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A Case of Timely Satellite Image Acquisitions in Support of Coastal Emergency Environmental Response Management

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ABSTRACT

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The synergistic application of optical and radar satellite imagery improves emergency response and advance coastal monitoring from the realm of "opportunistic" to that of "strategic." As illustrated by the Hurricane Ike example, synthetic aperture radar imaging capabilities are clearly applicable for emergency response operations, but they are also relevant to emergency environmental management. Integrated with optical monitoring, the nearly real-time availability of synthetic aperture radar provides superior consistency in status and trends monitoring and enhanced information concerning causal forces of change that are critical to coastal resource sustainability, including flooding extent, depth, and frequency.

ADDITIONAL INDEX WORDS: *Satellite optical and radar image data, coastal flooding and damage, strategic collections.*

INTRODUCTION

Among the various space-based imaging systems available for environmental response management, optical satellites operating in the visible to shortwave wavelengths of micrometers have been relied upon over several decades to provide synoptic and frequent information to track highly dynamic atmospheric phenomena, such as major storm systems. Adequate monitoring of the areas immediately affected (*e.g.,* landfall areas of tropical and extratropical storms and hurricanes) has been a difficult task. In the past, one of the greatest obstacles in using satellite optical sensors to monitor disasters in support of emergency response has been the acquisition of cloud-free images. Emergency response managers often lack up-to-date geospatial information of events in progress, such as the extent of coastal flooding in conjunction with storm surges. Although numerous examples exist of decisive collections of satellite optical data in the aftermath days or even weeks after an event, cloud coverage often obscures the impact areas, particularly during cyclonic storms (*e.g.,* see Ramsey, 1995).

One solution to collecting cloud-free images is the use of synthetic aperture radar (SAR) sensors operating in the wavelengths of centimeters aboard a variety of Earth observation satellites, such as the advanced synthetic aperture radar (ASAR) aboard the European Envisat, the C-band SAR aboard the Canadian Radarsat systems, the X-band SAR aboard the German Terra SAR-X, or the L-band SAR aboard the Japanese Advanced Land Observing Satellite. These cloud-penetrating sensors have recently proven to be valuable tools for surveying land and water surfaces during weather-related emergencies. The following examples of optical and radar-derived images collected via satellite before, during, and after Hurricane Ike along the Gulf of Mexico coast near Galveston, Texas, in September 2008 are a case in point.

HURRICANE IKE

The satellite imagery collected with the storm-surge flood event during the passage of Hurricane Ike over the central U.S. Gulf of Mexico coastal region provides an evocative illustration (see the cover of this *Journal of Coastal Research* issue) of the synergistic use of information derived from optical and SAR satellite imagery for emergency response. As shown in the hydrograph of Sabine Pass North tide, water level, and meteorology station (Figure 1), surge flooding of the southwestern Louisiana coast began mid- to late day on 11 September 2008 and peaked at more than 4 m above mean sea level around 0700 UTC on 13 September 2008 as Hurricane Ike made landfall at Galveston, Texas. Flood levels

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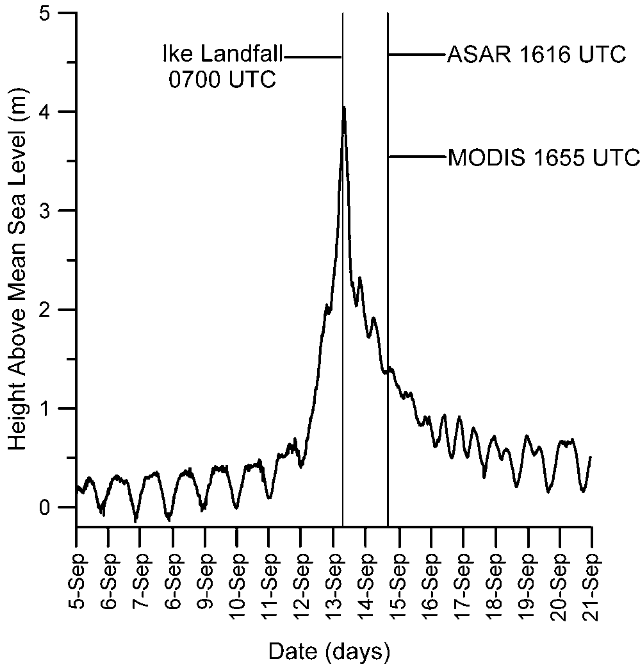

