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Using MODIS Terra 250 m imagery to map concentrations of total suspended matter in coastal waters

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Abstract

High concentrations of suspended particulate matter in coastal waters directly affect or govern numerous water column and benthic processes. The concentration of suspended sediments derived from bottom sediment resuspension or discharge of sediment-laden rivers is highly variable over a wide range of time and space scales. Although there has been considerable effort to use remotely sensed images to provide synoptic maps of suspended particulate matter, there are limited routine applications of this technology due in part to the low spatial resolution, long revisit period, or cost of most remotely sensed data. In contrast, near daily coverage of medium-resolution data is available from the Moderate-resolution Imaging Spectroradiometer (MODIS) Terra instrument without charge from several data distribution gateways. Equally important, several display and processing programs are available that operate on low cost computers.

The utility of MODIS 250 m data for analyzing complex coastal waters was examined in the Northern Gulf of Mexico. Using simple processing procedures, MODIS images were used to map the concentration of Total Suspended Matter (TSM). A robust linear relationship was established between band 1 (620–670 nm) MODIS Terra 250 m data and in situ measurements of TSM (r^2=0.89; n=52; MSE=4.74) acquired during six field campaigns. This study demonstrates that the moderately high resolution of MODIS 250 m data and the operating characteristics of the instrument provide data useful for examining the transport and fate of materials in coastal environments, particularly smaller bodies of water such as bays and estuaries.

Keywords: Total suspended matter; MODIS; Remote sensing

1. Introduction

Coastal waters are often characterized by high concentrations of suspended organic and inorganic material derived from seabed resuspension or discharge of particle-laden rivers. High concentrations of suspended materials directly affect many water column and benthic processes such as phytoplankton productivity (Cole & Cloern, 1987; Cloern, 1987; May et al., 2003), coral growth (Dodge et al., 1974; Miller & Cruise, 1995; Torres & Morelock, 2002; McLaughlin et al., 2003), productivity of submerged aquatic vegetation (Miller, 1980; Dennison et al., 1993), nutrient dynamics (Mayer et al., 1998), and the transport of pollutants (Martin & Windom, 1991) and other materials. The distribution and flux of suspended sediments are highly variable in coastal environments and vary over a broad spectrum of time and space scales. This variability renders most traditional field sampling methods as inadequate in studies to resolve sediment dynamics in complex coastal waters (Miller et al., 2003). Consequently, there is considerable interest in the use of remotely sensed data to provide synoptic maps of suspended materials such as suspended sediments in coastal waters.

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Numerous studies have demonstrated that remotely sensed data can map suspended sediments (see, e.g., Miller & Cruise, 1995; Stumpf, 1987; Stumpf & Pennock, 1989; Tassan, 1994; Warrick et al., 2004); however, the routine use of remote sensing for monitoring sediment dynamics in many environments has been limited. There are several factors that limit the application of remote sensing to coastal waters. These factors include the characteristics of remote sensing instruments, their associated costs, or the availability of processing software. The most common limitation is an instrument's spatial or ground resolution. For example, the nominal spatial resolution of data from the Advanced Very High Resolution Radiometer (AVHRR), and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instruments is 1 km. Although these data are adequate for studying mesoscale and larger-scale processes on the continental shelf, 1-km spatial resolution data are often too large to examine coastal horizontal gradients, particularly in estuaries and bays (Nittrouer & Wright, 1994). In contrast, the Landsat series of instruments [Thematic Mapper (TM), Enhanced Thematic Mapper (ETM+)] have a spatial resolution of 30 m, but the orbital characteristics of the Landsat satellites yield a revisit time of about 16 days. Hence, Landsat sensors cannot capture the temporal dynamics of coastal waters. Although airborne systems have the advantage that the user can define instrument deployment parameters (e.g., time flown, area covered, and spatial resolution), most airborne systems are expensive to operate and processing the data is often costly and difficult. Generally, the limited availability of remote sensing data and processing software has also restricted the widespread application of remote sensing to coastal studies (Miller, 1993). With most data, until recently, other limitations were associated with data often limited to commercial systems, scientific algorithms (e.g., atmospheric correction) and software processing systems.

