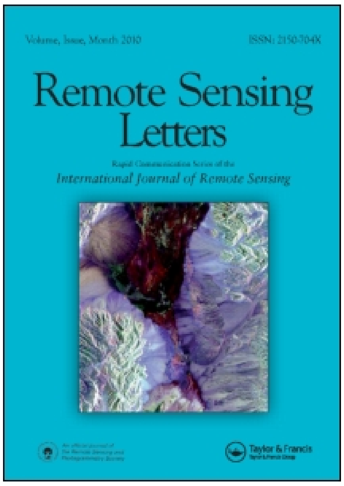

Remote Sensing Letters
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t915281289

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First published on: 17 June 2010

To cite this Article D'sa, Eurico J. , Korobkin, Mitsuko and Ko, Dong S.(2011) 'Effects of Hurricane Ike on the Louisiana-Texas coast from satellite and model data', Remote Sensing Letters, 2: 1, 11 — 19, First published on: 17 June 2010 (iFirst)
To link to this Article: DOI: 10.1080/01431161.2010.489057
URL: http://dx.doi.org/10.1080/01431161.2010.489057

Remote Sensing Letters
Vol. 2, No. 1, March 2011, 11–19

Taylor & Francis
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Effects of Hurricane Ike on the Louisiana–Texas coast from satellite and model data

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(*Received 8 March 2010; in final form 22 April 2010*)

The river-influenced Mississippi–Louisiana–Texas (MsLaTex) coast in the northern Gulf of Mexico was in 2008 impacted by Hurricane Ike that made landfall along the Texas coast on 13 September 2008, causing widespread damage due to storm surge and coastal inundation. We examine the effects of the hurricane on the MsLaTex coast using remote sensing, model simulation and field observations. Moderate resolution imaging spectroradiometer sea surface temperature imagery indicated an approximately 2–4°C decrease in temperature to the right of the hurricane track. The high-resolution (~2 km) three-dimensional Navy Coastal Ocean Model simulation and tide data suggested the generation of a coastally trapped 'barotropic Kelvin' wave during the passage of Ike, which may have contributed to an earlier than expected surge in sea level. A distinct elevated band of suspended particulate matter (SPM) concentration extending from Louisiana to Texas (~90.5–94.5°W) coast was observed offshore in sea-viewing wide field-of-view sensor-derived imagery of 17 and 25 September that appeared to be associated with the coastally trapped Kelvin wave that was enhanced west of the Mississippi Canyon. Two intermittent wind events on 15 and 21 September likely kept the SPM in suspension for an extended period. Subsequently, on 27 and 30 September, SPM decreased along the elevated band and near the landfall site but increased near the bays and passes due to receding flood waters. Off the Atchafalaya and Mississippi deltas a large pulse of river discharge containing elevated SPM levels caused a plume around the two river deltas and its offshore dispersion into the open Gulf of Mexico.

1. Introduction

The coastal region comprising the states of Mississippi, Louisiana and Texas (MsLaTex) is influenced by the Mississippi River which is the seventh largest in terms of water and sediment discharge among the major rivers of the world. This coastal region is also economically important, supplying approximately 20% of the United States' energy needs and one-third of the fisheries yield. This region has been particularly vulnerable to energetic events, and in 2008, Hurricanes Gustav and Ike impacted the MsLaTex coast causing widespread damage to the region. Hurricane Gustav made landfall along the Louisiana coast as a Category 2 hurricane on 1 September. On 10 September, Hurricane Ike entered the Gulf of Mexico as a Category 1 hurricane and intensified as it moved slowly north-westward over the

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Remote Sensing Letters
ISSN 2150-704X print/ISSN 2150-7058 online © 2011 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431161.2010.489057

