Ocean Color Reveals Sand Ridge Morphology on the West Florida Shelf

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Abstract—Inner shelf sand ridges are common features along many sandy coastlines. Here, I demonstrate that ocean color imagery from the operational satellite instrument Moderate Resolution Imaging Spectroradiometer can clearly show their morphology, including orientation, width, length, spacing, thickness, and distribution, on the inner west Florida shelf between the Big Bend and the Florida Bight (about 500 km N–S) up to 35 m water depth and 150 km from the shoreline. Some of the sand ridges were previously unknown due to lack of in situ data. Most of the periodic, parallel, and static features agree well with the existing high-resolution bathymetry. However, there are also mismatches between the bathymetric features and those revealed by the consistent satellite measurements, suggesting possible errors in the bathymetry data. Using a simple optical model, I show that the 500-m resolution imagery can accurately reveal sand ridge thickness from several meters to < 1 m. Because of the repeated and synoptic coverage, these medium-resolution ocean color imagers provide unprecedented capability in studying distributions and changes of the sand ridge morphology, which are otherwise expensive and difficult to obtain.

Index Terms—Image analysis, image processing, measurement, Medium Resolution Imaging Spectrometer (MERIS), Moderate Resolution Imaging Spectroradiometer (MODIS), morphology, ocean color, remote sensing, sand ridge, Sea-viewing Wide Field-of-view Sensor (SeaWiFS).

I. INTRODUCTION

SUBMERGED inner shelf sand ridges are common features in many coastal regions, for example, on the Nova Scotian shelf, the North American Middle Atlantic Bight, the inner shelf of South America, and the tide-dominated shelf of the North Sea. These benthic features have been studied extensively since the 1960s by using a variety of techniques including in situ surveys and numerical modeling (see, for example, [1], [4], and references therein). More recently, modern stratigraphic framework tools (digital high-resolution seismic, chirp sonar, vibracoring, etc.) have enabled researchers to learn more details on a ridge’s history and formation [5].

Although capable of revealing ridge details, the in situ techniques are costly and time consuming. For example, it took millions of dollars and nearly ten years to study some of the inner shelf ridges off west-central Florida of the U.S. (Fig. 1a); also see [6]). On the other hand, in theory, remotely sensed color imagery can be used to map shallow-water bathymetry [15]. However, most published works to date used either high-resolution satellite imagery (e.g., SPOT [11]) or hyperspectral airborne imagery (AVIRIS [12]), and the study areas were relatively small. Because of the influence of cloud cover and turbidity on the mapping accuracy, it is difficult to obtain optimal data for a given location from these sensors.

Ocean color imagers from modern satellite sensors such as the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) provide near-daily coverage of the global ocean. However, no reports on their application in sand ridge studies could be found in the current literature. Here, using the west Florida shelf (WFS) as an example, I demonstrate how ocean color data from these operational sensors can complement the field techniques in mapping sand ridge morphology and their distributions.

II. STUDY AREA

The WFS is one of the broadest continental shelves in North America (Fig. 1). Between 24.5° N and 30° N and bounded by the Florida Keys and the Big Bend, the shallow shelf is of great importance to fishery and recreation for its world-renowned coral reefs and beaches. Intensive field surveys have determined that the middle shelf from north of Tampa Bay to south of Charlotte Harbor is a mixed siliciclastic–carbonate shelf that contains a wide variety of sand ridges separated by extensive areas of exposed Neogene-aged karstified limestone [8]. The shallow region is characterized as interspersed by thin veneers (sheets and ridges) of coarse carbonate sand and finer grained siliciclastic (quartz-dominated) sediments that range from a few centimeters to more than 4 m thick [5], [8], [14]. However, nearly all surveys were restricted to the inner shelf that is typically within 20–30 km of the shoreline (Fig. 1, dotted line), and it is unclear if and how far these sand ridge features extend further offshore.