There have been significant recent advances in remote sensing technology and in the development of instrument-specific data distribution and processing systems. These advances have greatly facilitated the use of remotely sensed data by a larger user community beyond traditional instrument science teams. Key examples are the SeaWiFS and AVHRR projects where effective web-based data distribution gateways have been established. Additionally, the SeaWiFS project has developed a robust data display and processing software package [SeaWiFS Data Analysis System (SeaDAS)] that is freely distributed to the user community. This approach is now a critical element of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) which consists of a suite of satellite instruments, processing software, and data distribution systems.

The Terra spacecraft was launched as the first EOS mission on December 18, 1999. The Moderate-resolution Imaging Spectroradiometer (MODIS) instrument on Terra provides data, and subsequent operational products, for the land, ocean, cryosphere, and atmosphere. Another EOS spacecraft, Aqua, was launched in May 2002 and carries a second MODIS instrument. The MODIS instruments collect reflected and emitted energy from the Earth surface in 36 spectral bands from 0.4 to 14.4 μm. High sensitivity radiometric data are recorded at nominal spatial resolutions of 250 m (bands 1–2), 500 m (bands 3–7), and 1000 m (bands 8–36). The spectral range of MODIS band 1 is 620–670 nm and the range of band 2 is 841–876 nm. Terra and Aqua are in sun-synchronous orbits. The Terra (formally EOS AM) spacecraft crosses the equator at 10:30 AM local time (descending node), and the Aqua (formally EOS PM) spacecraft crosses at 1:30 PM local time (ascending node) thereby potentially providing two views of a given area each day. Each instrument acquires near-global coverage every 1–2 days. The instruments began providing science data in February 2000 and June 2002 on the Terra and Aqua spacecraft, respectively.

The use of remote sensing to map suspended sediment concentration is well established for a variety of water types. A common method is to relate remotely sensed reflectance measured in the red portion (ca. 600–700 nm) of the visible spectrum to parameters of water column sediment or particulate matter concentration. This approach is reasonably robust in coastal and inland waters because scattering from suspended materials frequently dominates the reflectance spectra when compared to pure water and phytoplankton absorption (Kirk, 1994; Mobley, 1994). MODIS band 1 provides coverage in the red spectral region (620–670 nm) at a sensitivity sufficient for coastal water studies. Therefore, the characteristics of MODIS band 1 data, such as its medium spatial resolution (250 m), red band reflectance, high sensitivity, and near daily coverage, suggest that these images may be well suited for examining suspended particulates in coastal environments, particularly smaller bodies of water such as bays and estuaries.

This study examined the relationship between MODIS Terra band 1 data and concentrations of Total Suspended Matter (TSM) obtained from three coastal systems of the Northern Gulf of Mexico, USA. In addition, a simple procedure was developed for the selection, acquisition, processing, and display of MODIS 250 m data such that the algorithm derived can easily be applied by most users to a wide range of studies of suspended matter in coastal waters.

2. Methods

2.1. Field samples

Surface water samples were obtained from three different environments in the Northern Gulf of Mexico (Lake

