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Detecting the spatial and temporal variability of chlorophyll-*a* concentration and total suspended solids in Apalachicola Bay, Florida using MODIS imagery

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Apalachicola Bay, Florida, accounts for 90% of Florida's and 10% of the nation's eastern oyster (*Crassostrea virginica*) harvesting. Chlorophyll-*a* concentration and total suspended solids (TSS) are two important water quality variables, among other environmental factors such as salinity, for eastern oyster production in Apalachicola Bay. In this research, we developed regression models of the relationships between the reflectance of the Moderate-Resolution Imaging Spectroradiometer (MODIS) Terra 250 m data and the two water quality variables based on the Bay-wide field data collected during 14–17 October 2002, a relatively dry period, and 3–5 April 2006, a relatively wet period, respectively. Then we selected the best regression models (highest coefficient of determination, R^2) to derive Bay-wide maps of chlorophyll-*a* concentration and TSS for the two periods. The MODIS-derived maps revealed large spatial and temporal variations in chlorophyll-*a* concentration and TSS across the entire Apalachicola Bay.

1. Introduction

Apalachicola Bay is one of 39 estuaries along the northern Gulf of Mexico (Pennock *et al*. 1999). The Bay is a highly productive and relatively pristine estuarine system that supports diverse and abundant commercially, recreationally and ecologically important species (Livingston *et al*. 2000, Huang *et al*. 2002). For example, Apalachicola Bay accounts for 90% of Florida's and 10% of the nation's eastern oyster (*Crassostrea virginica*) harvesting (Livingston *et al*. 2000). Chlorophyll-*a* concentration and total suspended solids (TSS) are two important water quality variables, among other environmental factors such as salinity, temperature and velocity, which affect oyster production in the Bay (Dekshenieks *et al*. 2000, Wang *et al*. 2007). The concentration of chlorophyll-*a* is a widely used, integrative bio-indicator of phytoplankton

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abundance, an important food resource to oysters (Dekshenieks *et al*. 2000, Han and Jordan 2005, Schalles 2006). High TSS can cause significant mortalities during the earliest phase of larval development and result in decreased oyster filtration rates (e.g. Dekshenieks *et al*. 2000).

Water quality in estuarine ecosystems is affected by many natural and anthropogenic factors. For example, in shallow water estuaries of the Gulf of Mexico, tides, wind and river discharge can easily re-suspend surficial sediments, causing high turbidity and changes in salinity regimes (McKee and Baskaran 1999, Huang *et al*. 2002, Livingston 2006). Apalachicola Bay is a river-dominated, bar-built shallow estuary. It receives freshwater flows from the Apalachicola, Chattahoochee, and Flint River system (ACF), which drains over 60,000 km^2 of Georgia, Alabama, and Florida (Livingston 2006). Consequently, human activities such as land use change, development and upstream water diversion in the ACF basin greatly affect the water quality of Apalachicola Bay. The spatial and temporal patterns of water quality in the Bay reflect the spatial and temporal heterogeneity of these controlling factors. The spatial and temporal variability in chlorophyll-*a* concentration and TSS greatly affects the spatial and temporal variations in oyster production in the Bay (Wang *et al*. 2008). Hence, detecting and mapping water quality across the entire Bay are crucial to environmental monitoring and can help us to identify sensitive and vulnerable areas for detailed study, management, or restoration, if necessary, in the Apalachicola Bay system.

Because the distributions of water quality variables in shallow Gulf of Mexico estuaries are spatially and temporally variable, one of the best synoptic approaches to understand the variations in water quality variables to support resource management practices is via remote sensing. The Moderate-Resolution Imaging Spectroradiometer (MODIS) 250 m bands were effective in detecting water quality in bays and estuaries because of their medium but sufficient spatial resolution, sufficient sensitivity to water quality variables, especially suspended sediment, and near daily coverage (e.g. Li *et al*. 2003, Miller and McKee 2004, Miller *et al*. 2005). Significant relationships have been found between MODIS bands or band ratios and chlorophyll-*a* concentration (Zhang *et al*. 2003, Zhu *et al*. 2004, 2005) and TSS (Miller and McKee 2004; Miller *et al*. 2005).

In this research, our objectives were: (1) to examine the relationships between surface reflectance from MODIS imagery and chlorophyll-*a* concentration and TSS based on the Bay-wide field data collected during 14–17 October 2002 and 3–5 April 2006; (2) to derive Bay-wide maps of chlorophyll-*a* concentration and TSS for two of the periods based on the best regression models; and (3) to detect and explain the spatial and temporal variations in chlorophyll-*a* concentration and TSS in Apalachicola Bay, Florida.

2. Methods

2.1 *Study area*

Apalachicola Bay is located in the Florida panhandle (figure 1). The Bay covers an area of 996 km^2 and has an average depth of three metres. The Bay is connected to the Gulf of Mexico through four major inlets: Indian Pass and West Pass at the western end, and East Pass and Lanark Reef at the eastern end. Most of the freshwater discharged into the Bay flows from the Apalachicola River. The Bay is part of the coastal lowlands, with the characteristic attributes of low elevations and poor drainage. The substrate of the Bay is predominately soft silt and clay with