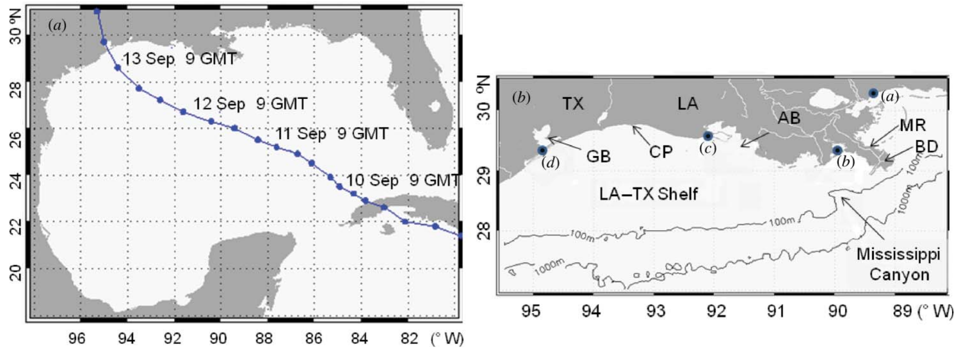

Figure 1. (*a*) Track of Hurricane Ike in the Gulf of Mexico. (*b*) Mississippi–Louisiana–Texas (MsLaTex) shelf showing the bathymetry, the location of tide gauges and the domain of the MsLaTex nested NCOM model. Tide gauge locations are labelled as (a) Bay Waveland Yacht Club, MS; (b) Grande Isle, LA; (c) Freshwater Canal Locks, LA; (d) Galveston Pleasure Pier, TX. The abbreviations are as follows: TX, Texas; LA, Louisiana; AB, Atchafalaya Bay; CP, Calcasieu Pass; GB, Galveston Bay; MR, Mississippi River; BD, birdsfoot delta.

south-eastern Gulf; it made landfall along the north end of Galveston Island, TX, at 0700 UTC 13 September (figure 1(*a*)) as a strong Category 2 hurricane with maximum winds of 48.87 m s^{-1}. Ike's large size generated a storm surge of over 3.7 m and inundated a large coastal region from Galveston eastward to the Louisiana coast (East *et al.* 2008). However, tide gauge measurements also indicated rapid rise in water levels along the Texas and southwest Louisiana coasts approximately 24 hours before Ike made landfall that surprised coastal residents and emergency personnel.

Both satellite remote sensing and model simulations have been used to study the effects of hurricanes in coastal and oceanic waters. The passage of Hurricane Dennis in 2005 led to a decrease in sea surface temperature (SST) along the right side of the hurricane track and to sediment resuspension in waters shallower than 50 m in the eastern Gulf of Mexico (Hu and Muller-Karger 2006). Increases in satellite-derived suspended particulate matter (SPM) were reported in coastal (Walker 2001) and offshore waters (Dickey *et al.* 1998) following the hurricane passage. Satellite ocean colour assessment of Hurricanes Katrina and Rita which struck the Louisiana coast in 2005 revealed high turbidity levels indicative of intense resuspension that quickly returned to pre-storm conditions following Hurricane Katrina, whereas elevated levels were observed for a longer duration following Hurricane Rita (Lohrenz *et al.* 2008). Strong wind bursts have been shown often to excite coastally trapped waves (Ko *et al.* 2003a). A numerical simulation model of sea levels and currents on the shelf along with tide gauge observations suggested the presence of a coastally trapped wave that progressed westward as a surge associated with the strong atmospheric forcing of Hurricane Frederic in 1992 as it crossed the eastern Gulf of Mexico (Ly 1994). Coastally trapped waves were also modelled for Hurricane Ivan in 2004 as it progressed along the coast of the Gulf of Mexico (Zamudio and Hogan 2008).

Ike caused storm surge for the entire Gulf of Mexico, from south-western Florida to the western Texas and was the fourth costliest hurricane to affect the United States. In this study we examine the effects of Ike on the MsLaTex coast using remote sensing, field data and the outputs of a high-resolution (~2 km) Navy Coastal Ocean Model (NCOM).

2. Materials and methods

2.1 *NCOM models*

The high-resolution (~2 km) MsLaTex NCOM model (figure 1(*b*) – model domain) is nested within the larger Intra-Americas Sea Ocean Nowcast/Forecast System (IASNFS) regional model with lower horizontal resolution (~6 km) that is operational at the Naval Research Laboratory (Ko *et al.* 2003b). The NCOM is a hybrid sigma-*z* vertical coordinate system based on the Princeton Ocean Model with the IASNFS regional model assimilating real-time satellite sea surface height (SSH) and SST. IASNFS provides sea level variation, three-dimensional ocean currents, temperature and salinity as open boundary conditions to the nested MsLaTex coastal model. Model topography is based on the NRL Digital Bathymetric Data Base (DBDB2) and the National Geophysical Data Center (NGDC) hydrographic data with a domain that includes both shallow and deep waters. The model is driven by wind, heat fluxes, solar radiation and air pressure, and assimilates satellite altimeter data and satellite SST (Ko *et al.* 2008).

