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Charles W. Finkl
Christopher Makowski *Editors*

Remote Sensing and Modeling

Advances in Coastal and Marine Resources

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Remote Sensing and Modeling

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Preface

Remote sensing is a very large field of study that involves many different types of sensors, platforms (videographic stations, satellites, aircraft, UAVs or drones [flying robots], etc.), and purposes (research, surveillance, warfare). Recent advances in the field focus on merging technologies in GIS (Geographic Information Systems), robotics, and numerical modeling, as these endeavors tend to reinforce each other. The coastal zone is a complex system, parts of which are difficultly accessible under the best of conditions. During inclement weather or when high-energy conditions prevail, study of coastal systems and environments often requires the acquisition of remotely sensed data that cannot be directly collected by humans. Nevertheless, even under optimal weather conditions the use of remote sensing techniques is advantageous for many reasons, not the least of which is the fact that enormous datasets can be collected over large spatial scales in relatively short time spans. Data acquisition covers a wide array of surface, intertidal, and submarine environments.

This book is not a comprehensive review of recent advances in remote sensing, as the field of study is too large to handle and such a broad view is beyond the scope of our subject area. Instead, this volume in the Coastal Research Library contains selected vignettes that make up 20 chapters. These examples of advances are considered in four parts, each with several chapters. Part I (Remote Sensing and Mapping of Coastal Biophysical Environments) contains seven chapters. The first chapter (Remote Sensing of Coastal Ecosystems and Environments), by Vic Klemas, sets the stage for the volume by providing an overview of remote sensing of coastal biophysical environments. Considered here are advances in sensor design and data analysis techniques as related to hyperspectral imagers, LiDAR, and radar systems. Chapter 2 (Advanced Techniques for Mapping Biophysical Environments on Carbonate Banks Using Laser Airborne Depth Sounding (LADS) and IKONOS Satellite Imagery) by Charles W. Finkl, Christopher Makowski, and Heather Vollmer, investigates recent advances in the mapping of seafloor environments on carbonate shelves using the example of southern Florida. Interpretation of seafloor data derived from LADS and IKONOS imagery was used to develop new cognitive mapping techniques and classification systems that are useful for the study of large areas. Chapter 3 (Terrestrial Lase Scanner Surveying in Coastal Settings) reports on advances associated with the proliferation of commercially available tripod-mounted terrestrial laser scanner (TLS) systems that use the phase difference or the time-of-flight of emitted pulses of light to rapidly acquire high-density topographic and surface reflectance data. Chapter 4 (Advances in Applied Remote Sensing to Coastal Environments Using Free Satellite Imagery), by Cristina Lira and Rui Taborda, reports on advances associated with Landsat 8, which supports improved radiometric and spectral resolutions (compared to previous Landsat platforms). Discussed here are potentialities of these new sensors for temporal coverage, frequency of coverage, radiometric resolution, and spectral resolution. Chapter 5 (Remote Sensing and Modeling of Coral Reef Resilience), by Anders Knudby, Simon J. Pittman, Joseph Maina, and Gwilym Rowlands, reviews the state of the art of coral reef resilience mapping, based on remote sensing, spatial distribution modeling, and process modeling. Case studies illustrate coarse-scale mapping of reef exposure to climate-driven disturbances, intermediate-scale mapping of water quality and its influence on coral bleaching susceptibility, and fine-scale mapping of local factors that influence the ability of reefs to resist and rebound from climate-driven disturbance. Chapter 6 (An Assessment of Physiographic Habitats, Geomorphology and Evolution of Chilika Lagoon (Odisha, India) Using Geospatial Technology), by Ashis Kr. Paul, Sk Majharul Islam, and Subrata Jana, studies the geomorphologic changes, ecologic responses, and evolution of the Chilika Lagoon using geospatial technology with temporal image data. Lastly, Chap. 7 (Foreshore Applications of X-band Radar), by G. M. Jahid Hasan and Satoshi Takewaka, employed an X-band nautical radar system to examine alongshore propagation of low frequency run-up motion, as well as estimate the morphodynamic parameters from two typhoon events in the Pacific Ocean.