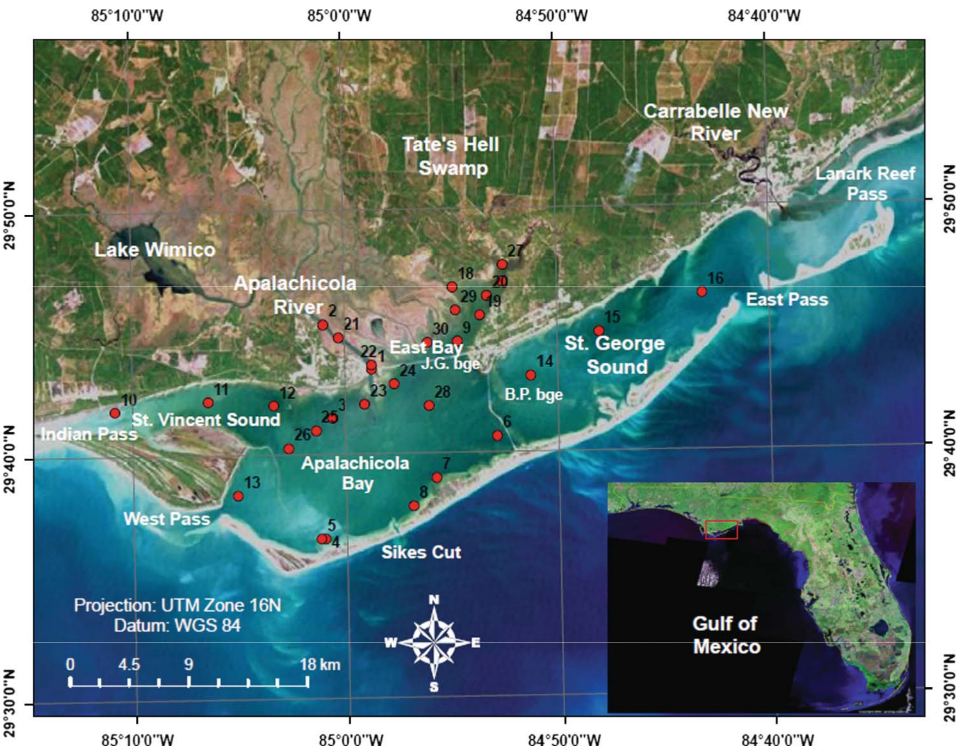

Figure 1. Map showing the location and structure of Apalachicola Bay ecosystem using satellite imagery (Bay image: Courtesy of Northwest Florida Water Management District (NWFWMD); Florida State image: Florida Landsat GeoCover 2000 data, http://geology.com/satellite/florida-satellite-image.shtml) and the sampling stations in October 2002 (#1–#19) and in April 2006 (#20–#30) in Apalachicola Bay, Florida.

some sandy areas (Dardeau *et al*. 1992, Sanger *et al*. 2002). The dominant salt marsh plants surrounding the Bay are black needlerush (*Juncus roemerianus*) and sawgrass (*Cladium*). The upland vegetation is predominately a pineland forest of slash pine, saw palmetto and sand pine (Sanger *et al*. 2002). Tides in Apalachicola Bay are mixed, with an uneven high and low tide and a range of 0.2 to 0.6 m (Dardeau *et al*. 1992, Huang *et al*. 2002). Water in the Bay is moderately stratified (Dardeau *et al*. 1992).

2.2 In situ *data collection and laboratory analysis*

Field water quality measurements in Apalachicola Bay were collected during 14–17 October 2002, a relatively dry period, and 3–5 April 2006, a relatively wet period, respectively. In Apalachicola Bay, May to December is a relatively dry season while January to April is a relatively wet season in terms of freshwater discharge into the Bay. Apalachicola River discharge near Sumatra station during 1977–2001 showed the ranges of discharge from 426 to 700 $m^3\ s^{-1}$ in dry season and from 858 to 1335 $m^3\ s^{-1}$ in wet season. We selected 19 sampling stations for October 2002 and 11 sampling stations for April 2006, which were distributed throughout the entire Bay (figure 1). For the 2002 sampling stations, three stations (#10, #11, #12) were removed because samples at these stations were collected on 15 October immediately following a storm and these stations were also too shallow for accurate estimates of surface water reflectance because of 'bottom effects' (i.e. secchi disk transparency was less than 150% of bottom depth; see Hladik 2004). At each station, we collected bulk water samples from the upper 0.5 m of the water column for the analysis of chlorophyll-*a* concentration and TSS. GPS coordinates and the time of sampling were also recorded. All laboratory procedures were consistent with Standard Methods for the Examination of Water and Wastewater (American Public Health Association 1998). For details of TSS and chlorophyll-*a* analyses, refer to Hladik (2004).

2.3 *MODIS data acquisition*

We obtained the MODIS Terra 250 m data covering the entire Apalachicola Bay from the NASA Goddard Earth Science (GES) Distributed Active Archive Center (DAAC). We used MODIS Terra data rather than MODIS Aqua because our field samples were mostly taken in the morning to early afternoon corresponding to Terra's imaging time. MODIS data that covered the periods of *in situ* water sampling (i.e. 14–17 October 2002 and 3–5 April 2006) were selected. MODIS data are stored as data granules in the Hierarchal Data Format (HDF)-EOS format. The DAAC dataset MOD02QKM (calibrated radiances level L1B at 250 m, http://daac.gsfc.nasa.gov/data/datapool/MODIS/01_Level_1/index.html) was downloaded via file transfer protocol (FTP). MOD02QKM files contain the MODIS 250 m Band 1 (620–670 nm) and Band 2 (841–876 nm) image data. For the 2002 data, we selected the 17 October image (MOD02QKM.A2002290.1600.004.2003249022706.hdf) as the working image because the image of 14 October was not available and the images of 15 and 16 October had dense cloud coverage over the Apalachicola Bay. Although it is preferable to have both the *in situ* data collection and MODIS data coincide, in reality it is hard, if not impossible, to have such coincidence between satellite images and field spatial data, especially in estuaries such as the Apalachicola Bay system. Satellite data temporally mismatched with *in situ* data are often considered suitable for such studies as long as the tidal and weather conditions in the system between satellite and data collection dates are similar and water quality parameters remain relatively stable (e.g. Baban 1997, Han and Jordan 2005). The storm on 15 October 2002 could produce a re-suspension of sediments and associated benthic algae, thus affecting water quality data. Therefore, we examined the water quality data for the sampling week from the National Estuarine Research Reserve System-wide Monitoring Program (SWMP) of NOAA (NOAA/OCRM/SWMP 2006). We found that turbidity either was not significantly affected in most areas (e.g. daily average of ~10 formazin nephelometric unit (FNU) prior- and post-storm in areas between Station #9 and #30 in East Bay) or recovered to pre-storm (14 October) level at the time of our sample collection on 16 and 17 October for some eastern areas (e.g. daily average from ~35 FNU on 15 October to ~7 FNU for both prior- and post-storm in areas near Station # 26 in St. Vincent Sound). Meanwhile, there was no phytoplankton bloom observed during field sampling after the storm. We also examined the MODIS reflectance data in Bands 1 and 2 from the image of October 13 (some areas of the Apalachicola Bay were cloud-free) with similar tidal and weather conditions as 14 October and working image (17 October). We found that there were no significant differences (<10% for the compared cloud-free Bay area) in the reflectance data between the two images. These examinations indicated that the 17 October image could be used to represent the water quality conditions during the period of field sample collection for 2002. For 2006, we selected the 4 April image (MOD02QKM.A2006094.1640.005.2006096190829.hdf) because the image was the only cloud-free one in 3–5 April, and the majority of the samples were collected on that day (eight out of 11 samples). In addition, tidal and weather conditions on 3, 4 and 5 April were similar (or sunny and mild with a refreshing breeze); therefore TSS and chlorophyll-*a* would remain relatively stable.

