owing to water logging; hence, this outcome will create an observable ecosystem change. Of course, coastal wetlands may augment due to increases in sediment and organic matter input. The wetland could migrate upland if there is sufficient space and no barriers.

Technologies such as GPS, satellite monitoring, or laser ranging offer an opportunity for effective field data on changing sea levels. In the past, tide gauges were the most important tool for measuring and quantifying sea level changes. Due to their scattered locations, the derived quantities have been of limited use. Moreover, distinguishing between natural and anthropogenic effects as well as between relative and absolute changes in sea level is virtually impossible. However, precise orbits, improved antenna/receiver design, better antenna models, and robust kinematic software contribute to attaining centimeter-level precision in the vertical component of GPS measurements from floating platforms. This new high level of precision makes it possible to obtain GPS-derived water level time series suitable for the determination of tidal data, mapping sea surface topography, satellite altimeter calibration, and the determination of boundary conditions for numerical models and model verification.

Hence, with the assist of accurate GPS data, an absolute determination of sea level change is in the offing. A possible use of these accurate data sets would be to modify tide gauges such that they are retrofitted with networked, long-term GPS stations.

Ocean surface topography data from the TOPEX/POSEIDON and Jason satellite altimetry missions provide high-resolution measurements, which samples, on a 10-day repeat cycle, the world ocean. Data relevant to sea level change include Jason-1 and TOPEX/Poseidon Sea Surface Height Anomaly (SSHA) products, which have a sea-level measurement accuracy of 4.2 cm.

Laser ranging has been used to study differential tectonic plate movements (lunar laser ranging) and estimate the ablation of ice sheets to centimeter accuracies (airborne lidar systems). Using ground based or airborne units, lidar technology could potentially aid in providing real-time data on sea level creep for targeted beach areas.

The calculation of the prospective evolution of threatened beach areas is not clear-cut. There exists no customary procedures, and the kinds of data required to make such predictions continue to be the source of scientific debate. A number of predictive approaches have been attempted (National Research Council, 1990), including:

- Extrapolation of historical data (e.g., coastal erosion rates),
- Static inundation modeling,
- Application of a simple geometric model (e.g., the Bruun Rule),
- Application of a sediment dynamics/budget model, or
- Monte Carlo (probabilistic) simulation based on parameterized physical forcing variables

Each of these approaches, however, has certain shortcomings or has been shown for certain applications to be invalid. Similarly, the input data required varies considerably and, for a given approach, existing data may be indeterminate or simply not exist. While a viable, quantitative predictive approach may not be available, the vulnerability to sea level rise of certain coastal environments can be estimated on a regional to national scale using available data on coastal geomorphology, rate of sea-level rise, past shoreline evolution, and other factors.

Notwithstanding, numerical modeling tenders the prospect of understanding the effects sea level rise would have on some local coastal environments. As an illustration, the Sea Level Affected Marsh Model (SLAMM) is a model developed to assess the impacts of accelerated sea-level rise due to global warming. SLAMM (the newest version is SLAMM4) can combine NOAA, USGS, and F&WS data available on the Internet to model coastal areas on a 30-m grid—providing high-resolution maps with sufficient detail to assess habitat loss and to facilitate visualization of impacts by decision makers. This model has been useful in estimating coastal wetland losses under various sea-level rise scenarios.

1.5 Mitigation Considerations

Coastal communities will be faced with a choice: to consider whether to protect themselves from sea level rise or to adapt to rising seawater levels. Avoiding erosion would require keeping waves from eroding the beach areas. Interception of incoming waves by offshore breakwaters or by armoring the beach represents two possible methodologies for mitigation of sea level rise effects. Offshore breakwaters bound the energy of incoming waves. Revetments protect the beach area and are valuable for dealing with moderate size waves.

Methods used for the prevention of sea level rise, inundation, and storm surge also limit erosion. Seawalls, levees, and bulkheads are vertical wall structures made of materials of various strengths, depending on the size of the waves. With a rising sea, however, these structures may require protection themselves. Accurate forecasts of future sea level rise could enable a determination of an adequate structural design so that their construction is cost-effective for their entire lifetime.

Beaches are important to tourism-based economies, the use of different engineering structures might not be a satisfactory course to take given the risk of erosion, inundation, or storm surge. A potential option is beach nourishment, which is the dredging of offshore sand and dispersing it over eroded beach areas. Any rise in sea level could significantly increase the expense of this method, since it the amount of sand now required for dispersal would be greater.