2.2 *Satellite data*

Level-2 SST product from the moderate resolution imaging spectroradiometer (MODIS) and Level-1 ocean colour data from the sea-viewing wide field-of-view sensor (SeaWiFS) were obtained from NASA's Ocean Colour website (http://www.oceancolor.gsfc.nasa.gov). Level-1 SeaWiFS data were processed into Level-2 SPM using NASA's SeaWiFS Data Analysis System (SeaDAS) software. For aerosol calculation, multi-scattering with two-band model selection mode without near-infrared correction was applied. Pixels with excessive cloud cover or stray light, large solar zenith angles (>75°), large sensor zenith angles (>60°) and with total radiance greater than the knee value were masked out. Level-1 data were processed using SeaDAS software and a SPM band ratio algorithm (D'Sa *et al.* 2007). The Level-2 SST data from MODIS were binned into 1-km resolution using SeaDAS software to calculate 5-day averages.

2.3 *Field data*

Tidal data in this article were obtained from NOAA's Tides and Currents website (http://tidesandcurrents.noaa.gov) and referenced to mean low water (MLW) levels. The storm surge heights were measured at coastal tide stations as the difference between the forecast tide and the observed rise of water. Wind data were obtained from the National Data Buoy Center website (http://www.ndbc.noaa.gov) for a station located near Grande Isle, LA. River discharge data were obtained from the United States Army Corps of Engineers website (http://www.mvn.usace.army.mil) from the Tarbert Landing station, MS.

3. Results and discussion

3.1 *Hurricane effect on SST*

A common manifestation of hurricane passage is a drop in SST due mainly to wind-driven mixing in the upper ocean. A comparison of SST imagery before and after the hurricane passage (figures 2(*a*) and (*b*)) reveals an approximately 2–4°C storm-induced cold wake to the right of Hurricane Ike's track, which is similar to the range detected by the GOES-12 geostationary satellite (Walker *et al.* 2009).

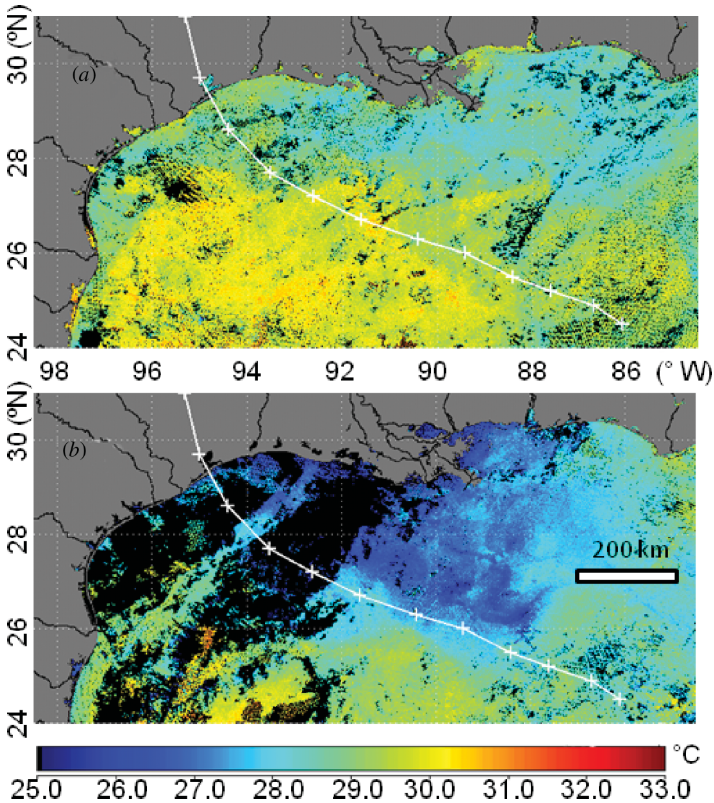

Figure 2. MODIS Terra imagery depicting SST distribution averaged over a 5-day period (*a*) before (6–10 September) and (*b*) after (14–18 September) the passage of Hurricane Ike.