2.4 *Image preprocessing*

We used the ENVI v4.2 (Research Systems, Inc. Boulder, CO; http://www.RSInc.com/envi) software program to preprocess the MODIS data. The preprocessing included geometric correction, the 'bow-tie' correction, and atmospheric correction. MODIS uses a whiskbroom scanner with a maximum scan angle of 55° to either side of the flight line. This MODIS configuration makes the leading edge of one scan overlay the trailing edge of the next scan at scan angles greater than 24° from nadir. The overlap of the adjacent scan lines causes a repetition of features in the image at every 10th scan line. This effect is referred to as the 'bow-tie' effect and has to be corrected to restore the original geometry (Wolfe *et al*. 1998). First, we used the 'Georeference MODIS' and 'bow tie correction' functions in ENVI v4.2 to georectify the MODIS data and correct for 'bow tie' effects. The corrected MODIS 2-band data are in UTM zone 16N projection and WGS 84 datum. Secondly, we subset the imagery to focus on the Apalachicola Bay area (covering 29° 33′–29° 48′N, 84° 33′–85° 17′W). Thirdly, we used the image-based 'dark object subtract (DOS)' method to remove the atmospheric influences based on the assumption that the aerosol type and size distribution does not change over the distance from which the dark pixel is selected (Miller and McKee 2004). This technique is simple but can successfully account for scattering in the shorter wavelength bands including the MODIS Band 1 (red band), although it is less accurate in the infrared region, and has been successfully used in some coastal waters in the northern Gulf of Mexico (e.g. Miller and McKee 2004). The minimum reflectance values in each band were used for the dark-pixel subtraction. Fourth, we identified any bad lines in the 2002 MODIS data and applied the 'replace bad lines' method to improve the quality of the MODIS data. Lastly, we identified the water area of Apalachicola Bay as our region of interest (ROI) and used this ROI to build a mask (1: for ROI, 0 for land and outside the bay) based on Band 2 reflectance. The mask separated water pixels from land pixels when applied to the subset images of 17 October 2002 and 4 April 2006. The MODIS pixel reflectance values corresponding to the field sample locations were recorded for the analysis of the relationship between reflectance and water quality parameters (i.e. chlorophyll-*a* concentration and TSS).

2.5 *Regression and mapping*

In the regression analysis, we logarithmically transformed data of chlorophyll-*a* concentration and TSS, our dependent variables. Our three independent variables were: reflectance of a single band or band ratio, logarithmically transformed band ratio (or $\log_{10}[b_2/b_1]$), and ratio of logarithmically transformed single band (or $\log_{10}(b_2)/\log_{10}(b_1)$). The coefficient of determination, R^2, was used to select the best models for estimating chlorophyll-*a* concentration and TSS in the two time periods. Then the best models for chlorophyll-*a* concentration and TSS were used for the water quality mapping using MODIS imagery. Maps showing the spatial patterns of chlorophyll-*a* concentration and TSS in Apalachicola Bay were generated using ‘band math’ in ENVI. Finally, we computed difference maps for chlorophyll-*a* concentration and TSS during the two periods to examine the temporal variations in chlorophyll-*a* concentration and TSS in Apalachicola Bay, Florida.

3. Results

3.1 *Relationships between chlorophyll-*a* concentration, TSS and surface reflectance*

Regression models indicated that there are significant relationships between MODIS surface reflectance and TSS and chlorophyll-*a* concentration during 14–17 October 2002, a relatively dry period and 3–5 April 2006, a relatively wet period in Apalachicola Bay. The best models for chlorophyll-*a* concentration and TSS for October 2002 were the linear equations with logarithmically transformed chlorophyll-*a* concentration, TSS, and the ratio of Band 2:Band 1 (logarithmically transformed) (figures 2(*a*) and 2(*c*)), while the best model for April 2006 was described by the exponential relationship between chlorophyll-*a* concentration and the reflectance in Band 1 as well as the logarithmically transformed TSS and the two logarithmically transformed bands (figures 2(*b*) and 2(*d*)). The equations determining the reflectance–water quality relationships are listed below.

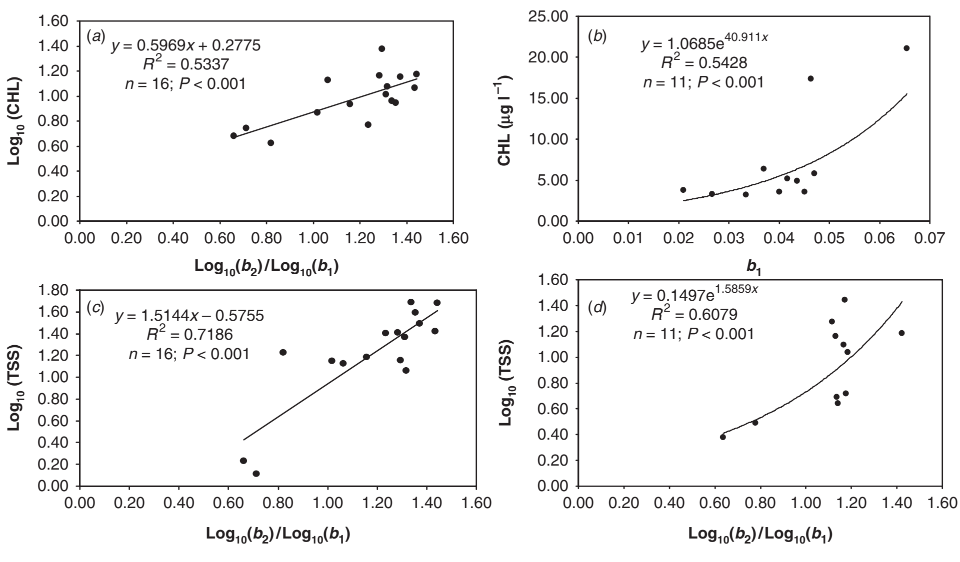

Figure 2. The best regression models ($p < 0.001$) for chlorophyll-*a* concentrations in: (*a*) October 2002 and (*b*) April 2006; and TSS in: (*c*) October 2002 and (*d*) April 2006 using MODIS 250 m bands for Apalachicola Bay, Florida.