III. DATA AND METHOD

Ocean color data from SeaWiFS (1997–present) and MODIS (1999–present for Terra and 2002–present for Aqua) at a nominal resolution of 1 km were processed using the software SeaDAS (version 5.1) developed at the NASA Goddard Space Flight Center (GSFC). Note that, when a ground station is not available, these data can be ordered from GSFC at no cost. First, effects due to different atmospheric conditions and solar/viewing geometry were removed, and normalized water-leaving radiance (nLw) for each band, representing the radiance...
Fig. 1. (a) Enhanced RGB image (500-m resolution; 555, 469, and 443 nm as R, G, and B, respectively) showing sand ridges on nearly the entire shallow WFS, as outlined by the dashed line (an area of about 46 000 km$^2$). Some of the ridges are more apparent in other images. The white lines show approximate isobaths from 10, 20, 30, to 50 m. The dotted line delineates the approximate boundary where historical geological surveys were conducted (an area of about 5400 km$^2$). The inset figures show the sand ridge features for the red and black boxes, respectively. (b) Bathymetry anomaly between 0- and 50-m isobaths, derived from the NGDC data and remapped to 500-m resolution. Anomaly was derived as the difference between bathymetry and a 35 $\times$ 35 pixel running mean to manifest the underlying depth contrast. (Red arrows) Note the areas with no bathymetry data near Tampa Bay and the Big Bend and south of Charlotte Harbor. More images are available as auxiliary materials.

leaving the ocean surface under an imaginary nadir sun without atmosphere, was derived. Then, chlorophyll-a concentration (Chl) and fluorescence line height (FLH, for MODIS only) were derived by using empirical algorithms. The SeaWiFS/MODIS data products were mapped to a cylindrical equidistance projection, and enhanced RGB (ERGB) composite images were generated by using 555/551-, 490/488-, and 443/443-nm bands for the RGB channels, respectively. Most computer codes were from SeaDAS, with some customized codes developed in house.

The entire SeaWiFS series (> 7000 images from the University of South Florida (USF) ground station) was visually examined to determine the best dates when bottom features on the WFS could be identified. Then, concurrent MODIS data were reprocessed but with the 469- and 555-nm bands (500-m resolution) included. The products were mapped, and ERGB images were generated using the 555-, 469-, and interpolated 443-nm bands. These 500-m data were used to study the benthic features.

Bathymetry data at 3-arcsec resolution (about 90 m) were obtained from the U.S. National Geophysical Data Center (NGDC), National Oceanic and Atmospheric Administration, and mapped to the same projection at 500-m resolution. The data were originally collected by several agencies using a variety of methods including sounding. To help visualize the bathymetric features, the data were first smoothed using a 35 $\times$ 35 pixel running window, and an anomaly image was generated by subtracting the smoothed data [Fig. 1(b)].

IV. Results

Between late 1997 and the present, some spring images clearly showed features that were generally parallel to each other but more or less oblique to the shoreline [Fig. 1(a)]. These features were obscured by high turbidity in winter and coastal runoff in summer and autumn. No clear image was found in the spring of 2003 and 2005, indicating interannual variability in coastal water clarity. Viewed in ENVI with the link-image function, these features remain static over time, suggesting that they are indeed benthic features instead of water column properties. These static features reach an offshore distance ranging from 50 km between Tampa Bay and Charlotte Harbor to 150 km around 28.3° N and 84.2° W.

Due to limited resolution of the printing matter and the large size of the study area, the details of these features cannot be visualized here. However, full-size images at 500-m resolution are available as auxiliary materials, an example of which is presented in Fig. 1(a). Two zoomed-in small areas, outlined by the red and black squares, help visualize the sand ridges. Their characteristics are in perfect agreement with the NGDC bathymetry (Figs. 1(b) and 2). However, there are some areas that show differences, particularly between Tampa Bay and Charlotte Harbor. Indeed, the MODIS images show dominant NE–SW ridge orientation in this region, whereas such an orientation is less apparent in the bathymetry data (Fig. 1). Furthermore, MODIS-derived depth contrast (see next) occasionally differs from the bathymetry (Fig. 2(b), red arrows). Because of
the perfect consistency among multiple MODIS measurements, this suggests possible errors in the bathymetry data.

When viewed in full resolution, the MODIS images show details of the sand ridge morphology, some of which were previously unknown. Sand ridges over almost the entire shallow shelf are apparent, as outlined by the dashed line in Fig. 1(a), extending from the shoreline to > 30-m isobath. This covers an area of about 46 000 km², which is much larger than previously studied (Fig. 1(a), dotted line). More importantly, the images can fill some of the bathymetry data gaps between Tampa Bay and the Big Bend and in the near-shore areas south of Charlotte Harbor [Fig. 1(b)].