3.2 *Storm surge and coastally trapped waves due to Ike*

Figures 3(*a*)–(*d*) shows the mean sea levels (MSL) measured at the various stations along the MsLaTex coast (figure 1(*b*)) along with SSH simulated by NCOM during the passage of Hurricanes Gustav and Ike. The comparisons indicate that model simulation of SSH generally compared well to field data except during the Hurricane Ike storm surge where it underestimated measured sea levels along the MsLaTex coast. Differences were greater along the western Louisiana and Texas coast (figure 3). Hurricane Gustav which made landfall west of the birdsfoot delta on 1 September caused a storm surge in the eastern Louisiana coast, as indicated in the MSL/SSH data at stations (*a*) and (*b*) and are shown for comparison to the storm surge caused by Hurricane Ike. Ike's storm surge was larger in size and extended over a larger region than Gustav (figures 3(*a*)–(*d*)). The MSL/SSH suggest that water levels to the east of Grande Isle (figure 3(*b*)) began to rise on 11 September, 2 days before Ike's landfall at Galveston Island, TX. NCOM SSH of 11 and 12 September (figures 4(*a*) and (*b*)) also predicted a significant storm surge along the Mississippi and the southeast Louisiana coast. Water levels at stations (*c*) and (*d*) that are west of Grande Isle began to rise on 12 September, as Ike moved further to the west. Although NCOM SSH simulation were lower than that measured, both tide station data and NCOM SSH indicated the early surge caused by Ike which propagated westward and peaked along eastern Texas coast

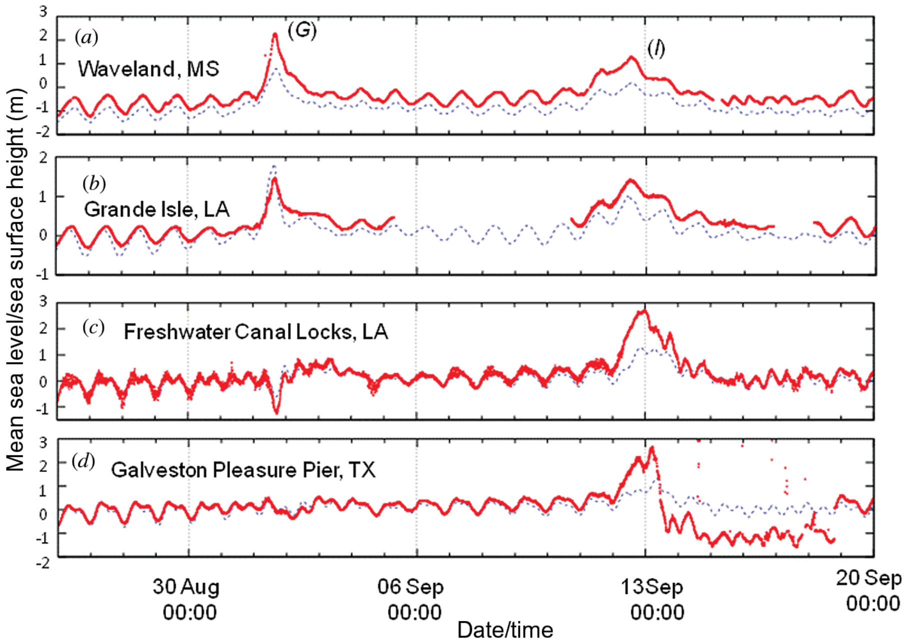

Figure 3. (*a*)–(*d*) Mean sea level (MSL) from NOAA stations (solid lines) and sea surface height (SSH) from NCOM (dotted lines) along the Louisiana–Texas coast corresponding to locations shown in figure 1(*a*). (*G*) and (*I*) denote storm surge events due to Hurricanes Gustav and Ike.