Part II (Advances in the Study and Interpretation of Coastal Oceans, Estuaries, Sea-Level Variation, and Water Quality) brings together in five chapters some disparate advances under a larger umbrella with examples from the coastal ocean, estuaries, and gulfs. Chapter 8 (Digital Ocean Technological Advances), by Xin Zhang, Xiaoyi Jiang, Suixiang Shi, and Tianhe Chi, considers the Digital Ocean (DO) as a new research domain of Digital Earth. Here, DO technological advances are introduced for (1) data sources, (2) three-dimensional ocean data integration platform, (3) dynamic tide data visualization, (4) integration and sharing of remote sensing products, (5) computational ocean model data integration service, and (6) spatio-temporal model of marine disasters. In Chap. 9 (A New Statistical-Empirical Hybrid Based Model to Estimate Seasonal Sea-Level Variation in the Gulf of Paria from River Discharge) by Carol Subrath-Ali, new insight is provided for the quantitative role of the Orinoco River in South America. This chapter reports on a vertically integrated 2D numerical modeling suite that is applied to the execution of a series of experiments to ascertain variation of coastal water levels from river discharge. The modeling advance here shows how a third order model function, which is dependent only on river discharge, can estimate the average monthly river-driven water level in the Gulf of Paria. In a similar vein, Chap. 10 (Advances in Modeling of Water Quality in Estuaries) by K.I. Ascione,

F. Campuzano, G. Franz, R. Fernandes, C. Viegas, J. Sobrinho, H. De Pablo, A. Amaral, L. Pinto, M. Mateus, and R. Neves, posits that water quality models complement studies about the status of estuarine waters. This chapter serves as an exemplar showing how advanced modeling applications can be used to perform water quality studies in Portuguese estuaries. Boundary conditions for hydrodynamics and biogeochemistry, provided by the Portuguese Coast Operational Model, are downscaled by using nested domains with increasing resolution from the regional to the local scale. Chapter 11 (Advances in Video Monitoring of the Beach and Nearshore: The Long-Term Perspective), by Ana Nobre Silva and Rui Taborda, summarizes recent developments on the use of video systems in the understanding of yearly to decadal beach morphological changes and describes the application of such a video system deployed at Nazaré, Portugal. While Chap. 12 (Advances in Application of Remote Sensing Techniques to Enhance the Capability of Hydrodynamic Modeling in Estuary), by A.K.M Azad Hossain, Yafei Jia, Xiaobo Chao, and Mustafa Altinakar, provides evidence that the application of remote sensing techniques for estuarine water quality studies can be advanced by integrating them with numerical models.

Part III (Advances in Coastal Modeling Using Field Data, Remote Sensing, GIS and Numerical Simulations) contains five chapters that consider integrated approaches to coastal modeling. Chapter 13 (Developments in Salt Marsh Topography Analysis Using Airborne Infrared Photography), by Francisco Andrade, Jackson Blanton, M. Adelaide Ferreira, and Julie Amft, shows how only recently have remote-sensing techniques become widely available to obtain high-resolution topographic data in salt marshes. These authors describe how a detailed digital elevation model (DEM) of the Duplin River (Georgia, southeastern USA) with a 1 m^2 resolution was constructed through the classification and analysis of a time-series of 7 IR (infrared) aerial photography mosaics taken at 1 h intervals from low-to high-water during a rising tide. In Chap. 14 (Examining Material Transport in Dynamic Coastal Environments: An Integrated Approach Using Field Data, Remote Sensing and Numerical Modeling), Richard L. Miller, Ramón López, Ryan P. Mulligan, Robert E. Reed, Cheng-Chien Liu, Christopher J. Buonassissi, and Matthew M. Brown describe an integrated approach based on field measurements, remote sensing and numerical modeling that examines the transport of dissolved (colored dissolved organic matter (CDOM), dissolved organic carbon (DOC)) and particulate material (total suspended matter (TSM)) within a complex coastal system, the Albemarle-Pamlico Estuarine System (APES), North Carolina, USA. The advanced Delft3D numerical model is used to simulate freshwater and DOC transport following major rain events. Chapter 15 (Simulated Management Systems Developed by the Northern Gulf Coastal Hazards Collaboratory (NG-CHC): An Overview of Cyberinfrastructure to Support the Coastal Modeling Community in the Gulf of Mexico), by a team composed of Robert R. Twilley, Steve Brandt, Darlene Breaux, John Cartwright, Jim Chen, Greg Easson, Patrick Fitzpatrick, Kenneth Fridley, Sara Graves, Sandra Harper, Carola Kaiser, Alexander Maestre, Manil Maskey, William H. McAnally, John McCorquodale, Ehab Meselhe, Tina Miller-Way, Kyeong Park, Joao Pereira, Thomas Richardson, Jian