The size, shape, and orientation of the identified sand ridges vary spatially. North of Tampa Bay, the parallel ridges are first oriented SE–NW and then turn to E–W at about 25-m isobath. Near the Big Bend, the ridge orientation changes to E–W and then to NE–SW in the north. In areas where no bathymetry data or historical survey data are available, sand ridge patterns are also visible in the MODIS images. South of Tampa Bay, sand ridges are oriented primarily NE–SW and then gradually tilted to E–W below 26° N.

The ridge width and spacing generally increase with water depth. Around 10-m isobath, sand ridges are 1–2 pixels (approximately < 1 km) wide, with about 1–2 pixels in between. Between 10- and 20-m isobaths, the size and inter-ridge space are nearly doubled. Further offshore, they are spaced by about 7–8 km with several kilometers in width.

Harrison et al. [7] reported that some of the near-shore ridges northwest of Tampa Bay were parallel to the shoreline and detached from the beach. While occasional shore-parallel ridges were identified between Tampa Bay and Charlotte Harbor in MODIS images, the dominant orientation is oblique to shoreline. Furthermore, the 250-m-resolution images from the 645-nm band (not shown here) show that many ridges in this region are close to (< 2 pixels) and sometimes appear to be attached to the beach.

The contrast between the paralleling ridges in Fig. 1(a) resulted from differences between bottom depths and also possibly between bottom albedos (reflectance). Fig. 3 shows that as bottom depth decreased almost linearly from the west (offshore) to the east (inshore) along an artificial transect, nLw555 increased exponentially. The stability of the MODIS FLH (an indicator of the surface biomass concentration) along this transect suggests that the changes in nLw555 were primarily due to the bottom (depth and albedo) rather than the water column. The average bottom albedo and water attenuation were derived using a simple optical model

\[ nLw555 (Z) \equiv C_1 \cdot e^{-2K Z} + C_2 \cdot (1 - e^{-2K Z}) \]  

with the two terms representing the contributions from the bottom and the water column, respectively. Here, Z is the bottom depth, K is the attenuation coefficient that needs to be determined through nonlinear regression, and C₁ is related to bottom albedo (A) as follows: \( A \approx 2\pi \cdot C_1 / F_0 \) (\( F_0 \) is the solar constant at 555 nm, 183.76, and the factor two is to take care of the conversion of radiance and irradiance across the air-sea interface). Table I lists the regression results. Except for the MODIS/Aqua image on March 25, 2007, when moderate sun glint was found for most pixels, the derived bottom albedo was consistent from the three sensors in different years, with an average of ~22%, typical for sandy materials.

The thickness of the sand ridges along the NW–SE transect (Figs. 1(a) and 2) was estimated using the inverse (1) and the derived K values; small water column contributions were omitted. This serves to derive the depth difference between the bright and dark features. Therefore, the average nLw555 along the transect was used as a reference, and the depth difference between each pixel and the reference was derived. The depth differences derived from MODIS and from the bathymetry are shown in Fig. 2(b). Note that negative values represent ridge crests, whereas positive values represent ridge troughs. Therefore, MODIS-derived ridge relief (thickness) along the transect was estimated as 2–3 m. These values agree well with data derived from the NGDC bathymetry, with rms differences of about 0.5 m for the individual MODIS data (Table I) and 0.37 m for the averaged MODIS data.

V. Discussion

Geolocation errors in MODIS data are typically less than 150 m [17]. Therefore, the repeated measurements by the MODIS instruments provide a potential means to estimate temporal changes in sand ridge morphology at > 0.5-km scales. Such changes, however, are unlikely to occur in decadal scale because the age scale of the WFS sand ridges is in thousands of years [5]. In contrast, where ridges may migrate 50 m/year [3], decadal changes may be revealed by the medium-resolution imagery. Additionally, under extreme conditions such as severe storms (hurricanes), some changes in local morphology may occur and be detectable by modern satellite sensors.