Restoring other mechanisms of natural systems can also protect against erosion and storm surge. For example, dunes can provide a reservoir of sand to slow erosion and act as a levee against storm surges. Also, some marshes are supplied with sufficient sediment during floods to keep up with sea level rise. Where dunes have been destroyed or rivers levied to prevent flooding, restoring these natural mechanisms may be fruitful. Adjustment to the physical consequences of sea level rise may sometimes be more appropriate than prevention. In anticipation of erosion, some communities may prohibit construction in the most hazardous areas, and abandonment may even be necessary.

2.0 Sea Level Rise: Relevant Research

Due to the importance of sea level research, various international (e.g., International Ocean Commission (IOC) and United Nations Environment Programme (UNEP)) and U.S. agencies (e.g., NOAA, the National Aeronautics and Space Administration (NASA), and the United States Geological Survey (USGS) are involved in improving measurements and conducting research in this area.

2.1 Intergovernmental Agencies Funding Global Sea Level Rise Research

The Intergovernmental Oceanographic Commission (IOC) of UNESCO provides member states of the United Nations with an essential mechanism for global cooperation in the study of the ocean. The IOC assists governments in addressing their individual and collective ocean and coastal problems through the sharing of knowledge, information, and technology and through the coordination of national programs.

The World Meteorological Organization (WMO) is a specialized agency of the United Nations with a mandate to coordinate and provide an appropriate framework for international cooperation in the field of meteorology and in related fields of environmental concern such as hydrology, geophysics, geochemistry, and physical oceanography.

The United Nations Environment Programme (UNEP) is the voice for the environment within the United Nations system. UNEP acts as a catalyst, advocate, educator, and facilitator to promote the wise use and sustainable development of the global environment. To accomplish this, UNEP works with a wide range of partners, including United Nations entities, international organizations, national governments, non-governmental organizations, the private sector, and civil society.

The International Council for Science (ICSU) mobilizes the knowledge and resources of the international science community to identify and address major issues of importance to science and society. ICSU also facilitates interaction amongst scientists across all disciplines and from all countries and provides independent, authoritative advice to stimulate constructive dialogue between the scientific community and governments, civil society, and the private sector.

Permanent Service for Mean Sea Level (PSMSL)

- Established in 1933, PSMSL is the global data bank for long-term sea level change information from tide gauges.
- Reports to the International Association for the Physical Sciences of the Ocean Commission on Mean Sea Level and Tides (IAPSO/CMSLT).

- Supported by United Kingdom Natural Environment Research Council (NERC), Federation of Astronomical and Geophysical Data Analysis Services (FAGS), and the IOC

Global Sea Level Observing System (GLOSS)

- International program conducted under the auspices of the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) of the WMO and the IOC.
- Operational system of the Global Ocean Observing System (GOOS), a permanent global system for observations, modeling and analysis of marine and ocean variables to support operational ocean services worldwide.
- Supported by IOC, UNEP, WMO, and ICSU.

Global Ocean Data Assimilation Experiment (GODAE)

- A global system of observations, communications, modeling and assimilation designed to deliver regular, comprehensive information on the state of the oceans, in a way that will promote and engender wide utility and availability of this resource for maximum benefit to the community.
- Sponsored by IOC.
- The U.S. component of GODAE or the USGODAE Project consists of United States academic, government and military researchers working to improve assimilative ocean modeling as part of the International GODAE Project. Two U.S. Federal Agencies actively involved in this work are the Navy Fleet Numerical Meteorology and Oceanography Center (FNMOC) and NOAA National Centers for Environmental Prediction (NCEP).

2.2 U.S. Agencies Involved in Sea Level Rise Research

National Oceanographic Partnership Program (NOPP) - The focus of NOPP is the development of an integrated, sustained ocean observing system for the United States. Members of NOPP include the following:

- U.S. Navy
- National Oceanic and Atmospheric Administration (NOAA)
- National Science Foundation (NSF)
- National Aeronautics and Space Administration (NASA)
- Department of Energy (DOE)
- Environmental Protection Agency (EPA)
- U.S. Coast Guard (USCG)
- U.S. Geological Survey (USGS)
- Defense Advanced Research Projects Agency (DARPA)
- Minerals Management Service (MMS)
- Office of Science and Technology Policy
- Office of Management and Budget (OMB)
- Department of State
- U.S. Army Corps of Engineers (USACE)
- Department of Homeland Security (DHS)

NOAA - National Ocean Service (NOS)

- Oceanic Research and Applications Division (ORAD) provides the primary research and development support for oceanic remote sensing within NOAA.