Figure 1. Hydrograph data related to mean sea level collected from midnight of 05 September 2008 to midnight of 21 September 2008 at the Sabine Pass North tide, water level, and meteorology station located at 93°52′12″ longitude and 29°43′48″ latitude. Hydrograph data were obtained from the National Ocean Service (2009).

above mean sea level persisted for some time after the immediate passage of the hurricane. During this time of flooding, dense cloud cover prevented useful collections of satellite optical data of the ground situation. In anticipation of the landfall of Hurricane Ike, a request was made by the state of Texas to enact the International Charter for space and major disasters under the Committee for Earth Observation Systems. This charter allows for the international coordination of space agencies and their Earth observation satellite assets to program, acquire, and deliver satellite imagery of impacted disaster areas on a high-priority basis (International Charter). The objective is to supply national or regional authorities in emergency response management with useful satellite imagery for disaster assessment and relief operations. Following the enactment of the charter, the European Space Agency's Envisat satellite acquired imagery of the Galveston area with its ASAR sensor during the first available overpass on 14 September 2008 at 1611 UTC, about 33 hrs after Hurricane Ike made landfall. The Envisat ASAR imagery provided the first synoptic view of the extensive flooding of coastal marshes and population centers in southwest Louisiana (Figure 2 and the cover illustration). Figure 2 and the cover graphic depict a prehurricane ASAR image from 03 August 2008. Graphic renditions of the ASAR images collected before and after the hurricane were used by U.S. Federal Emergency Management Agency personnel stationed in Lake Charles, Louisiana, to help plan search and rescue missions (S. Wilson, U.S. Geological Survey National Wetlands Research Center, personnel communication).

The key to the successful acquisition and fast delivery of the Envisat ASAR imagery obtained after passage of Hurricane Ike was the planning process, because radar image capture from orbiting satellites must be preprogrammed; it may not be available continuously, as is the case for weather satellite data, for example. As expected, coastal flooding was well detected on the radar imagery, thus offering U.S. Federal Emergency Management Agency valuable tactical support information for its work in and around these areas. The radar-dark signature of permanent water bodies and newly flooded areas tends to contrast well against nonflooded areas. The Envisat ASAR imagery following the hurricane also provided some unique and, for the untrained observer, often intriguing signatures of nearshore and offshore water surfaces that are associated with the physical properties of the ocean, local and regional wind regimes, or vessel traffic. These signatures could be difficult to interpret based on the ASAR imagery alone.

In the absence of *in situ* measurements, a comparison with other, concurrent remote sensing data can be helpful in interpreting the radar images. In this case, uncertainties in the interpretation of the ASAR image were resolved through a complementary analysis of image data obtained by the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the National Aeronautics and Space Administration's Terra satellite (Figure 3 and the cover illustration). Collection of the MODIS (250-m resolution) image occurred 44 minutes after the ASAR image was obtained on 14 September 2008.

The MODIS image shows extensive cloud cover dominating the impacted coastal region, as well as the passage of an atmospheric frontal system oriented from the southwest to the northeast. As happens with other satellite optical sensors, the dense cloud cover documented in the MODIS image obscured useful ground information, emphasizing the limitations of disaster monitoring based on satellite optical sensors. However, the weather front clearly evidenced on the MODIS image is helpful in interpreting the bright area trending northeast to southwest on the ASAR image, because it confirms that this feature was caused by wind-roughened water surfaces. Although the causal event for this feature could have been surmised by experienced radar users, comparison of the radiometric MODIS image and ASAR data, which were collected nearly simultaneously, provides valuable, if not conclusive, evidence of this explanation.