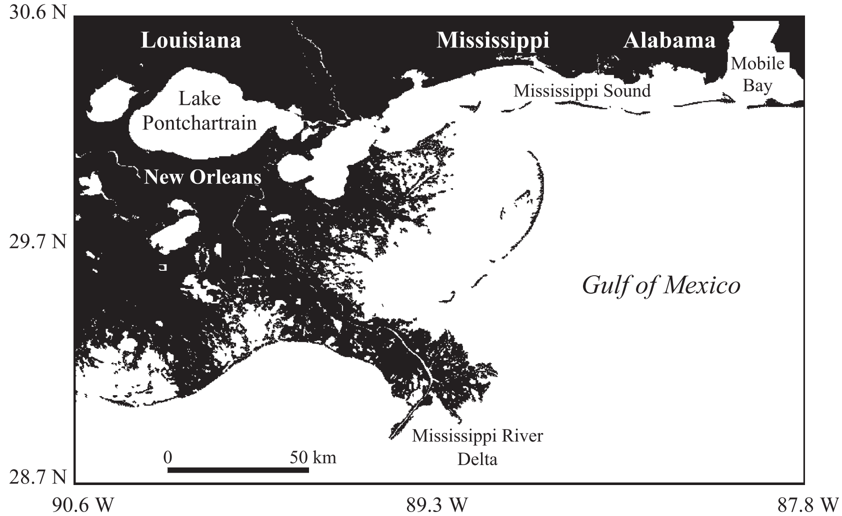

Fig. 1. Location map of the three study areas (Lake Pontchartrain, Mississippi River Delta, and Mississippi Sound) in the northern Gulf of Mexico.

Pontchartrain, Mississippi River Delta, and Mississippi Sound; Fig. 1) during six field campaigns (Table 1) and filtered for the determination of Total Suspended Matter (TSM). Lake Pontchartrain is a shallow urbanized estuary adjacent to New Orleans, LA where suspended matter is primarily derived from bottom sediment resuspension (Miller et al., in press). The bottom sediment type of Lake Pontchartrain is generally homogenous and dominated by small grain size particles consisting of clay, silty-clay, and silt, with only very small pockets of large grain size particles such as sand and silt-sand (Flowers & Isphording, 1990). The input of suspended sediments from the Mississippi River dominates the particulate environment (water column and seabed) of the Mississippi River Delta region. Surface shelf sediments adjacent to the Mississippi River are homogeneously fine-grained (silts and clays) in the upper meter of the seabed and within the river plume (Abu El-Ella & Coleman, 1985; Corbett et al., 2004). Mississippi Sound is a protected shallow environment developed by the coast and a barrier island system.

Table 1
Location, date, and source of TSM samples used in this study

Environment	Date	Source
Lake Pontchartrain, LA	19 May 2002	McKee[a]
Lake Pontchartrain, LA	23 May 2002	McKee[a]
Mississippi River Delta	15 July 2003	McKee[a]
Mississippi River Delta	10 October 2003	McKee[a]
Mississippi River Delta	17 March 2002	Miller[b]
Mississippi Sound, MS	16 May 2001	Moncreiff[c]

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Suspended materials of fine-grained sediments (silts and clays) are derived from several rivers and bottom sediment resuspension (Doyle & Sparks, 1980).

The concentrations of optically active substances such as chlorophyll *a* and Colored Dissolved Organic Matter (CDOM) in each of the three environments can vary significantly both spatially and temporally primarily as a function of freshwater input (i.e., source of nutrients and CDOM) and suspended sediment concentration. For example, chlorophyll *a* concentration and CDOM absorption in the Mississippi River Delta region are often correlated to salinity and therefore vary significantly between periods of low and high river discharge. Significant interannual variations in each parameter may also be observed as a function of changes in total volume discharge during each flow period. Representative values for midshelf chlorophyll *a* concentrations are <1 and 17.34 mg m^{-1} during low and high river flow, respectively (D'Sa & Miller, 2003). Similarly, representative CDOM absorption coefficients at 440 nm [$a_{CDOM}(440)$] associated with the Mississippi River plume are 1.3, 0.8, 0.6, and 0.45 m^{-1} at salinities of 0, 5, 15, and 35, respectively (Del Castillo, in press). The range of monthly average chlorophyll *a* concentrations in Lake Pontchartrain is 5.2–15.4 mg m^{-1} (Dow & Turner, 1980); $a_{CDOM}(440)$ generally is within 2–4.5 m^{-1} (Miller et al., 2002). Typical chlorophyll *a* concentrations in Mississippi Sound range from 1 to 13 mg m^{-1} (Arnone, personal communication) while the average $a_{CDOM}(440)$ within Mississippi Sound is 3.5 m^{-1} (Miller et al., 2002).