- Center for Operational Oceanographic Products and Services (CO-OPS) collects, analyzes, and distributes historical and real-time observations and predictions of water levels, coastal currents, and other meteorological and oceanographic data.
- National Oceanographic Data Center (NODC) archives and provides public access to global oceanographic and coastal data, products, and information.
- National Coastal Data Development Center (NCDDC) delivers access to and integrates diverse coastal data for public use.
- Joint Archive for Sea Level (JASL) - The JASL is responsible for the collaborative archive referred to as the Research Quality Data Set.

Oceanic Research and Applications Division (ORAD) Laboratory for Satellite Altimetry (LSA)

- LSA specializes in the analysis of satellite altimeter data related to problems in physical oceanography and marine geophysics.

  LSA Sea Level Change Projects
  - Near-Real Time Analyses
  - Topex/Poseidon Historical Sea Level
  - ERS Altimetry
  - Geosat Follow-On
  - Geophysics Research
  - Geophysics Products
  - Sea Floor Topography

EPA - Sea Level Rise Reports: These reports provide information on how future climate change may impact particular coastal regions and outline adaptive actions that may mitigate such potential changes.

- Nationwide Impacts - *"The Cost of Holding Back the Sea"*
- Beach Erosion and Barrier Islands **-** *"Sea Level Rise and Barrier Islands"*
- Saltwater Intrusion – "*Salinity in the Delaware Estuary"*
- Floods – "*Greenhouse Effect and Sea Level Rise"*
- Impacts on Other Nations – "*IPCC Response Strategies Report"*
- Estimates of Future Sea Level Rise – "*The Probability of Sea Level Rise"*
- Coastal Wetlands – "*Greenhouse Effect, Sea Level Rise, and Coastal Wetlands"*
- Do We Need To Do Anything Now? – "*Greenhouse Effect and Sea Level Rise: A Challenge for this Generation"*

NAVOCEANO - Naval Oceanographic Office (NAVOCEANO) provides operational products for observing sea level rise from satellite altimeter data.

- Altimetry Data Fusion Center (ADFC) at NAVOCEANO coordinates with NASA to provide rapid delivery of TOPEX altimeter data and with NOAA Laboratory for Satellite Altimetry (LSA) to provide rapid delivery of data from the European Earth Remote Sensing satellite (ERS-2).
- The Navy operates the Geosat Follow-On (GFO) altimeter satellite and provides these data directly to NAVOCEANO.
- NAVOCEANO is actively working to incorporate future altimeter mission data sets. The data expected from JASON-1 and ENVISAT will be delivered to NAVOCEANO.

USGS - The National Assessment of Coastal Change Hazards is a multi-year effort to identify and quantify the vulnerability of U.S. shorelines to coastal change hazards such as the effects of severe storms, sea-level rise, and shoreline erosion and retreat.

- The National Assessment of Shoreline Change Project develops standardized methods for mapping and analyzing shoreline movement for consistent updates to shoreline erosion and accretion records.
- Digital Shoreline Analysis System (DSAS) version 2.0 is a program (developed by USGS) based on GIS software (ARCView extension) for calculating shoreline changes.
- Subsidence and Sea Level Rise in Southeastern Louisiana: *Implications for Coastal Management and Restoration*. A collaborative USGS project for developing an objective and reliable scientific database on subsidence and sea-level rise within the Mississippi River delta plain.

2.3 Sea Level Rise Research within NASA

NASA research related to sea level changes is being conducted mainly at the Jet Propulsion Laboratory (JPL). Work associated with this research involves the generation of satellite data, products and models useful for sea level research and monitoring and on collaborative work with researchers at Universities. However, data from the recently launched ICESat's Laser Altimeter System (GLAS) are being distributed from other NASA centers.