Tao, Amelia Ward, Jerry Wiggert, and Derek Williamson, explains how a collaboratory was established to catalyze collaborative research via enhanced CI (cyberinfrastructure) to reduce regional vulnerability to natural and human disasters by facilitating high performance modeling to test hypotheses focused on engineering design, coastal system response, and risk management of coastal hazards. This advanced technology is used to promote collaborative environmental modeling in coastal systems. Chapter 16 (Advancement of Technology for Detecting Shoreline Changes in East Coast of India and Comparison with Prototype Behavior), by Ramasamy Manivanan, discusses how the information predicted by cross-shore and longshore impact mathematical model match the information shown by satellite imagery. Thus, satellite information can be useful for the overall calibration of the mathematical models. Chapter 17 (Advances in Remote Sensing of Coastal Wetlands: LiDAR, SAR, and Object-Oriented Case Studies from North Carolina), by Thomas R. Allen, reviews the different advancements from the use of Light Detection and Ranging (LiDAR), space-borne Synthetic Aperture Radar (SAR), and multi-sensor and object-oriented image analysis techniques, which aid the inventorying, monitoring, and management of coastal wetlands.

Part IV (Advances in the Management of Coastal Resources Using Remote Sensing Data and GIS) contains three chapters that extol the virtues of numerical simulations and satellite remote sensing tools for research and management. Chapter 18 (Numerical Simulations and Satellite Remote Sensing as Tools for Research and Management of Marine Fishery Resources), by Grinson George, discusses modeled and satellite remote sensing data that support research, technology-development, and management of marine fishery resources. Of interest here is the fact that numerical simulations and remote sensing data of the marine environment provides sufficient cues in the form of surrogate databases that support monitoring, surveillance, and management of marine fishery resources in the context of an ecosystem approach. Chapter 19 (Identifying Suitable Sites of Shrimp Culture in Southwest Bangladesh Using GIS and Remote Sensing Data), by Shak Md. Bazlur Rahaman, Khandaker Anisul Huq, and Md. Mujibor Rahman, shows how satellite imagery and GIS data (e.g. water and soil quality, shrimp culture area, method and production, source and seasonal availability of water, drainage system, water logging, disease outbreak, sanitation facility, road communication, electricity supply, land use pattern, land elevation, hazard frequency, fisheries statistics, and population census data) were collected in studies of site suitability. The advanced methodology in this study shows how to formulate shrimp culture policy for sustainable development. And in Chap. 20 (A Multi-Criteria Approach for Erosion Risk Assessment Using a New Concept of Spatial Unit Analysis, Wave Model, and High Resolution DEMs), by Helena Granja, José Pinho, and João Mendes, field data and model outputs were integrated, processed, and analyzed within a GIS interface in order to assess the vulnerability to erosion and to produce associated risk maps using a multi-criteria approach.

When discussing advancements in the remote sensing and modeling of biophysical coastal systems, researchers have made many great strides in recent years. This volume of the Coastal Research Library (CRL), while presenting a wide range of topics related to the innovative technologies associated with the development and improvement of coastal remote sensing and modeling, also offers a look into the many parts of the world where these advancements are being implemented. For example, a new seasonal sea-level variation model is introduced along the Orinoco River in South America, the advancement of water quality models is presented for estuaries in Portugal, the use of remote sensing and GIS data is shown to further the advancement of shrimp fisheries in Bangladesh, and by incorporating Laser Airborne Depth Sounding (LADS) and IKONOS satellite imagery, a new level of mapping biophysical environments on carbonate banks is achieved in south Florida. The following chapters establish the ongoing advancements in the fields of remote sensing and modeling, as well as provide a comprehensive look into diverse coastal environments where these studies are being conducted.