TSM concentration (mg/l) was determined gravimetrically following the procedures outlined by Strickland and Parsons (1972). A known volume of water was filtered through either preweighed 0.2-μm Nuclepore nylon filters (Lake Pontchartrain and Mississippi River Delta samples) or 0.7-μm GF/F filters (Mississippi Sound samples). All filters were rinsed with Milli-Q water to remove salts, dried, and then reweighed on a high precision balance. Samples were filtered at sea or stored in acid-washed amber plastic bottles until filtered. Stored samples were filtered within 1 week of collection. These water samples were obtained by two independent research teams for investigations not directly related to remote sensing. Only samples obtained within 30 minutes before or after a MODIS Terra overpass were used in this analysis.

2.2. MODIS imagery

MODIS data are available without charge from several data archive and distribution centers. Specific data can be selected for a given geographic region and time period using a web-based query and ordering system offered at several data portals. For example, data for this study were obtained directly from the NASA EOS Data Gateway (EDG). The EOS gateway provides links to data from NASA and its affiliated centers. Access is available to most users. MODIS data are readily available from the NASA Goddard Earth Science (GES) Distributed Active Archive Center (DAAC).

MODIS imagery were obtained for days corresponding to field measurements of TSM (described below). MODIS data are stored as data granules (5 min time of data collection) in the HDF-EOS format. Hierarchal Data Format (HDF) is an efficient structure for storing multiple sets of scientific, image and ancillary data, in a single file. The DAAC data sets MOD02QKM (calibrated radiances level L1b full swath at 250 m) and MOD03 (geolocation fields level L1A at 1 km) were ordered and downloaded via file transfer protocol (ftp) client software. MOD02QKM files contain the MODIS 250 m band 1 and 2 image data. Earth geolocation points for georeferencing the image data are maintained in a corresponding MOD03 file. Individual data sets are embedded in the file as an Scientific Data Set (SDS). The SDS name for MODIS 250 m image data in a MOD02QKM file is EV_250_RefSB.

Upon downloading MODIS 250 m data to a local system, the data were displayed to assess image quality and then processed using the HDFLook 4.1 software. HDFLook was developed under collaboration between the Laboratoire d'Optique Atmospherique and GES DAAC for the XWindows computer environment and has been tested on all major UNIX platforms, Linux and MAC OS. Hence, HDFLook can be operated on a wide range of low cost computer systems. HDFLook is available free of charge from several NASA MODIS web sites. HDFLook batch scripts were used to extract a region of interest corresponding to field measurements from the main MOD02QKM file, the data converted from calibrated radiances to percent surface reflectance [water leaving radiance/top of atmosphere irradiance×cos(solar zenith angle)], the image georeferenced, and output as a generic two band HDF file.

Although HDFLook is a useful program to display and extract subscenes from MODIS data files, the ENVI 3.4 (Research Systems, Boulder, CO) image analysis software was used to further process and analyze the HDFLook generated data files. The geopositional accuracy of each file was assessed by overlaying a high resolution vector coastal database onto each image. The file map coordinates were adjusted manually, if necessary, by changing the coordinate offsets. Land and clouds were masked using an empirical threshold algorithm based on band 2 reflectance. Images were visually inspected to insure that all pixels within the study area were free of sun glint. Atmospheric radiance was removed using a simple clear water (dark-pixel subtraction) technique (see, e.g., Gordon & Morel, 1983). The darkest pixel in the image was used to estimate the aerosol contribution throughout the entire scene. This approach assumes that the aerosol type and size distribution does not change over the distance from which the dark pixel is selected. This assumption has been demonstrated to be applicable for various studies (Hu et al., 2000; D'Sa et al., 2002). Due to the limited number of field samples, data match-ups were made by manually navigating to a sample location and then recording the MODIS reflectance value for the corresponding pixel.