<u>Jet Propulsion Laboratory (JPL) Assets</u>

The Physical Oceanography Distributed Active Archive Center (PO.DAAC) is responsible for archiving and distributing data relevant to the physical state of the ocean. PO.DAAC distributes ocean surface topography data from the TOPEX/POSEIDON and Jason satellite altimetry missions. In combination, the satellites provide high-resolution measurements, sampling the global ocean on 10-day exact repeat cycles. These are joint missions between CNES, the French space agency, and NASA. Other PO.DAAC products relevant to sea level changes include the Jason-1 and the TOPEX/Poseidon Sea Surface Height Anomaly (SSHA) products (sea-level measurement accuracy 4.2 cm)

GRACE (Gravity Recovery And Climate Experiment) comprises a set of twin satellites that use a satellite-to-satellite microwave tracking system to measure the Earth's gravity field and its time variability. Such measurements are directly coupled to long-wavelength ocean circulation processes and to the transport of ocean heat to the Earth's poles. A recently released GRACE Gravity model 02 (October 29, 2004) has been used in conjunction with the sea surface height (Topex/Posedon altimeters) to generate ocean surface currents that would be useful for sea level change studies.

<u>The ICESat/GLAS Data at the National Snow and Ice Data Center</u>

The NSIDC archives and distributes Level-1 and Level-2 data from the Geoscience Laser Altimeter System (GLAS) instrument aboard the Ice, Cloud, and land Elevation (ICESat) satellite that was launched by NASA on 12 January 2003. The instrument will measure ice sheet topography and associated temporal changes and cloud and atmospheric properties over land and sea that will be useful for sea level change studies.

<u>NASA Funded Study on Sea Level Rise in the Chesapeake Bay</u>

NASA currently funds a project through the University of Maryland to further demonstrate the utility of satellite imagery for monitoring and assessing the impacts of sea level rise on the coastal regions of Chesapeake Bay. The project has the following objectives: (1) use Landsat imagery to assess if further sea level degradations to vegetation cover in coastal marshes has occurred over the past decade; (2) use satellite radar imagery to estimate the level of shoreward migration that has occurred in various regions; (3) combine Landsat and radar imagery to estimate changes in marsh areas over the past decade; and (4) use radar imagery to estimate the shoreward extent of inundations that occur during extreme storm events where sea levels reach levels 2 to 3 meters above mean high water.

3.0 NASA Partner Relevant Programs

While many research programs on the effects of sea level rise on coastal communities are ongoing, decision support tools (DSTs) to address this issue are few. Two decision support tools with potential for assimilation of NASA Earth Science products, data and models are the Wave-current Surge Information System (WAVCIS) and NOAA's Center for Sponsored Research (CSCOR) project to study the Ecological Effects of Sea Level Rise (EESLR) in the State of North Carolina. WAVCIS is used operationally in Louisiana and Mississippi to provide real-time information to emergency response agencies during storms and hurricanes and to provide data on coastal waves, currents, and storm surges for research associated with sea level rise. NOAA EESLR uses ecological forecasting methods to provide managers and planners the modeling and mapping tools needed to assess the impacts of future sea level rise on land use, especially in shallow near-shore environments. Here we provide a brief description of these two programs and evaluate NASA Earth Science satellite products and modeling capabilities to support the programs.

3.1 WAVCIS Decision Support Tool

Sea level rise during storms and hurricanes is a real concern for coastal Louisiana and Mississippi since many coastal low-lying regions are often inundated because of these events. WAVCIS (WAVe-Current Information System) is a wave-current and surge-monitoring program for coastal Louisiana that provides information on sea state (wave height, period, direction of propagation, water level, surge, near surface current speed and direction) and meteorological conditions in real time. WAVCIS involves the deployment of instrumentation in deep and shallow waters off the Louisiana coast and some areas along the Mississippi coast (Figure 3). These data are transmittal by a solar-powered cellular link to a base station at Louisiana State University (LSU) where the observations eventually undergo quality control, post-processing, and archiving in an online database. The information is then made available on the World Wide Web and is accessible to computers with an Internet connection and web browser to coastal managers and public. However, use of this data at present requires permission from the WAVCIS manager. Various data displays are available for the real-time information as well as some archived data. The Federal Emergency Management Agency (FEMA), LSU Hurricane Center, and NOAA use WAVCIS as an emergency response tool for providing the public information on evacuations or early warnings during storm threats in the Gulf of Mexico.

WAVCIS provided critical information in 2002 during Tropical Storm Isidore on September 26, and Hurricane Lili on October 3. WAVCIS presently has five operational stations, three under construction, and four in planning stages (Figure 3). Data that are posted and available from archives for each of the WAVCIS stations include both oceanographic and meteorological parameters.