(stations (*a*)–(*d*)). The MSL peaks in figure 3 were recorded at (*c*) 2348 UTC on 12 September, and at Calcasieu Pass, LA station (not shown) at 0742 UTC on 13 September. The instrument likely failed at station (*d*) during the surge, but the highest storm surge during Ike actually occurred east of Galveston Bay near station (*d*), according to the National Hurricane Center's tropical cyclone report. This storm surge caused widespread inundation along the Texas coast that was especially enhanced east of Galveston on the Bolivar Peninsula (East *et al.* 2008).

The MSL/SSH data in figures 3(*a*) and (*b*) during Ike (11–13 September) have an unusual shape. That is, unlike during Gustav, the peaks during Ike were wider and have more than one local maximum. This pattern could be due to coastally trapped waves formed during the passage of Ike as it slowly moved along the MsLaTex coast. Coastally trapped waves form as hurricane winds force the ocean water against the coast and create a bulge of high sea level. They can amplify the storm surge while travelling alongside the coast with the moving hurricane, which was the case for Hurricane Dennis in 2005 (Morey *et al.* 2006). NCOM simulation of SSH shown in figures 4(*a*) and (*b*) for 11 (1200 UTC) and 12 (0600 UTC) September seems to confirm the existence of such waves. Unlike a storm surge which moves towards the coast, a trapped wave moves alongshore and was therefore easily identified in the NCOM SSH. Furthermore, a time–distance plot of SSH simulated by NCOM along 28.5°N latitude (figure 4(*c*)) suggests the appearance of a large wave at the Mississippi Canyon (~90°W longitude) as Ike approached the MsLaTex coast on 12 September. Because this wave travelled from 90°W to 95°W in about 8 hours, its speed was estimated at 17 m s^{-1}. Assuming the average water depth $H = 30$ m along 28.5°N

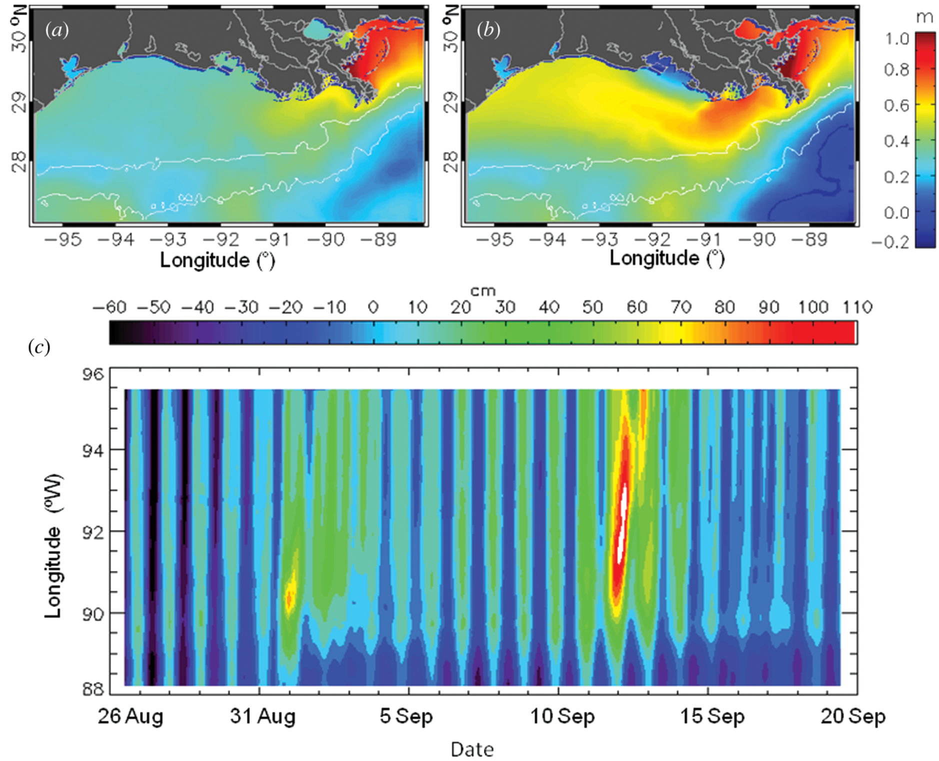

Figure 4. NCOM SSH on (*a*) 11 September at 1200 UTC and (*b*) 12 September at 0600 UTC. (*c*) Time–distance plot of NCOM SSH along the 28.5°N latitude.