The orientation of a sand ridge should be perpendicular to the direction of the bottom currents (e.g., [7]); these currents are the driving force in ridge formation. Hence, the asymmetry of its spatially varying orientation can be used to infer the dominant current direction in climatological scale. For example, between Tampa Bay and Charlotte Harbor where the shallow isobaths

![Fig. 2.](Image)
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Fig. 3. Properties along a W–E transect at 28.175° N off northwest of Tampa Bay [Fig. 1(a)]. To remove noise, a running window of 15 × 15 pixels was used along the transect. The properties include the following: nLw555 (mW · cm−2 · µm−1 · sr−1), Chl (mg · m−3), and FLH (mW · cm−2 · µm−1 · sr−1) from several satellite passes. Also shown is the bottom depth from the NGDC bathymetry. Note that, because of the simple algorithm used to estimate FLH and because of the low signal-to-noise ratio, most of the FLH values are negative but can still be used on a relative sense [10]. The constant FLH indicates that changes in Chl are artifacts due to the bottom effects.

TABLE I
RESULTS OF THE NONLINEAR REGRESSION OF USING (1) TO DERIVE THE BOTTOM ALBEDO (A) AND ATTENUATION COEFFICIENT (K) FOR THE W–E TRANSECT OFF TAMPA BAY IN FIGS. 1(a) AND 3. NOTE THAT THESE REGRESSION RESULTS ONLY DEPEND ON A COARSE-RESOLUTION BATHYMETRY (15 × 15 500-m PIXELS OR 7.5 × 7.5-km2 RESOLUTION) THAT CAN BE OBTAINED FROM THE GLOBAL ETOP02 DATA. THE REGRESSION ACCURACY WAS MEASURED BY THE RELATIVE RMS (%) DIFFERENCE BETWEEN THE FITTED AND ORIGINAL nLw555. THE LAST COLUMN LISTS THE RMS DIFFERENCE BETWEEN THE MODIS-DERIVED AND NGDC BATHYMETRY-DERIVED BOTTOM-DEPTH CONTRASTS (ΔZ)’S ALONG THE NW–SE TRANSECT IN FIG. 1(a). AFTER THE INDIVIDUAL MODIS-DERIVED DEPTH CONTRASTS WERE AVERAGED, THE RMS DIFFERENCE REDUCED TO 0.37 m

<table>
<thead>
<tr>
<th>Image</th>
<th>C1</th>
<th>C2</th>
<th>K (m−1)</th>
<th>A (%)</th>
<th>RMS (%)</th>
<th>RMS (ΔZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 3/23/2000</td>
<td>6.69</td>
<td>0.33</td>
<td>0.0777</td>
<td>22.9</td>
<td>4.7</td>
<td>-</td>
</tr>
<tr>
<td>A 4/05/2006</td>
<td>6.38</td>
<td>0.33</td>
<td>0.0756</td>
<td>21.0</td>
<td>4.5</td>
<td>0.45 m</td>
</tr>
<tr>
<td>A 3/25/2007</td>
<td>5.33</td>
<td>0.27</td>
<td>0.0675</td>
<td>17.3</td>
<td>3.8</td>
<td>0.57 m</td>
</tr>
<tr>
<td>T 3/28/2007</td>
<td>6.49</td>
<td>0.36</td>
<td>0.0819</td>
<td>21.7</td>
<td>5.4</td>
<td>0.50 m</td>
</tr>
</tbody>
</table>

Note: S: SeaWiFS; A: MODIS/Aqua; T: MODIS/Terra. C1 and C2 have units of mW cm−2 µm−1 sr−1. Depth contrast from SeaWiFS was not derived because of its coarser resolution (1 km) than MODIS (500 m).

(< 30 m) are nearly parallel to the shoreline, the imagery shows that the sand ridges are not strictly perpendicular to the isobaths but rather rotated clockwise. This suggests that the bottom-current vectors also flow in a direction that is rotated clockwise relative to the isobath lines. This is confirmed by the in situ autonomous acoustic Doppler current profiler measurements in this area [16]. In other WFS areas where no in situ data are available, current direction inferred from sand ridge orientation also agrees well with those derived from numerical models [16]. There are, however, several unexplained features. One area lies immediately north of Charlotte Harbor where the ridges first appear near-parallel to the shoreline and then make a near-90° turn [Fig. 4(a)]. A second example is south of Tampa Bay where, among the dominant shore-oblique ridges, there are some small shore-parallel ridges [Fig. 4(b)]. It is unclear what caused these sharp changes in ridge orientation.