Oceanographic parameters include wave information (wave height and period), current information (speed and direction), water depth, salinity, sea surface temperature, and turbidity. Meteorological parameters include wind speed and direction, air temperature, barometric pressure and visibility. Remote sensing data include the NOAA GOES-12 (geostationary) satellite infrared imagery. The on-going utility of WAVCIS to the coastal community and its use by state and Federal agencies provides an opportunity for NASA to contribute to the system through the assimilation of Earth Science data, products, and models.

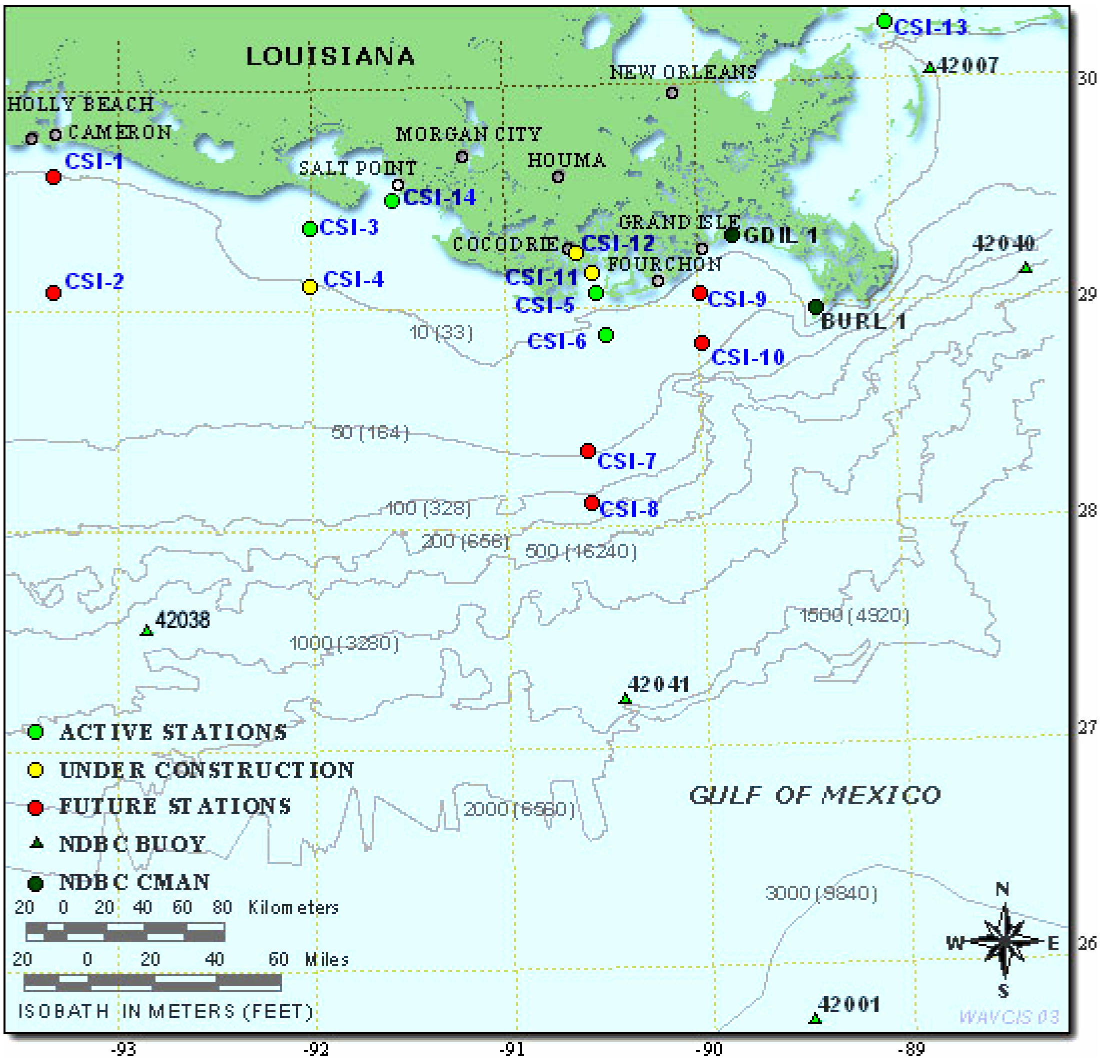

Figure 2 - Wave-current surge monitoring stations of coastal Louisiana

3.2 WAVCIS Sponsors and Collaborators

WAVCIS sponsors include NOAA, FEMA, the National Park Service, Louisiana Oil Spill Research and Development Program, Louisiana State University, MMS, NAVOCEANO, and the Louisiana Department of Natural Resources. WAVCIS collaborators include NOAA National Data Buoy Center (NDBC), U.S. Coast Guard, and the LSU Hurricane Center.