For chlorophyll-*a* concentration in the dry period:

$$\log_{10}(\mathrm{CHL}) = .5969[\log_{10}(b_2)/\log_{10}(b_1)] + 0.2775; \\ (R^2 = 0.53, n = 16, p < 0.001), \tag{1}$$

for chlorophyll-*a* concentration in the wet period:

$$\mathrm{CHL} = 1.0685\mathrm{e}^{[40.911(b_1)]}; (R^2 = 0.54, n = 11, p < 0.001), \tag{2}$$

for TSS in the dry period:

$$\log_{10}(\mathrm{TSS}) = 1.5144[\log_{10}(b_2)/\log_{10}(b_1)] - 0.5755; \\ (R^2 = 0.72, n = 16, p < 0.001), \tag{3}$$

and for TSS in the wet period:

$$\log_{10}(\mathrm{TSS}) = 0.1497\mathrm{e}^{\{1.5859[\log_{10}(b_2)/\log_{10}(b_1)\}}; \\ (R^2 = 0.61, n = 11, p < 0.001), \tag{4}$$

where CHL is chlorophyll-*a* concentration, b_1 and b_2 are reflectance of MODIS Band 1 (620–670 nm) and Band 2 (841–876 nm), respectively.

3.2 *Spatial variability in chlorophyll-*a *concentration and TSS*

The MODIS-derived spatial patterns of chlorophyll-*a* concentration and TSS in Apalachicola Bay during the two periods are shown in figures 3(*a*), 3(*b*), 4(*a*) and 4(*b*). For October 2002, high chlorophyll-*a* concentrations (>14 μg l^{-1}) were found near West Pass and south-western St. George Sound, whereas low chlorophyll-*a* concentrations (<8 μg l^{-1}) were found in the Apalachicola River and eastern part of East Bay (figure 3(*a*)). This pattern can be attributed to the storm on 15 October 2002 that resulted in the re-suspension of sediments and associated benthic algae caused by the wind driven mixing of the water column. Wind action in the shallow Apalachicola Bay System is associated with periodic peaks of phytoplankton production because of turbulent mixing of sediment inorganic nutrients into the euphotic zone (Iverson *et al.* 1997, Livingston 2006). For April 2006, high chlorophyll-*a* concentrations (>15 μg l^{-1}) were found in East Bay, near St. Vincent Sound and along shorelines, whereas low chlorophyll-*a* concentrations (<4 μg l^{-1}) were found in the middle of Apalachicola Bay and St. George Sound (figure 3(*b*)). This pattern of high chlorophyll-*a* concentrations in East Bay and low concentrations in other areas, such as the middle portion of the Bay and St. George Sound, is representative of the distribution of chlorophyll-*a* concentration without any severe disturbances such as hurricanes and heavy storms. The high chlorophyll-*a* concentrations in East Bay, near river mouth, along shorelines, and near St. Vincent Sound reflect the higher phytoplankton growth that is likely caused by nutrient additions of the run-off from Tate's Hall watershed and discharge from the Apalachicola River. The high concentration of chlorophyll-*a* near St. Vincent Sound may be associated with the stronger tidal mixing, the long wind fetch along the axis of the Bay, and dynamic surface winds from the east and west directions, which play a significant role in most of the volume exchanges between the Bay and the Gulf, as well as salinity variations within the Bay (Huang *et al.* 2002).

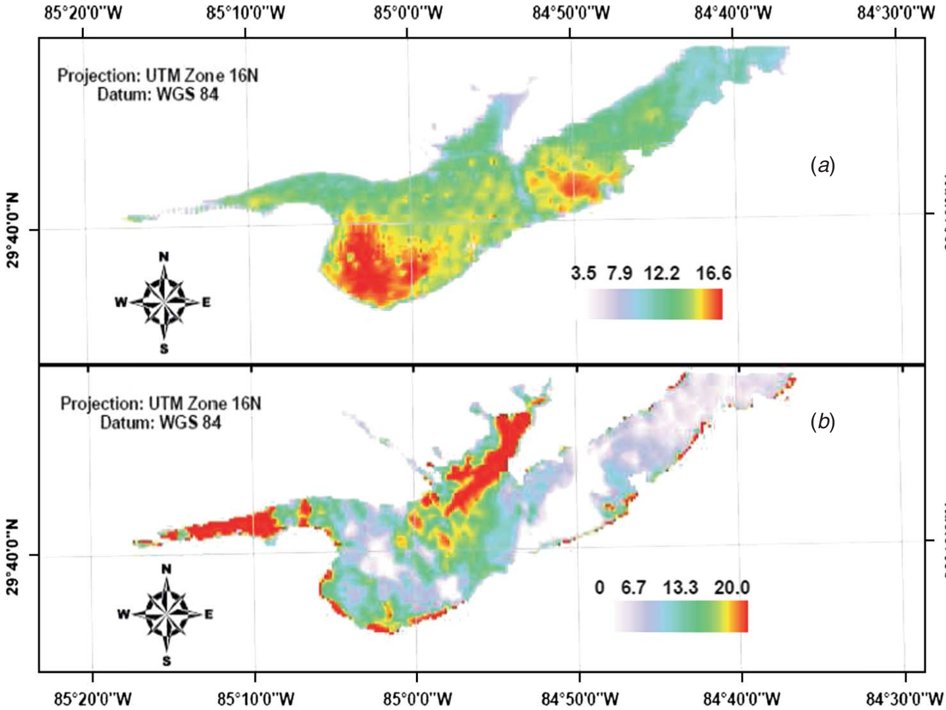

Figure 3. Maps of chlorophyll-*a* concentration (μg l^{-1}) on 17 October 2002 (*a*) and 4 April 2006 (*b*) in Apalachicola Bay, Florida.