The ocean color data also revealed asymmetry in ridge shapes. For example, along the NW–SE transect line in Fig. 1(a), the ridge slope that is south of the crest appears steeper than the northern slope (Fig. 2(b), dashed arrow). This agrees well with the findings of Harrison et al. [7], even though their spatial scale was much smaller. The asymmetry around the ridge crest may indicate the asymmetry in the current magnitude; in this case, SW current may be stronger than NE current, as shown in the work of Harrison et al. [7].

The depth contrast (and, consequently, ridge relief or thickness) derived in Fig. 2 from MODIS is a simplification. This is due to the mean attenuation coefficient used, the omission of the water column contribution, and the mean bottom albedo used for both ridge crest and trough. Indeed, if water column contribution were taken into account, the derived contrast would be nearly doubled and different from the bathymetry-derived contrast. To compensate for this effect, higher/lower than the mean albedo must be used for ridge trough/crest. In fact, this difference between the albedo values was confirmed by in situ side-scan sonar mapping, which showed low backscatter and fine-grained (< 0.25 mm) mixed quartz and carbonate sand on the crest, and higher backscattering and coarse-grained (> 2.0 mm) shell and limestone gravel in the trough [7].
There are limitations in using MODIS data to detect small bathymetric features in that only two 500-m bands are available. Landsat Thematic Mapper/Enhanced Thematic Mapper Plus or SPOT data have higher spatial resolution (30–15 m), but their spatial coverage is limited (~180 km) and their sensitivity is much lower than that of MODIS [9]. Furthermore, it is difficult to find suitable data (cloud free, optimal water clarity, and near-shore to offshore coverage) for ridge studies from their 16-day repeated coverage. The Medium Resolution Imaging Spectrometer (MERIS), as an operational sensor, is equipped with more spectral bands that can potentially derive not only the depth contrast [i.e., ridge thickness, Fig. 2(b)] but also the absolute bottom depth at 300-m full resolution (FR) (e.g., [13]). Unfortunately, MERIS FR data are not collected operationally. Search of the FR data under optimal water clarity conditions for the study region is underway to derive the bathymetry and sand ridge morphology at higher resolution.

Finally, in the perspective of ocean color algorithm development, the profiles shown in Fig. 3 have significant implications. The near-constant FLH indicates that the water is nearly homogenous in biomass along the transect. Therefore, the increases of nLw555 for \( Z < 40 \) m and the increases of Chl for \( Z < 30 \) m are due to the bottom effects only. While the former is real, the latter is indeed an artifact due to the empirical Chl algorithm. The bottom-induced errors in the Chl estimates can be 1000% or larger, from the realistic 0.15–0.2 mg \( \cdot m^{-3} \) for \( Z > 30 \) m to the erroneous 1.5–2 mg \( \cdot m^{-3} \) for \( Z < 10 \) m. Clearly, this presents a significant error source in any attempt to use satellite-derived Chl or Chl anomaly to monitor suspicious events, for example, harmful algal blooms. Although empirical methods are available to partially correct the errors (e.g., [2]), operational use of the methods and more rigorous approaches are yet to be developed and validated.

VI. CONCLUSION

Sand ridge morphology in synoptic scales has been shown by ocean color imagery from operational satellite measurements. The case study here on the WFS clearly demonstrates the unprecedented capability of the medium-resolution (500-m) MODIS ocean color imagery in revealing details of the ridge morphology, including width, length, orientation, spacing, and thickness. This is attributed to the high sensitivity (signal-to-noise ratio), moderate resolution, and accurate radiometric calibration and navigation of the satellite instruments. In addition to this first demonstration, the time series of ocean color data yielded valuable information on sand ridge distribution over the WFS, some of which was previously unknown due to the limited and costly nature of in situ surveys. In particular, the color imagery showed sand ridges on nearly the entire WFS to at least 30-m isobath, whose morphological patterns are more coherent than those revealed by the incomplete high-resolution bathymetry data.

Because of the availability of the global ocean color data, similar methods may be applied to study sand ridges elsewhere in a cost-effective yet efficient way to complement field techniques that are capable of revealing more details such as the ridge formation and history.

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