Further support for the complementary use of satellite-based radar and radiometric technology is illustrated by of the occurrence of marsh dieback after Hurricane Ike. Although coverage of the impact area by the Landsat 5 Thematic Mapper (TM) satellite was not as timely as that of Envisat ASAR or Terra MODIS, Landsat TM images acquired on 29 September 2008 (the first possible cloud-free collection) reveal abnormal browning of the saline-to-fresh coastal marshes (shown in hues of purple, blues, and reds in Figure 4 and the cover illustration). Still within the summer growth season—and, therefore, before the usual onset of senescence (Ramsey and Rangoonwala, 2006)—the sudden marsh die-

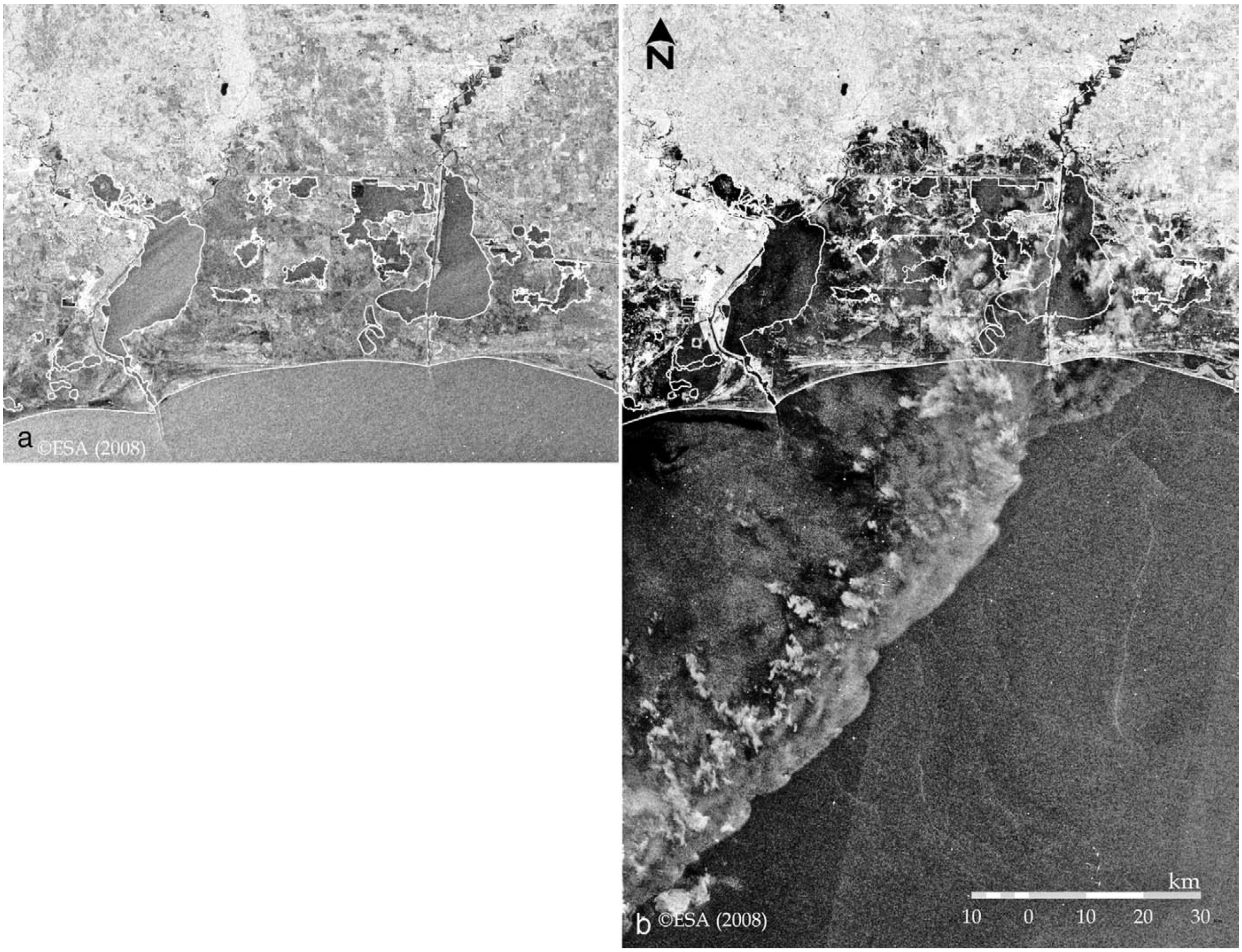

Figure 2. Envisat advanced synthetic aperture radar (ASAR) images acquired (a) before (03 August 2008) and (b) after (14 September 2008) Hurricane Ike landfall. Permanent water bodies and coastlines were adapted from a Louisiana geographic information system digital map (Louisiana State University, 2007). Dark inland areas indicate flooding. The northeast to southwest bright feature on the posthurricane ASAR image is explained in Figure 3.

back could be correctly surmised as being related to the storm surge from Hurricane Ike. This is particularly evident when compared to a Landsat TM image acquired before the hurricane (Figure 4). The spatial juxtaposition of the marsh dieback documented on the posthurricane Landsat TM image and the flood extent determined from the before- and after-hurricane Envisat ASAR images confirm that saline water intrusion associated with the September 13 storm surge caused the dieback. Although the exact nature of surge-related marsh dieback cannot be determined from these satellite images, the spatial coincidence documents that surge waters were the causal agent.

ENVIRONMENTAL RESPONSE MANAGEMENT

Emergency response performance and planning and environmental response management depend on accurate and up-to-date geospatial information and monitoring techniques to capture the dynamics of features and events that are crucial for response activities. Emergency and environmental response both benefit from strategic monitoring of coastal resources and planning for timely data acquisition. The day-and-night and nearly all-weather mapping capabilities provided by SAR technology shift data acquisition planning from the realm of target of opportunity to that of strategic deployment. When properly calibrated, nearly real-time SAR data can be directly compared with preevent SAR data or with optical images to highlight event-related changes, such as flood extent or levee failure. In emergency situations, time-critical information of this nature can help response managers and on-site personnel to minimize loss of lives and reduce damage to properties. For environmental resource managers, strategic and synoptic monitoring of impact areas at timely intervals also offers direct observation of causal forces detrimental to coastal resource sustainability, such as prolonged