Unlike the spatial patterns in chlorophyll-*a* concentrations, which are regulated by not only physical factors such as wind, river flow, turbulent eddies, tidal and topographic fronts, but also factors such as light, temperature, nutrients (e.g. nitrogen and phosphorus) as well as biological factors such as zooplankton grazing (Iverson *et al.* 1997, Livingston 2006), the spatial patterns in Bay-wide TSS tend to be largely impacted by physical factors such as wind, tides, river flow as well as the physical settings of bay bottom topography. The modelling study of Huang *et al.* (2002) indicated that wind plays an important role in the transport process in Apalachicola Bay. A plot of wind speed for 14–21 October 2002 is presented in figure 5 showing that north wind was dominant during 16–17 October 2002. Strong wind occurred on 16 October 2002 at 4 m s^{-1} and caused sediment re-suspension in the Bay. On 17 October 2002, wind speed reduced to about 2 m s^{-1}, which resulted in settling of suspended sediments. However, north winds pushed higher sediment water to the south, resulting in elevated TSS in the southern area near West Pass (figure 4(*a*)). The 4 April 2006 date was a less windy and sunny day. Higher (>20 mg l^{-1}) TSS concentrations were found in the south-western part of St. George Sound and near West Pass, two areas near shallow oyster bars (figure 4(*b*)). This is mainly because of the features of the physical settings of the Bay, as water depths are shallower in these high TSS areas than in other parts of the Bay and sediments can be easily re-suspended by tidal forcing, although we did observe a wind-driven high TSS (38.1 mg l^{-1}, not used for April 2006 modelling and mapping in one station at 16:10 h on 3 April 2004, during high winds, compared with our other stations). This re-suspension driven by tide and the Bay's physical setting might be an important mechanism for bay-wide TSS patterns with less influence from wind forcing.

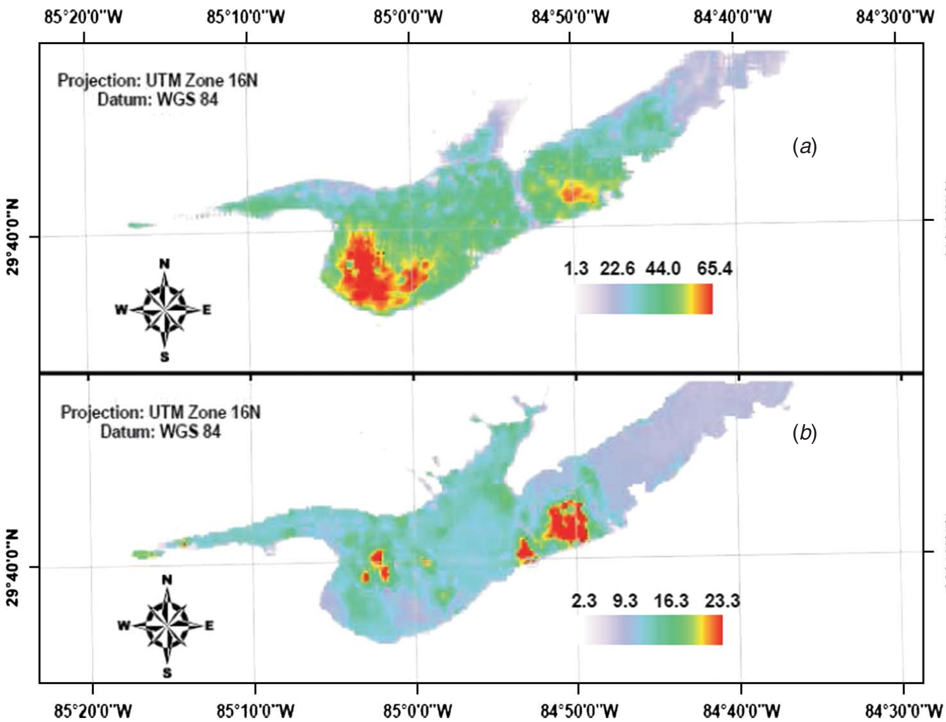

Figure 4. Maps of TSS (mg l^{-1}) on 17 October 2002 (*a*) and 4 April 2006 (*b*) in Apalachicola Bay, Florida.

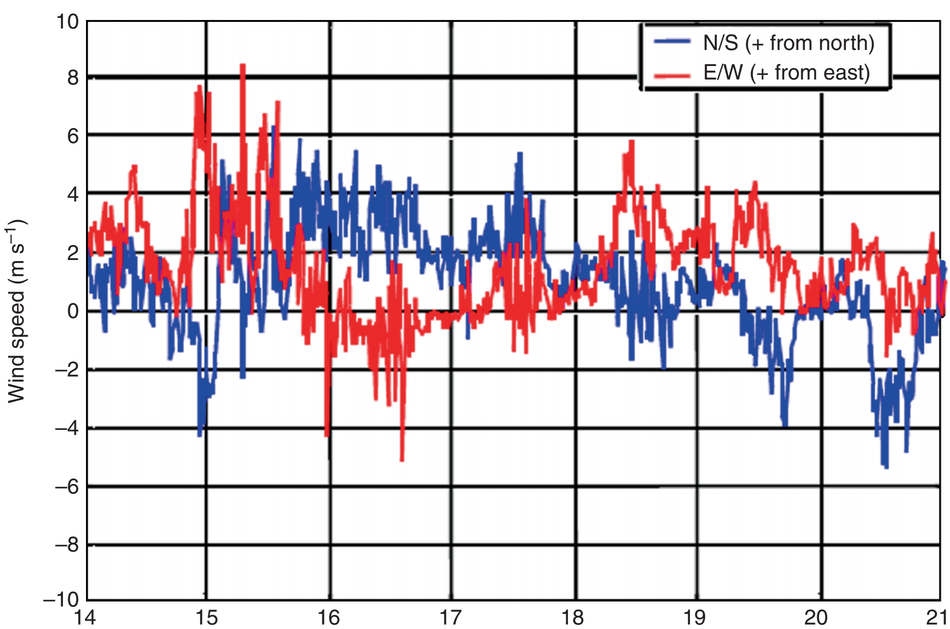

Figure 5. Dynamics of wind speed (m s^{-1}) during 14–21 October 2002 in Apalachicola Bay, Florida.