3.3 NOAA Ecological Effects of Sea Level Rise (EESLR) Program

The EESLR program within NOAA Center for Sponsored Coastal Ocean Research (CSCOR) evaluates the potential impact of long-term sea level rise on a specified coastal region, 25 to 50 years in the future. The program is designed to help coastal managers and planners prepare for changes in coastal ecosystems due to land subsidence and sea level rise. North Carolina, which has over 300 miles of ocean beaches and over 4000 miles of estuarine shoreline, is one of the current study areas of the program. With much of the coastal area less than 20 feet above mean sea level (MSL) and a larger percentage less than 5 feet above MSL, a rising sea level along the North Carolina coast would have lead to the gradual inundation of wetlands and low dry lands, erosion of beaches, more frequent and severe flooding, and greater salinity of rivers, bays, aquifers, and wetlands. These scenarios would likely affect the State's environment, public health and economy through changes on human uses of the coast, e.g., tourism, development, transportation, commercial and recreational fishing, agriculture, and nature viewing activities.

EESLR uses a four-stage approach to predict and assess the ecosystem impacts of sea level rise in coastal North Carolina. This approach consists of a hydrodynamic tide model of the study area, a high-resolution, topographic/bathymetric digital elevation model (DEM) that integrates recent airborne LIDAR (Light Detecting and Ranging) topographic data and bathymetric data, a hydrodynamic coastal flooding model that integrates the DEM and tide models to predict and assess sea-level rise impacts, and a suite of ecological sub-models that will be integrated with the coastal flooding models to demonstrate landscape responses relevant to critical natural resources. These ecological models will address the landward migration of wetlands, wetland species composition and change due to salinity increases, changes in submerged aquatic vegetation (SAV) beds due to inundation and salinity increases, changes in turbidity and effects of decreased light penetration, and oyster bed movements. These physical-ecological models (Clark et al. 2001) will help managers and planners to better assess and predict the fate of ecologically and economically valuable natural resources threatened by sea level rise. These proactive approaches will help planners begin to assess the impacts of future sea level rise when making land use decisions, especially in vulnerable shallow near-shore environments and coastal wetlands and could therefore be part of a decision support system. Applications include fish-stock assessment, design of marine protected areas, and other resource management issues.

Near term (2004-2005) research plans for the project include the completion of the hydrodynamic tidal model that will be expanded to simulate the influence of winds on water levels. Further enhancements planned include the addition of wind waves to the model and a three-dimensional version of the model that incorporates salinity and temperature. The DEM will be completed when bathymetry is combined with land elevation data from the State's topographic LIDAR survey to produce the bathymetric/topographic elevation model with a spatial resolution of 10 to 30 m in the horizontal. The coastal flooding model (CFM), which combines the tide and water level model and the DEM, will be developed by expanding the existing tide model grid to cover low-lying land areas and then populating the grid's land cells with DEM-based elevation values. The CFM will then be used to assess land inundation due to storm surges and sea level rise and will be enhanced to incorporate surface and subsurface flow, wetlands, and intertidal areas. Mid-term goals of the project include funding peer-reviewed research proposals to mine archived data for incorporation within ecological modeling linking the DEM and hydrological models. Long-term goals include field and laboratory studies to validate the models.

Physical processes of interest to this study include fluctuations of sea water (astronomical tides, storm surges, and wind waves), basin water flow (currents, river flows, salinity, temperature, and turbidity), subsurface hydrology, changes in land forms (erosion, sedimentation, and accretion), the effects of the atmosphere (winds, precipitation, and evaporation), and the impacts of human activity on the system (dredging, alterations of drainage, and beach protection). Understanding the marsh response to sea level rise requires information on organic matter accumulation, inorganic sedimentation, and erosion. Assessment of the ecological impacts of sea level rise necessitates the development of predictions of habitat extent and quality for several habitats deemed as "strategic" for the North Carolina coast (Moorhead and Brinson 1995). Some of these include nursery and spawning areas for anadromous fish, oyster reefs, and areas of submerged aquatic vegetation

3.4 Collaborators

NOAA Office of Coast Survey (OCS), National Geodetic Service (NGS), and the Center for Operational Products and Service (COOPS) directly involves the North Carolina Division of Coastal Management Strategic Planning Unit in the planning and focusing of the research program for the EESLR pilot program in the State of North Carolina (the Albermarle Pamlico Estuarine System, or APES).