latitude, the speed of a coastally trapped Kelvin wave would also be $\sqrt{gH} = 17$ m s^{-1}, where g is the gravitational acceleration. This wave appeared to have arrived along the eastern Texas coast on 12 September (figure 4(*c*)) and could have resulted in the elevated sea level observed at Calcasieu Pass (not shown) and Galveston stations (figures 1(*b*) and 3(*d*)) before Ike made landfall on 13 September. This wave may also explain the puzzle of Ike's unusual traits that included a forerunner wave that flooded parts of Louisiana and Texas coast in advance of the storm's anticipated surge (http://coastalcontractor.net/article/321.html).

3.3 ***Hurricane effects on coastal SPM***

Surface SPM distribution derived from SeaWiFS ocean colour data for 17, 25, 27 and 30 September (figure 5) reveals elevated SPM along the Louisiana–Texas coast that persisted even 12 days following landfall of Hurricane Ike (figures 5(*a*) and (*b*)). Two wind events (not shown) of elevated easterly and north-easterly winds of about 12 m s^{-1} on 15 and 21 September may have kept the SPM in suspension or caused additional resuspension, especially in the nearshore waters. Similar persistence in elevated suspended sediments following Hurricane Rita were attributed to the intense wind event that could have kept the relatively fine grain sediments in suspension for a longer period of time (Lohrenz *et al*. 2008). A partially cloud-free SeaWiFS image of 17 September indicated the presence of an elevated band of SPM