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Part I
Remote Sensing, Mapping and Survey of Coastal Biophysical Environments

Chapter 1
Remote Sensing of Coastal Ecosystems and Environments

Victor V. Klemas

Abstract Advances in sensor design and data analysis techniques are making remote sensing systems suitable for monitoring coastal ecosystems and their changes. Hyperspectral imagers, LiDAR and radar systems are available for mapping coastal marshes, submerged aquatic vegetation, coral reefs, beach profiles, algal blooms, and concentrations of suspended particles and dissolved substances in coastal waters. Since coastal ecosystems have high spatial complexity and temporal variability, they benefit from new satellites, carrying sensors with fine spatial (0.4–4 m) or spectral (200 narrow bands) resolution. Imaging radars are sensitive to soil moisture and inundation and can detect hydrologic features beneath the vegetation canopy. Multi-sensor and multi-seasonal data fusion techniques are significantly improving coastal land cover mapping accuracy and efficiency. Using time-series of images enables scientists to study coastal ecosystems and to determine long- term trends and short- term changes.

1.1 Introduction

Coastal ecosystems, including marshes, mangroves, seagrasses and coral reefs, are highly productive and act as critical habitats for a wide variety of plants, fish, shellfish, and other wildlife. For instance, coastal wetlands provide flood protection, protection from storm and wave damage, water quality improvement through filtering of agricultural and industrial waste, and recharge of aquifers (Morris et al. 2002; Odum 1993). Since more than half of the U.S. population lives in the coastal zone, coastal ecosystems have been exposed to a wide range of stress-inducing alterations, including dredge and fill operations, hydrologic modifications,

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pollutant run-off, eutrophication, impoundments and fragmentation by roads and ditches (Waycott et al. 2009). Furthermore, with events such as the hurricanes of 2004, 2005 and 2012 annual losses to coastal communities can total billions of dollars. Environmental impacts from coastal storms include beach erosion, wetland destruction, excessive nutrient loading, algal blooms, hypoxia and anoxia, fish kills, releases of pollutants, spread of pathogens, and bleaching of coral reefs.

Over the long term, coastal communities are also facing a rising sea level. The substantial sea level rise and more frequent storms predicted for the next 50–100 years will affect coastal towns and roads, coastal economic development, beach erosion control strategies, salinity of estuaries and aquifers, coastal drainage and sewage systems, and coastal wetlands and coral reefs (Gesch 2009; IPCC 2007; NOAA 1999). Coastal areas such as barrier islands, beaches, and wetlands are especially sensitive to sea-level changes. A major hurricane can devastate a wetland (Klemas 2009). Rising seas will intensify coastal flooding and increase the erosion of beaches, bluffs and wetlands, as well as threaten jetties, piers, seawalls, harbors, and waterfront property. Along barrier islands, the erosion of beachfront property by flooding water will be severe, leading to greater probability of overwash during storm surges (NOAA 1999).

Since coastal ecosystems have high spatial complexity and temporal variability, they require high spatial, spectral and temporal resolutions. Recent advances in sensor design and data analysis techniques are making remote sensing systems practical and cost-effective for monitoring natural and man-made changes impacting coastal ecosystems. High resolution multispectral and hyperspectral imagers, LiDAR and radar systems are available for monitoring changes in coastal marshes, submerged aquatic vegetation, coral reefs, beach profiles, algal blooms, and concentrations of suspended particles and dissolved substances in coastal waters. Some of the ecosystem health indicators that can be mapped with new high-resolution remote sensors include natural vegetation cover, wetland loss and fragmentation, wetland biomass change, percent of impervious watershed area, buffer degradation, changes in hydrology, water turbidity, chlorophyll concentration, eutrophication level, salinity, *etc*. (Lathrop et al. 2000; Martin 2004; Wang 2010).