3.3 *Temporal variability in chlorophyll-*a *concentration and TSS*

The change maps of chlorophyll-*a* concentration and TSS for these two periods are used to examine the Bay-wide temporal variations in chlorophyll-*a* concentration and TSS. For most areas of the Bay, chlorophyll-*a* concentration tends to be higher in October 2002, a relatively dry period, than in April 2006, a relatively wet period (figure 6(*a*)). Our results are consistent with the monitoring data in Apalachicola Bay, which showed that the distributions of chlorophyll-*a* concentration tends to be bimodal, with two high chlorophyll-*a* concentrations in summer and fall in large areas of the Bay (NOAA/OCRM/SWMP 2006). This temporal variation is possibly caused by the accumulation of phytoplankton promoted by lower river inputs and long water residence time, as well as the increased growth of phytoplankton by relatively higher water temperature and light availability in October 2002 than in April 2006, although these conditions can also lead to limitation of phytoplankton growth as a result of low dissolved inorganic nitrogen (DIN) concentration (Iverson *et al*. 1997, Gameiro *et al*. 2004). In contrast, the chlorophyll-*a* concentration in East Bay and St. Vincent Sound tends to be higher in April 2006 than that in October 2002 (figure 6(*a*)). This might be because of the comprehensive impacts of freshwater flows, storms, tides and winds, as well as changes in upland land use and land cover by agricultural activities and urban development in upland floodplains and watersheds. For example, this winter–spring maximum of chlorophyll-*a* concentration was observed to be coincident with low salinity observations by high freshwater inflows

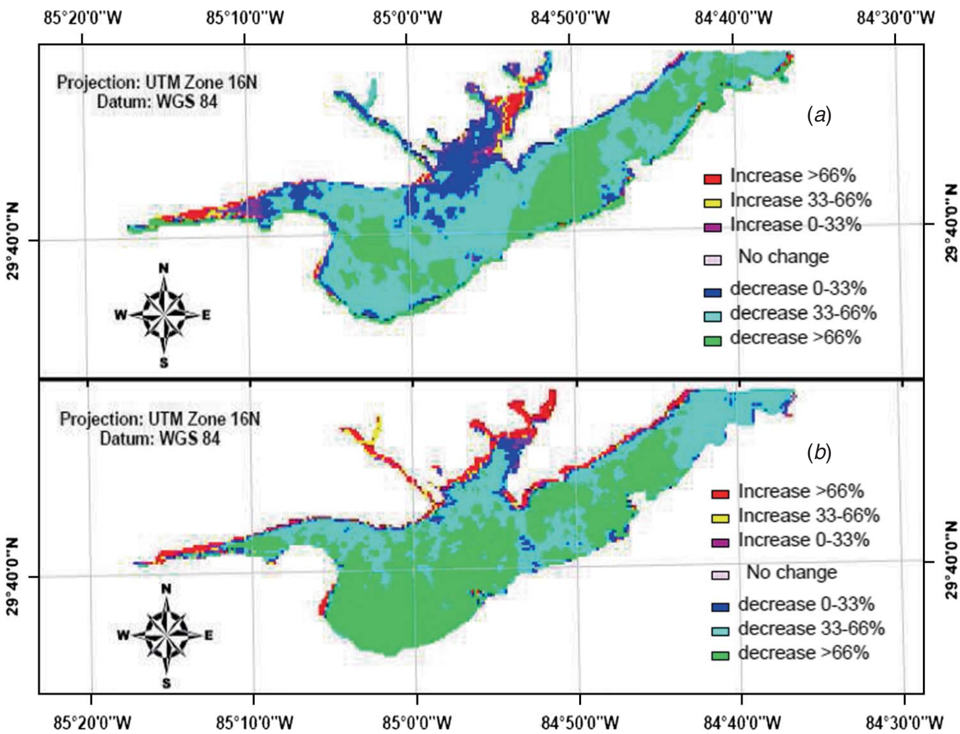

Figure 6. Maps of changes in (*a*) chlorophyll-*a* concentration and (*b*) TSS from 17 October 2002 to 4 April 2006 in Apalachicola Bay, Florida.

that transfer more nutrients and organic matter (e.g. washing floodplain detritus into the East Bay) in Apalachicola Bay during May 1995 to April 1996 (Pennock *et al.* 1999, Livingston 2006). This high winter–spring chlorophyll-*a* concentrations can also be attributed to low zooplankton grazing during the cooler months (Iverson *et al.* 1997). Information on the spatial distribution of chlorophyll-*a* concentration is useful for oyster management. The low chlorophyll-*a* concentration in April 2006 in waters at Cat Point (near Station #14) in St. George Sound and Dry Bar (near Station # 26) in middle Apalachicola Bay (figure 1) might explain the lower oyster production in these oyster bars in the spring than in summer (Ingle 1950, Livingston *et al.* 2000, Wang *et al.* 2008). For example, Wang *et al* (2008) found, both from model simulations and field experiment, that oyster growth rates tend to be less than 1 mg ash-free dry weight (AFDW) per oyster per day at both oyster bars during springtime when food (indicated by chlorophyll-*a* concentration) levels are low, much lower than growth rates ($\sim$ 2–6 mg AFDW per oyster per day) during summer time when food levels are normally high. It should be noted that there are also inter-annual variations in chlorophyll/phytoplankton biomass (Livingston 2006), leading to the increased complexity in spatial and temporal patterns in chlorophyll in the Apalachicola Bay System.