4.0 NASA Potential Contributions

4.1 Potential NASA WAVCIS Contributions

Since both Federal and State agencies for emergency preparedeness and coastal erosion decision support use WAVCIS, additional contributions from NASA Earth Science data would improve the system's effectiveness. Some of the NASA Earth Science data, products, and models that would enhance WAVCIS are briefly discussed below.

- *MODIS 250- and 500-m surface reflectance data*. MODIS provides daily morning (Terra) and afternoon (Aqua) medium resolution data that can be used to map changes in land-water interfaces.

- *Landsat 7 Enhanced Thematic Mapper Plus (ETM+)*. The 30-m spatial resolution data from this sensor would be useful in evaluating long-term changes in land cover that may result from sea level change associated with eustatic and isostatic processes and storms and hurricanes in coastal Louisiana.

- *MODIS standard products.* Estimates of sea surface temperature (SST) and chlorophyll concentration provide information on biological-physical coupling within coastal waters. The products could display how physical processes affect the biological components of productive coastal ecosystems.

- *SeaWinds (QuikSCAT) product.* Satellite wind products could provide information at locations not occupied by WAVCIS field stations.

- *Airborne Topographic Mapper (ATM)* is a scanning LIDAR developed and used by NASA for observing the Earth's topography and has been used to measure sea-surface elevation and ocean wave characteristics. It is capable of decimeter accuracy and, hence, can survey from the air.

- *Wavewatch III model*. Wavewatch III is a third generation wave model developed at NOAA/NCEP to provide predictions of 16 mean wave parameters including significant wave height, direction, and frequency. These model parameters would be useful to the WAVCIS system. Wavewatch III model is presently being developed for operation and integration with WAVCIS.

4.2 Potential NASA EESLR Contributions

NASA is not involved either directly or through collaborations in any activities associated with the EESLR pilot program in the State of North Carolina. However, there is a potential for NASA Earth Science data, products, and models to enhance the long-term success of the project. Since the information from the project would be available to State and Federal Agencies, additional remotely sensed and modeled data and products could benefit decision making for coastal management. Some of the NASA Earth Science data, products, and models that would enhance the EESLR projects are briefly discussed below.

- *MODIS 250- and 500-m surface reflectance data*. MODIS provides daily morning (Terra) and afternoon (Aqua) medium resolution data that can be used to map changes in land-water interfaces.

- *Landsat 7 Enhanced Thematic Mapper Plus (ETM+)*. The 30-m spatial resolution data from this sensor would be useful in evaluating long-term changes in land cover that may result from sea level change associated with eustatic and isostatic processes and storms and hurricanes in coastal Louisiana.

- *MODIS standard products*. SST would be useful to monitor physical processes and as inputs to models.

- *Airborne Topographic Mapper (ATM)* is a scanning LIDAR developed and used by NASA for observing the Earth's topography and has been used to measure sea-surface elevation and ocean wave characteristics. It is capable of decimeter accuracy and, hence, can survey from the air.

- *SeaWinds (QuikSCAT) products.* Wind vectors could be an important input to models required to estimate wind waves and currents.

- Wavewatch III. This model provides predictions of 16 mean wave parameters, such as significant wave height, direction, and frequency, useful to the EESLR study.

5.0 Summary and Conclusions

In this report, an outline of the environmental background and concomitant topics relating to sea level rise and its impact on coastal regions was discussed. Relevant DSS development in sea level rise assessment is still relatively slight.

However, the report documented that International, U.S. Agencies, and the interested research community places high significance on sea level change inquiries. This report referenced diverse regulations and policies related to sea level rise.

NASA involvement in sea level rise has been chiefly via the data streams of satellite sensors and their derived data products. WAVCIS (implemented in Louisiana) and the EESLR project (North Carolina) are decision support tools that are presently used for coastal management relating to sea level change. These coastal tools could provide improved decision-making capabilities if enhanced with the assimilation of NASA Earth Science products, data, and models. An enumeration and discussion of the germane NASA data sets and models is provided.

Albeit that sea level DSS development is still in its infancy, it is recommended that, since sea level rise research could benefit from NASA data products, that some initial discussions go forward with relevant researchers and agencies.

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