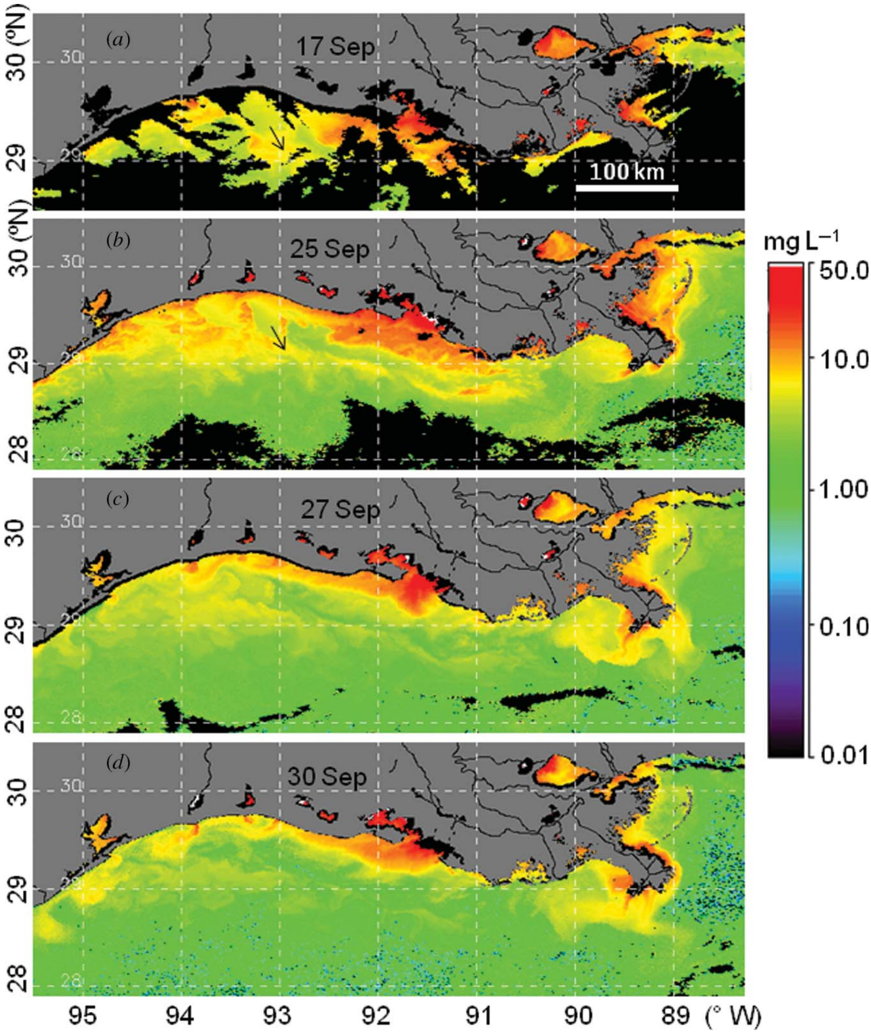

Figure 5. SeaWiFS-derived SPM for (*a*) 17, (*b*) 25, (*c*) 27 and (*d*) 30 September 2008. Arrows indicate the location of the elevated SPM bands.

that could be observed extending from the Texas coast eastward for about 100 km. Due to persistence of cloud cover, another clear satellite image that was available following the hurricane passage was for 25 September. Near and east of Galveston, SPM showed elevated values likely due to the discharge of inundated waters containing high SPM into the inner shelf coastal waters and resuspension due to two wind events on 15 and 21 September. However, the most unusual feature was a distinct and narrow band of elevated SPM observed starting near 28.5°N and 90.5°W (west of the Mississippi Canyon) and extending westward and merging with elevated levels of SPM in the coastal region east of Galveston (figure 5(*b*)). The elevated SPM band was distinct from the SPM observed in the nearshore coastal waters that appeared to be locally resuspended, most likely associated with the coastally trapped Kelvin wave as it propagated westward and amplified as it moved past the Mississippi Canyon (figure 4(*c*)). SPM along the band may have remained in suspension by the two wind events following the hurricane passage. By 27 and 30 September, SPM levels decreased along the coastal waters with the elevated offshore band dissipating into the water column. However, plumes of elevated SPM observed off Galveston Bay and also to its east and west (figures 5(*c*) and (*d*)) indicate receding flood waters exiting through the various bays and passes even two weeks following Hurricane Ike's landfall. River discharge increased from 15,460 to 17,414 $m^3 s^{-1}$ between 25 and 29 September which corresponded to a 12% increase in river discharge over a 4-day period. This pulse in river discharge could be related to increased precipitation associated with Hurricanes Gustav or Ike in the catchment of the Mississippi River. The increasing size of plume waters with elevated SPM levels observed off the Atchafalaya and birdsfoot deltas (figures 5(*c*) and (*d*)) could be mainly attributed to the large increase in river discharge, which peaked on 29 September. Plume waters with high SPM appeared to spread around the Mississippi delta extending southward into the oligotrophic waters of the northern Gulf of Mexico for about 100 km southward and appear similar to previous reported injection of storm-induced river plumes into the open Gulf of Mexico (Yuan *et al*. 2004).

4. Conclusions

The coastal ocean response to Hurricane Ike was studied using satellite remote sensing data, the outputs of a three-dimensional nested high-resolution coastal circulation model and field data. Model simulation and data at tide stations which generally agreed in magnitude and phase indicated the signature of a westward progressing coastally trapped wave that may have been responsible for an earlier than expected increase in sea level along the Louisiana and Texas coast. Model simulation indicated the Kelvin wave was enhanced west of the Mississippi Canyon and propagated towards the Texas coast at a phase speed of about 17 $m s^{-1}$. This enhanced wave may have contributed to intense sediment resuspension as it propagated westward and was observed as an elevated SPM band in SeaWiFS imagery 4 and 12 days following the hurricane passage. Two intermittent wind events likely kept the SPM in suspension for an extended period of time. Extensive coastal inundation and inland flooding due to the hurricane resulted in the waters receding through the various passes causing elevated suspended sediment levels even 2 weeks following hurricane landfall. A large pulse of river discharge likely associated with the storm precipitation caused a plume of elevated SPM observed in SeaWiFS imagery of 27 and 30 September around the deltas that moved offshore into the oligotrophic waters of the northern Gulf of Mexico.

Acknowledgements

This work was funded by a Minerals Management Service (MMS) project No. M08AX12685 and by NASA grant NNA07CN12A (Applied Sciences Program) to E. D'Sa, and by an ONR contract N00014-08WX-2-1170 (code 322 PO) to D.S. Ko.

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