3. Results and discussion

A significant (r^2=0.89, n=52) relationship was observed between TSM concentration (mg/l) and atmospherically corrected MODIS Terra band 1 data used in this study (Fig. 2). The relationship is consistent over the wide range of TSM concentrations measured-offshore (clear water) stations to Mississippi River plume stations (highly turbid). Moreover, the relationship is reasonably robust in that TSM data were acquired from three different (i.e., shallow urbanized estuary, coastal embayment, and river-dominated margin) systems by three different investigators. The simple atmospheric correction scheme also appears to be effective for the wide range of sky conditions that occurred during the sample dates (Table 1). The approach outlined here could be applied to other coastal or inland regions but the specific relationship between MODIS reflectance and TSM concentration (i.e., the slope of the regression line, Fig. 2) may vary as a consequence of optical characteristics of the TSM such as sediment type and particle size distribution.

A comparison of MODIS 250 m and 1 km data is shown in Fig. 3. As expected, the 250 m data provide considerably more detail in the horizontal distribution of suspended particulates, contain more pixels in small areas such as Biloxi Bay, and allow a closer inspection of water features closer to the shore and barrier islands.

The TSM algorithm was applied to daily MODIS Terra images acquired for the coastal region associated with the

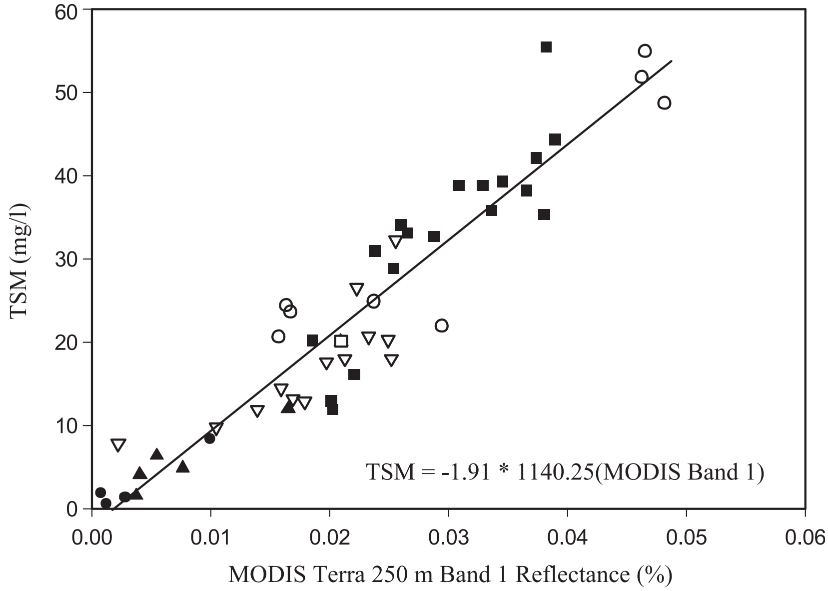

Fig. 2. Total Suspended Matter (TSM) concentration as a function of atmospherically corrected MODIS Terra 250 m band 1 reflectance. TSM data were obtained from six field campaigns: Mississippi Sound, 5/16/2001 (○); Mississippi River Delta (MRD), 3/17/02 (●); Lake Pontchartrain (LP), 5/19/02 (■); LP, 5/23/02 (△); MRD, 7/15/03 (□); and MRD, 10/20/03 (▲). The line is the least-squares fit to the data (r^2=0.89, n=52; MSE=4.74).