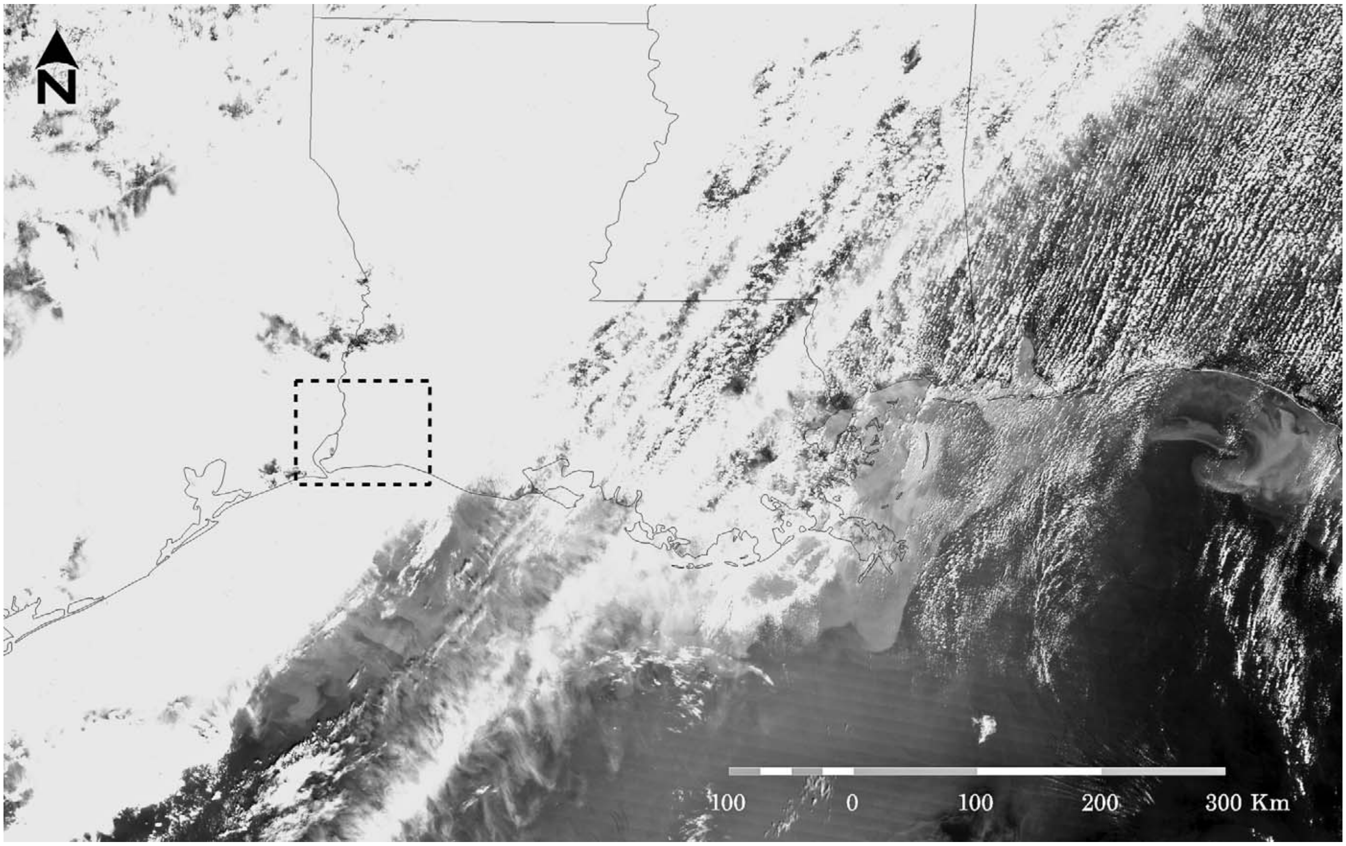

Figure 3. Moderate Resolution Imaging Spectroradiometer (MODIS) image collected on 14 September 2008, 44 minutes after acquisition of the posthurricane Envisat advanced synthetic aperture radar (ASAR) image that is depicted in Figure 2. The weather front displayed on the MODIS image substantiates that the bright area trending northeast to southwest on the posthurricane ASAR image was caused by wind-roughened water surfaces. The box indicates the location of the ASAR image (shown in Figure 2a) and the Landsat 5 Thematic Mapper images (shown in Figure 4).