With the rapid development of new remote sensors, data bases and image analysis techniques, potential users need guidance in choosing remote sensors and data analysis methods that are most appropriate for each specific coastal application (Yang 2009). The objective of this paper is to review those remote sensing techniques that are cost-effective and practical for shoreline delineation, wetland mapping and other coastal applications.

1.2 Wetland Mapping

For more than three decades remote sensing techniques have been used by researchers and government agencies to map and monitor wetlands (Dahl 2006; Tiner 1996). Traditionally, in addition to airborne sensors, the Landsat Thematic Mapper (TM) and the French SPOT satellite have been reliable data sources for

Fig. 1.1 The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite captured this image on September 26, 2008, 13 days after Hurricane Ike came ashore. The *brown* areas in the image are the result of a massive storm surge that Ike pushed far inland over Texas and Louisiana causing a major marsh dieback (Color figure online) (Credits: NASA/GSFC)

wetland and land cover mapping (Klemas 2011). Their 30 m and 10–20 m respective spatial resolutions and spectral bands have proven cost-effective for mapping land cover and changes in large coastal watersheds (Harvey and Hill 2001; Houhoulis and Michener 2000; Jensen 2007; Lunetta and Balogh 1999). Landsat TM and ETM+ imagery have also been used to study water turbidity and depth in marshes as well as the seasonal dynamics of inundation, turbidity, and vegetation cover (Bustamante et al. 2009; Ward et al. 2012).

More recently other medium spatial resolution satellite sensors, such as MODIS on NASA's Terra and Aqua satellites, have been used to map wetlands and study their interaction with storm surges. This is illustrated in Fig. 1.1, which shows an image of the Texas coast captured by MODIS on NASA's Terra satellite 13 days after Hurricane Ike made landfall on September 13, 2008. The storm's surge covered hundreds of kilometers of the Gulf Coast because Ike was a large storm, with tropical-storm-strength winds stretching more than 400 km from the center of the storm. Most of the shoreline in this region is coastal wetland. One can clearly distinguish the red-brown areas in the image which are the result of the massive storm surge that Ike had pushed far inland over Texas and Louisiana, causing a major marsh dieback. The salty water burned the plants, leaving them wilted and brown. The brown line corresponds with the location and extent of the wetlands. North of the brown line, the vegetation gradually transitions to pale green farmland

and dark green natural vegetation untouched by the storm's surge. The powerful tug of water returning to the Gulf also stripped marsh vegetation and soil off the land. Therefore, some of the brown seen in the wetlands may be deposited sediment. Plumes of brown water are visible as sediment-laden water drains from rivers and the coast in general. The muddy water slowly diffuses, turning pale green, green, and finally blue as it blends with clearer Gulf water (NASA/GSFC 2010; Ramsey and Rangoonwala 2005).

Many coastal ecosystems are patchy and exhibit considerable variations in their extent, spatial complexity, and temporal variability (Dahl 2006). Protecting them requires the ability to monitor their biophysical features and controlling processes at high spatial and temporal resolutions, such as that provided by aircraft and high spatial resolution satellite sensors (Adam et al. 2010; Klemas 2011). More recently, the availability of high spatial and spectral resolution satellite data has significantly improved the capacity for mapping salt marshes and other coastal ecosystems (Jensen et al. 2007; Laba et al. 2008; Ozesmi and Bauer 2002; Wang et al. 2010). High resolution imagery (0.4–4 m) can now be obtained from satellites, such as IKONOS and QuickBird. Major plant species within a complex, heterogeneous tidal marsh have been classified using multitemporal high-resolution QuickBird images, field reflectance spectra and LiDAR height information. *Phragmites*, *Typha* spp. and *S. patens* were spectrally distinguishable at particular times of the year, likely due to differences in biomass and pigments and the rate at which change occurred throughout the growing season. For instance, classification accuracies for *Phragmites* were high due to the uniquely high near-infrared reflectance and height of this plant in the early fall (Ghioca-Robrecht et al. 2008; Gilmore et al. 2010).