Mississippi River Delta during 21–23 October 2003 (2003294–2003296). The processed images for 2003294 and 2003296 are shown in Fig. 4. October is a period of moderately low discharge from the Mississippi River (Fig. 4). Data were obtained through the EDG from the Goddard Space Fight Center Distributed Active Archive Center (GSFC-ECS) 1 day following acquisition. Independent ground stations such as the X-band system at the NASA Stennis Space Center, MS, can provide data within a few hours of acquisition. Again, MODIS 250 m data provide sufficient spatial resolution to resolve fine-scale features in the images such as the plume from individual delta passes, complexity of TSM concentrations in nearshore waters, the sediment distribution in the associated bays, and the clear demarcation of frontal boundaries. This short time series clearly shows the significant effect of a frontal system passage 12 h prior to 2003296 MODIS overpass in which winds dramatically increased (2 m/s to sustained winds of 10 m/s) from the NW (variable, 270–360°). The characteristics of the Mississippi River plume rapidly changed from a generally diffuse, lobe-like plume to a distinct more concentrated plume extending to the southeast. The capability to resolve and track these features is key to numerous investigations that study the transport and fate of materials (including carbon), the coupling of seabed

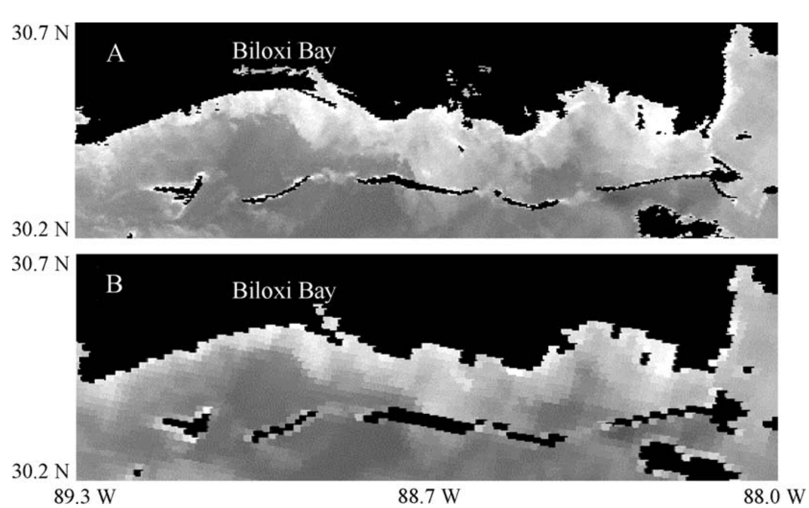

Fig. 3. Comparison of MODIS Terra (A) 250 m band 1 (620–670 nm) and (B) 1 km band 13 (662–672 nm) reflectance images of the Mississippi Sound (30–30.5° N, 88–89.3° W) acquired 4 April 2004. Land and clouds are masked black.