Similar to the change map of chlorophyll-*a* concentration, TSS concentrations also tend to be higher in October 2002 than in April 2006 for most areas of the Bay, whereas TSS tends to be higher in April 2006 than in October in Apalachicola River, some areas of the East Bay, and along coastal lines (figure 6(*b*)). The higher TSS in October 2002 than in April 2006 in most areas of the Bay is the reflection of the difference in wind-driven and tidally-driven mechanisms (Huang *et al.* 2002). On the other hand, the higher TSS in April 2006 than in October 2002 in some areas in the Bay is probably because of the relatively higher freshwater flows and rainfall in the upland watersheds in April 2006 than in October 2002 (data not shown) that may transport more sediment in these areas. This riverine source of sediments is another important mechanism influencing TSS in areas near rivers/creeks/tributary and close to upland systems. Operations of the Lake Seminole reservoir on the Georgia and Florida border may also affect TSS patterns.

4. Discussion

Our regression analysis demonstrated that MODIS 250 m data (Band 1: 620–670 nm and Band 2: 841–876 nm, corresponding to red and near-infrared bands) are sensitive and sufficient for detecting spatial and temporal variations in chlorophyll-*a* concentrations and TSS in shallow coastal and estuarine waters in the northern Gulf of Mexico, as previous studies have shown (e.g. Miller and McKee 2004). For our study periods (October 2002 and April 2006), MODIS 250 m data could explain $\sim$ 54% of the variations in chlorophyll-*a* concentrations and 61–72% of the variations in TSS in Apalachicola Bay (figure 2). Our analysis indicated that MODIS 250 m data are more effective in detecting spatial patterns of TSS than detecting chlorophyll-*a* concentrations. This is because the optical property of TSS is affected mostly by physical factors whereas the optical property of chlorophyll-*a* concentration is affected by multiple physical and biological factors (Hladik 2004, Zhu *et al.* 2004, 2005). The best regression models for chlorophyll-*a* concentration and TSS and MODIS reflectance in this research are in different forms (linear versus exponential; single band, band ratios versus logarithmically transformed data) for the two periods, indicating that the two water quality variables, especially chlorophyll-*a* concentration, tend to vary with seasonality. Previous studies have also shown the seasonality of chlorophyll-*a* concentration in estuaries (e.g. Zhu *et al.* 2004, 2005). Therefore, the relationships between MODIS data and chlorophyll-*a* concentration and TSS in a fine temporal scale (e.g. monthly) should be studied based on collecting MODIS data and field data at a fine temporal scale in future.

It has been found that the majority of algorithms for turbid waters utilize longer wavelengths in the red and near-infrared regions to quantify chlorophyll-*a* concentrations and TSS (see review by Hladik 2004). A field spectral study using the October 2002 water quality data and hyperspectral band reflectance (spectral range of 350–1050 nm with bandwidth per channel 1.5 nm) collected using a pair of Ocean Optics USB 2000 spectrometers (Ocean Optics, Inc., Dunedin, FL) in Apalachicola Bay has shown that a wavelength range of 500–700 nm is very sensitive to changes in water quality parameters, specifically chlorophyll-*a* concentration and TSS (Hladik 2004, Schalles 2006). While the maximum sensitivity was near 670 nm, wavelengths between 620 and 670 nm can effectively separate the contributions of chlorophyll-*a* concentration and TSS to spectral reflectance. Additionally, there were positive relationships between reflectance and chlorophyll-*a* concentration and TSS in the wavelength range 620–670 nm (Hladik 2004). Another field spectroscopic study of estuarine waters examining the relationship between near surface (0.5 m depth) TSS and reflectance in the interval 400–1100 nm (bandwidth: 2.8 nm) also indicated that reflectance increases with an increase in TSS (Doxaran *et al.*, 2002). The largest increase was observed between 600 and 700 nm for TSS concentrations in the range of 13–62 mg l^{-1}, and from 700 to 900 nm for TSS in the range of 13–985 mg l^{-1} (Doxaran *et al.* 2002).

Many factors affect reflectance, and thus the relationships between MODIS reflectance and water quality variables. These factors include sun irradiation, water surface conditions, sun elevation and taxonomic composition of the phytoplankton, pigment package effect, the particle size distribution of tripton, and the concentration of coloured dissolved organic matter (CDOM) (Gordon and Morel 1983, Hladik 2004). There is a minimum in reflectance near 670 nm because the maximum absorption of chlorophyll-*a* and the resultant trough are relatively sensitive to changes in chlorophyll-*a* at concentrations less than 20 μg l^{-1} (Hladik 2004). Given that the chlorophyll-*a* concentrations in our study are below 25 μg l^{-1}, this trough might have a significant impact on the chlorophyll-*a* models. Furthermore, higher TSS levels amplified reflectance and higher CDOM values suppressed reflectance (Hladik 2004, Schalles 2006). Finally, it should be noted that the 'bottom effects' and 'edge effects' on reflectance should be considered and therefore cautions should be taken when interpreting the MODIS-derived maps of water quality factors and their changes.

5. Conclusions

The remote sensing technique is suitable to examine the spatial and temporal variations in water quality variables. In this research, we established regression models for detecting chlorophyll-*a* concentration and TSS in Apalachicola Bay using reflectance of two MODIS 250 m bands. The MODIS-derived maps of chlorophyll-*a* concentration and TSS distributions during October 2002, a dry period, and April 2006, a wet period, revealed large spatial and temporal variations in chlorophyll-*a* concentration and TSS across the entire Apalachicola Bay. The Bay-wide spatial and temporal heterogeneities in chlorophyll-*a* concentrations are largely controlled by not only physical factors such as wind, river flow, turbulent eddies, tidal and topographic fronts, but also additional factors such as light, temperature, nutrients as well as biological factors such as zooplankton grazing. The Bay-wide spatial and temporal heterogeneities in TSS are primarily driven by physical factors such as wind, tidal forcing, freshwater flows, storms/hurricanes as well as upland land use and land cover changes and tend to show a quick response to changes in these environmental factors. This research is limited by the high cost in labour and time for field sampling and data collection (i.e. only two time periods). More field sampling and data collection in both spatial (i.e. more bay-wide monitoring stations) and temporal scale (i.e. more time periods) are needed to improve the MODIS reflectance-water quality models in the future. This research is important in that it can help us to identify sensitive and vulnerable areas for detailed study, management, or restoration, if necessary, in the Apalachicola Bay system.