High resolution imagery is more sensitive to within- class spectral variance, making separation of spectrally mixed land cover types more difficult than when using medium resolution imagery. Therefore, pixel-based techniques are sometimes replaced by object-based methods, which incorporate spatial neighborhood properties, by segmenting/partitioning the image into a series of closed objects which coincide with the actual spatial pattern, and then proceed to classify the image. "Region growing" is among the most commonly used segmentation methods. This procedure starts with the generation of seed points over the whole scene, followed by grouping neighboring pixels into an object under a specific homogeneity criterion. Thus the object keeps growing until its spectral closeness metric exceeds a predefined break-off value (Kelly and Tuxen 2009; Shan and Hussain 2010; Wang et al. 2004).

Small wetland sites are often mapped and studied using airborne sensors (Jensen 2007; Klemas 2011). Airborne georeferenced digital cameras, providing color and color infrared digital imagery are particularly suitable for accurate wetland mapping and interpreting satellite data. Most digital cameras are capable of recording reflected visible to near-infrared light. A filter is placed over the lens that transmits only selected portions of the wavelength spectrum. For a single camera operation, a filter is chosen that generates natural color (blue-green-red wavelengths) or color-infrared (green-red-near IR wavelengths) imagery. For multiple camera operation, filters that transmit narrower bands are chosen (Ellis and Dodd 2000).

Digital camera imagery can be integrated with GPS position information and used as layers in a GIS for a wide range of modeling applications (Lyon and McCarthy 1995). Small aircraft flown at low altitudes (*e.g.* 200–500 m) can also be used to guide field data collection (McCoy 2005). However, cost becomes excessive if the study site is larger than a few hundred square kilometers, and in that case, medium resolution multispectral sensors, such as Landsat TM (30 m) and SPOT (20 m), become more cost-effective (Klemas 2011).

1.3 Hyperspectral Remote Sensing of Wetlands

Airborne hyperspectral imagers, such as the Advanced Visible Infrared Imaging Spectrometer (AVIRIS) and the Compact Airborne Spectrographic Imager (CASI) have been used for mapping coastal wetlands and shallow water substrate (Fearns et al. 2011; Lesser and Mobley 2007; Li et al. 2005; Rosso et al. 2005; Ozesmi and Bauer 2002; Schmidt and Skidmore 2003; Thomson et al. 1998). Hyperspectral imagers may contain hundreds of narrow spectral bands located in the visible, near-infrared, mid-infrared, and sometimes thermal portions of the EM spectrum (Jensen et al. 2007).

The advantages and problems associated with hyperspectral mapping have been clearly demonstrated by Hirano et al. (2003) who used AVIRIS hyperspectral data to map vegetation for a portion of Everglades National Park in Florida. The AVIRIS provides 224 spectral bands from 0.4 to 2.45 μm, each with 0.01 μm bandwidth, 20 m spatial resolution, and a swath width of 10.5 km. Hirano et al. compared the geographic locations of spectrally pure pixels in the AVIRIS image with dominant vegetation polygons of the Everglades Vegetation Database and identified spectrally pure pixels as ten different vegetation classes, plus water and mud. An adequate number of pure pixels was identified to permit the selection of training samples used in the automated classification procedure. The spectral signatures from the training samples were then matched to the spectral signatures of each individual pixel. Image classification was undertaken using the ENVI spectral angle mapper (SAM) classifier in conjunction with the spectral library created for the Everglades study area. The SAM classifier examines the digital numbers (DNs) of all bands from each pixel in the AVIRIS data set to determine similarity between the angular direction of the spectral signature (*i.e.* color) of the image pixel and that of a specific class in the spectral library. A coincident or small spectral angle between the vector for the unknown pixel and that for a vegetation class training sample indicates that the image pixel likely belongs to that vegetation class. In the case of spectrally mixed pixels, the relative probability of membership (based on the spectral angle) to all vegetation classes is calculated. Mixed pixels are then assigned to the class of the greatest probability of membership (Hirano et al. 2003).