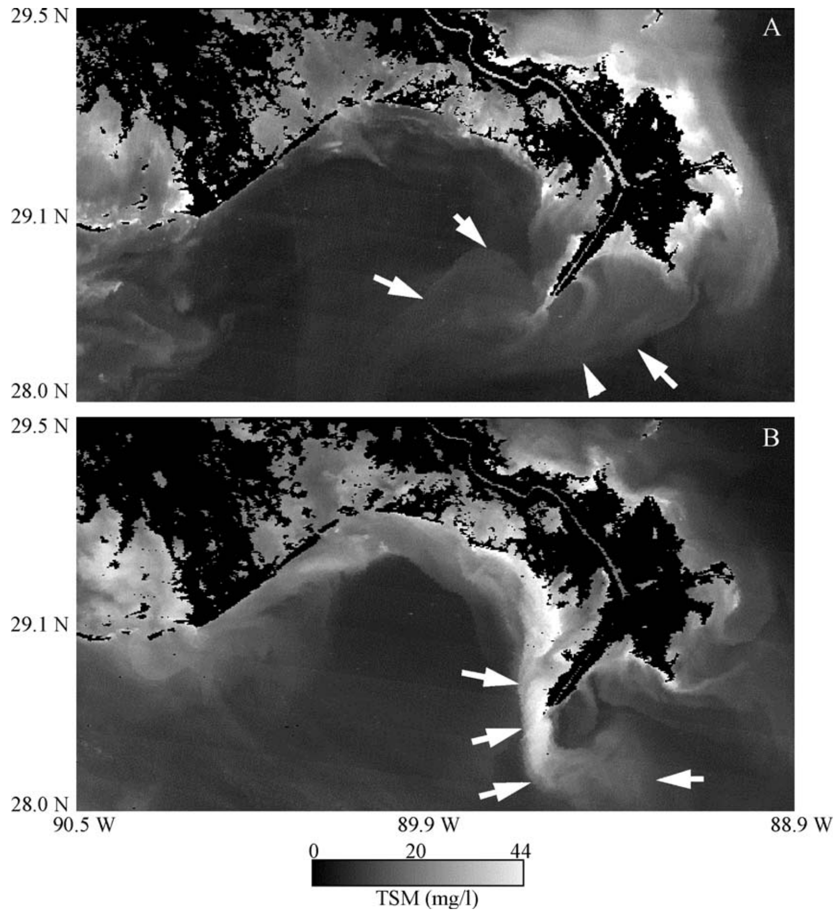

Fig. 4. Calibrated images of TSM of the Mississippi River Delta and adjacent waters derived from MODIS Terra Band 1 data for 21 October 2003 (A) and 23 October 2003 (B). Land is masked to black. Arrows indicate the "leading-edge" of the Mississippi River turbidity plume. High spatial variability is observed within each image as well as significant differences in the horizontal distribution of suspended particulates between the two days resulting from an increase in wind speed from the northwest prior to the MODIS overpass on 23 October 2003.

deposition with river discharge, and water column phytoplankton production.

4. Conclusions

Mapping the distribution of suspended particulates in coastal waters is critical to many scientific and environmental studies. Environmental managers and local decision makers must often know water quality parameters as well as the transport of materials over large areas of a coastal region. Frequently, data are acquired involving expensive and labor-extensive field programs to obtain data at the appropriate temporal and spatial scales. Although previous studies have shown a direct relationship between concentrations of suspended matter and remotely sensed data, the spatial resolution or frequency of remotely sensed data was inadequate to fully examine the dynamics of most coastal or smaller bodies of water (i.e., bays and estuaries). In addition, the availability of software and instrument specific algorithms to process remotely sensed data were often absent or restricted to a limited user community.

This study demonstrated that the characteristics of the MODIS Terra instrument provide data well suited for the study of suspended matter in dynamic coastal waters. The moderately high resolution of MODIS 250 m data was useful for mapping small-scale features of TSM concentration in different inland and coastal waters. Using simple processing procedures and readily available software, the rapid acquisition, processing, and analysis of MODIS data were possible. The near daily revisit period of the MODIS instrument enabled an analysis of short-term, yet significant, changes in the horizontal distribution of the sediment plume of the Mississippi River. MODIS 250 m data can also be used to derive optical properties that are coupled to TSM concentration in the coastal environment such as the beam attenuation coefficient (Arnone et al., 2002). Hence, MODIS data can potentially be used in a variety of research and coastal applications to provide unique information to scientists, decision makers and environmental managers. Equally important to the potential widespread use of MODIS images in coastal studies is the significant advances in the development and open distribution of analysis software including instrument specific algorithms. Similarly, the development of effective distribution gateways of MODIS data has greatly facilitated its widespread use.

The availability of two MODIS instruments (morning, afternoon) should greatly extend the utility of MODIS data as shown in this study. It is expected that a similar robust relationship will exist between MODIS Aqua data and TSM. This relationship will be examined in future studies dedicated to developing real-time applications of remotely sensed data for coastal studies.

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