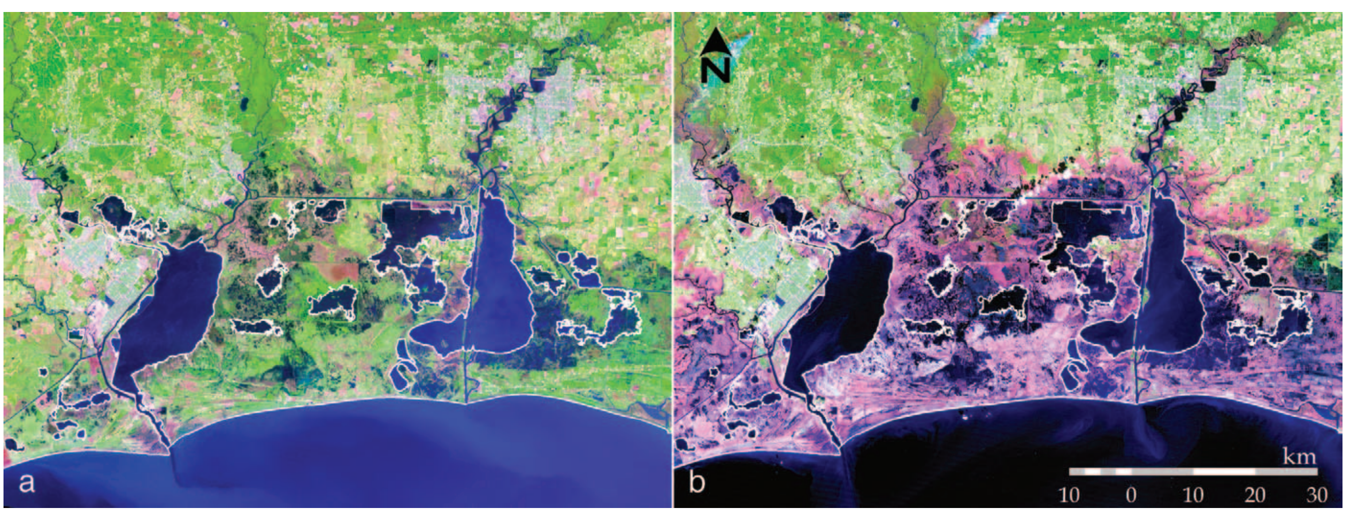

Figure 4. Landsat 5 Thematic Mapper (TM) images acquired (a) before (27 July 2008) and (b) after (29 September 2008) Hurricane Ike. The images are depicted as color composites of shortwave-infrared TM band 5 (red color, emphasizing water content), near-infrared TM band 4 (green color, emphasizing live biomass), and red TM band 3 (blue color, emphasizing pigment concentrations). In the composites, green hues depict healthy vegetation and purples, blues, and reds in the posthurricane image depict coastal marsh dieback.

flooding or elevated levels of salinity. As illustrated by flood extent mapping via SAR data (Figure 2), which took place under heavy cloud cover (Figure 3), and the subsequent mapping of marsh dieback via optical satellite data (Figure 4), the ability to directly observe changing conditions during adverse conditions can provide crucial support for accurately assessing coastal resource status and predicting trends.

While SAR is the sensor of choice for coastal flood monitoring, especially in emergency situations, optical imagery is often the preferred source of information for coastal resource monitoring and mapping. The case of Hurricane Ike, and data acquisitions around Galveston related to that event, shows that synergistic use of optical and radar satellite data is enhancing coastal resource information and the monitoring of status and trends. Moreover, the use of both types of data sources links coastal resource status and trends to causal forces, particularly flooding. Previous studies have demonstrated that SAR and optical data integrations have improved the detail and accuracy of coastal resource classification (Ramsey *et al.,* 2006). The use of SAR data has provided initial damage assessments and indications of short-term recovery trends of coastal wetland forests impacted by hurricane and high-force winds that are comparable to information derived from optical monitoring (Ramsey *et al.,* 2009). Coherence analysis of interferometric SAR (InSAR) data can provide better differentiation of some coastal forest types than can mapping with optical and SAR data, and high coherence in marshes indicates the ability to determine water level change with InSAR (Ramsey *et al.,* 2006). In addition, polarimetric SAR data have enhanced monitoring of coastal wetland recovery following stressful events. Polarimetric SAR and InSAR data increase the range of biophysical variables that are obtainable solely with passive optical data sources, particularly canopy biomass and height estimates (Ramsey *et al.,* 2006). The integration of analytical results derived from remote sensing technologies benefits emergency environmental response management through improved pre-event knowledge of the coastal resource landscape. This knowledge base includes information related to the distribution of vegetation types, their canopy structural parameters (useful in predicting surge retardation), and flooding characteristics. The ability to determine subcanopy flood extent, flood duration, and depth is of greatest relevance to emergency environmental response management (Lu and Kwoun, 2008; Ramsey, 1995).

CONCLUSION

The development and availability of nearly real-time SAR imaging capabilities for emergency response operations and, subsequently, the capability for innovative InSAR mapping of coastal resources are increasing the accuracy and detail of optical classifications and advancing coastal monitoring from the realm of "opportunistic" to that of "strategic." As illustrated by the Hurricane Ike example, the synergistic application of optical and radar satellite imagery offers improved emergency response and mapping options. These are clearly applicable and available to emergency environmental management, but they are also relevant to coastal resource managers for status assessments and trends prediction. The collection of coastal resource information at strategic intervals will allow emergency response agencies, resource managers, and policy makers to fully incorporate remote mapping products into their rapid-reaction preparations, management plans, and regulatory structure.

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