The hyperspectral data proved effective in discriminating spectral differences among major Everglades plants such as red, black and white mangrove communities and enabled the detection of exotic invasive species (Hirano et al. 2003). The overall classification accuracy for all vegetation pixels was 65.7 %, with different mangrove tree species ranging from 73.5 to 95.7 % correct. Limited spatial resolution was a problem, resulting in too many mixed pixels. Another problem was the complexity of image-processing procedures that are required before the hyperspectral data can be used for automated classification of wetland vegetation. The tremendous volume of hyperspectral image data necessitated the use of specific software packages, large data storage, and extended processing time (Hirano et al. 2003). A detailed accuracy assessment of airborne hyperspectral data for mapping plant species in freshwater coastal wetlands has been performed by Lopez et al. (2004).

A number of advanced new techniques have been developed for mapping wetlands and even identifying wetland types and plant species (Schmidt et al. 2004; Jensen et al. 2007; Klemas 2011; Yang et al. 2009). For instance, using LiDAR, hyperspectral and radar imagery, and narrow-band vegetation indices, researchers have been able not only discriminate some wetland species, but also make progress on estimating biochemical and biophysical parameters of wetland vegetation, such as water content, biomass and leaf area index (Adam et al. 2010; Artigas and Yang 2006; Filippi and Jensen 2006; Gilmore et al. 2010; Ozesmi and Bauer 2002; Simard et al. 2010; Wang 2010). The integration of hyperspectral imagery and LiDAR-derived elevation has also significantly improved the accuracy of mapping salt marsh vegetation. The hyperspectral images help distinguish high marsh from other salt marsh communities due to its high reflectance in the near-infrared region of the spectrum, and the LiDAR data help separate invasive *Phragmites* from low marsh plants (Yang and Artigas 2010).

Hyperspectral imaging systems are now available not only for airborne applications, but also in space, such as the satellite-borne Hyperion system, which can detect fine differences in spectral reflectance, assisting in species discrimination on a global scale (Christian and Krishnayya 2009; Pengra et al. 2007). The Hyperion sensor provides imagery with 220 spectral bands at a spatial resolution of 30 m. Although there have been few studies using satellite-based hyperspectral remote sensing to detect and map coastal vegetation species, results so far have shown that discrimination between multiple species is possible (Blasco et al. 2005; Heumann 2011).

1.4 Wetland Applications of Synthetic Aperture Radar (SAR)

Imaging radars provide information that is fundamentally different from sensors that operate in the visible and infrared portions of the electromagnetic spectrum. This is primarily due to the much longer wavelengths used by SAR sensors and the fact that they send out and receive their own energy (*i.e.*, active sensors). One of the most common types of imaging radar is Synthetic Aperture Radar (SAR). SAR technology provides the increased spatial resolution that is necessary in regional wetland mapping and SAR data have been used extensively for this purpose (Lang and McCarty 2008; Novo et al. 2002).

When mapping and monitoring wetland ecosystems, imaging radars have some advantages over sensors that operate in the visible and infrared portions of the electromagnetic spectrum. Microwave energy is sensitive to variations in soil moisture and inundation, and is only partially attenuated by vegetation canopies, especially in areas of lower biomass (Baghdadi et al. 2001; Kasischke et al. 1997a, b; Lang and Kasischke 2008; Rosenqvist et al. 2007; Townsend 2000, 2002; Townsend and Walsh 1998) or when using data collected at longer wavelengths (Hess et al. 1990; Martinez and Le Toan 2007).

The sensitivity of microwave energy to water and its ability to penetrate vegetative canopies, make SAR ideal for the detection of hydrologic features below the vegetation (Kasischke et al. 1997a; Kasischke and Bourgeau-Chavez 1997; Phinn et al. 1999; Rao et al. 1999; Wilson and Rashid 2005). The presence of standing water interacts with the radar signal differently depending on the dominant vegetation type/structure (Hess et al. 1995) as well as the biomass and condition of vegetation (Costa and Telmer 2007; Töyrä et al. 2002). When exposed to open water without vegetation, specular reflection occurs and a dark signal (weak or no return) is observed (Dwivedi et al. 1999). The radar signal is often reduced in wetlands dominated by lower biomass herbaceous vegetation when a layer of water is present due largely to specular reflectance (Kasischke et al. 1997a). Conversely, the radar signal is often increased in forested wetlands when standing water is present due to the double-bounce effect (Harris and Digby-Arbus 1986; Dwivedi et al. 1999). This occurs in flooded forests when the radar pulse is reflected strongly by the water surface away from the sensor (specular reflectance) but is then redirected back towards the sensor by a second reflection from a nearby tree trunk. The use of small incidence angles (closer to nadir) enhances the ability to map hydrology beneath the forest canopy due to increased penetration of the canopy (Bourgeau-Chavez et al. 2001; Hess et al. 1990; Lang and McCarty 2008; Töyrä et al. 2001).

1.5 Wetland Change Detection

Many coastal wetlands, such as the tidal salt marshes along the Louisiana coast, are generally within fractions of a meter of sea level and will be lost, especially if the impact of sea level rise is amplified by coastal storms. Man-made modifications of wetland hydrology and extensive urban development will further limit the ability of wetlands to survive sea level rise. To identify long-term trends and short term variations, such as the impact of rising sea levels and storm surges on wetlands, one needs to analyze time-series of remotely sensed imagery. High temporal resolution, precise spectral bandwidths, and accurate georeferencing procedures are factors that contribute to the frequent use of satellite image data for change detection analysis (Baker et al. 2007; Coppin et al. 2004; Shalabi and Tateishi 2007). A good example is the study of the onset and progression of marsh dieback performed by Ramsey and Rangoonwala (2010).

The acquisition and analysis of time-series of multi-spectral imagery is a challenging task. The imagery must be acquired under similar environmental conditions (*e.g.* same time of year, sun angle, *etc*.) and in the same or similar spectral bands. There will be changes in both, time and spectral content. One way to approach this problem is to reduce the spectral information to a single index, reducing the multispectral imagery into one single field of the index for each time step. In this way the problem is simplified to the analysis of a time-series of a single variable, one for each pixel of the images.

The most common index used is the Normalized Difference Vegetation Index (NDVI), which is expressed as the difference between the red and near infrared (NIR) reflectances divided by their sum (Jensen 2007). These two spectral bands represent the most detectable spectral characteristic of green plants. This is because the red (and blue) radiation is absorbed by the chlorophyll in the surface layers of the plant (*Palisade parenchyma*) and the NIR is reflected from the inner leaf cell structure (*Spongy mesophyll*) as it penetrates several leaf layers in a canopy. Thus the NDVI can be related to plant biomass or stress, since the NIR reflectance depends on the abundance of plant tissue, whereas the red reflectance indicates the surface condition of the plant. It has been shown by researchers that time-series remote sensing data can be used effectively to identify long term trends and subtle changes of NDVI by means of Principal Component Analysis (Jensen 2007; Young and Wang 2001; Yuan et al. 1998).

The pre-processing of multi-date sensor imagery when absolute comparisons between different dates are to be carried out, is much more demanding than the single-date case. It requires a sequence of operations, including calibration to radiance or at-satellite reflectance, atmospheric correction, image registration, geometric correction, mosaicking, sub-setting, and masking out clouds and irrelevant features (Coppin et al. 2004; Lunetta and Elvidge 1998).

Detecting the actual changes between two registered and radiometrically corrected images from different dates can be accomplished by employing one of several techniques, including post-classification comparison (PCC), spectral image differencing (SID), and change vector analysis (CVA). In PCC change detection, two images from different dates are independently classified. The two classified maps are then compared on a pixel-by-pixel basis. One disadvantage is that every error in the individual date classification maps will also be present in the final change detection map (Jensen 1996; Lunetta and Elvidge 1998).

Spectral image differencing (SID) is the most widely applied change detection algorithm. SID techniques rely on the principle that land cover changes result in changes in the spectral signature of the affected land surface. SID techniques involve the transformation of two original images to a new single-band or multi-band image in which the areas of spectral change are highlighted. This is accomplished by subtracting one date of raw or transformed (*e.g.* vegetation indices, albedo, *etc*.) imagery from a second date, which has been precisely registered to the image of the first date. Pixel difference values exceeding a selected threshold are considered as changed. This approach eliminates the need to identify land cover changes in areas where no significant spectral change has occurred between the two