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References

American Public Health Association, 1998, *Standard Methods for the Examination of Water and Wastewater*, 20th edn (Washington, DC: American Public Health Association).

Baban, S.M.J., 1997, Environmental monitoring of estuaries; estimating and mapping various environmental indicators in Breydon Water Estuary, U.K., using Landsat TM Imagery. *Estuarine, Coastal, and Shelf Science*, **44**, pp. 589–598.

Dardeau, M.R., Modlin, F.R., Schroeder, W.W. and Stout, J.P., 1992, Estuaries. In *Biodiversity of the Southeastern United States*, C.T. Hackney, S.M. Adams, and W.H. Martin (Eds.), pp. 614–744 (New York, NY: John Wiley & Sons).

Dekshenieks, M.M., Hofmann, E.E., Klinck, J.M. and Powell, E.N., 2000, Quantifying the effects of environmental change on an oyster population: a modeling study. *Estuaries*, **23**, pp. 593–610.

Doxaran, D., Froidefond, J.M. and Castaing, P., 2002, A reflectance band ratio used to estimate suspended matter concentrations in sediment-dominated coastal waters. *International Journal of Remote Sensing*, **23**, pp. 5079–5085.

Gameiro, C., Cartaxana, P., Cabrita, M.T. and Brotas, V., 2004, Variability in chlorophyll and phytoplankton composition in an estuarine system. *Hydrobiologia*, **525**, pp. 113–124.

Gordon, H. and Morel, A., 1983, *Remote Assessment of Ocean Color for Interpretation of Satellite Visible Imagery, a Review* (New York, NY: Spinger-Verlag).

HAN, L. and JORDAN, K.J., 2005, Estimating and mapping chlorophyll-a concentration in Pensacola Bay, Florida using Landsat ETM+ data. *International Journal of Remote Sensing*, **26**, pp. 5245–5254.

HLADIK, C.M., 2004, An evaluation of chlorophyll-a bio-optical algorithms and development of an improved algorithm. M.Sc. Thesis. Environmental Science Program, Creighton University, Omaha, NE, USA.

HUANG, W., JONES, W.K. and WU, T.S., 2002, Modeling wind effects on subtidal salinity in Apalachicola Bay, Florida. *Estuarine, Coastal and Shelf Science*, **55**, pp. 33–46.

INGLE, R.M., 1950, Summer growth of the American Oyster in Florida waters. *Science*, **112**, pp. 338–339.

IVERSON, R.L., LANDING, W., MORTAZAWI, B. and FULMER, J., 1997, Nutrient transport and primary productivity in the Apalachicola River and Bay. Report to the ACF/ACT Comprehensive Study. Northwest Florida Water Management District, Havana, Florida. Unpublished Report.

LI, R.R., KAUFMAN, Y.J., GAO, B.C. and DAVIS, D.O., 2003, Remote sensing of suspended sediments and shallow coastal waters. *IEEE Transactions Geoscience and Remote Sensing*, **41**, pp. 559–566.

LIVINGSTON, R.J., 2006, *Restoration of Aquatic Systems* (Boca Raton, FL: CRC Press).

LIVINGSTON, R.J., LEWIS, F.G., WOODSUM, G.C., NIU, X.F., GALPERIN, B., HUANG, W., CHRISTENSEN, J.D., MONACO, M.E., BATTISTA, T.A., KLEIN, C.J., HOWELL IV, R.L. and RAY, G.L., 2000, Modeling oyster population response to variation in freshwater input. *Estuarine, Coastal and Shelf Science*, **50**, pp. 655–672.

MCKEE, B.A. and BASKARAN, M., 1999, Sedimentary processes of Gulf of Mexico estuaries. In *Biogeochemistry of Gulf of Mexico Estuaries*, T.S. Bianchi, J.R. Pennock, and R.R. Twilley (Eds), pp. 63–85 (New York, NY: John Wiley & Sons).

MILLER, R.L. and MCKEE, B.A., 2004, Using MODIS Terra 250 m imagery to map concentrations of total suspended matter in coastal waters. *Remote Sensing of Environment*, **93**, pp. 259–266.

MILLER, R.L., DEL CASTILLO, C.E., CHILMAKURI, C., MCCORQUODALE, A., GEORGIOU, I., MCKEE, B.A. and D'SA, E.J., 2005, Using multi-temporal MODIS 250 m data to calibrate and validate a sediment transport model for environmental monitoring of coastal waters. In *3rd International Workshop on the Analysis of Multi-Temporal Remote Sensing Images*, 16–18 May 2005, Biloxi, Mississippi, USA, pp. 200–204.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, OFFICE OF OCEAN AND COASTAL RESOURCE MANAGEMENT, NATIONAL ESTUARINE RESEARCH RESERVE SYSTEM-WIDE MONITORING PROGRAM (NOAA/OCRM/SWMP), 2006, Centralized Data Management Office, Baruch Marine Field Lab, University of South Carolina. Available online at: http://cdmo.baruch.sc.edu (accessed 25 September 2009).

PENNOCK, J.R., BOYER, J.N., HERRERA-SILVEIRA, J.A., IVERSON, R.L., WHITLEDGE, T.E., MORTAZAVI, B. and COMIN, F.A., 1999, Nutrient behavior and phytoplankton production in Gulf of Mexico estuaries. In *Biogeochemistry of Gulf of Mexico Estuaries*, T.S. Bianchi, J.R. Pennock, and R.R. Twilley (Eds), pp. 109–162 (New York, NY: John Wiley & Sons).

SANGER, D.M., ARENDT, M.D., CHEN, Y., WENNER, E.L., HOLLAND, A.F., EDWARDS, D. and CAFFREY, J., 2002, A synthesis of water quality data: Estuarine research reserve system-wide monitoring program (1995–2000), National Estuarine Research Reserves Technical Report Series 2002: 3. South Carolina Department of Natural Resources, Marine Resources Division Contribution No. 500. 135 p.

SCHALLES, J.F., 2006, Optical remote sensing techniques to estimate phytoplankton chlorophyll a concentrations in coastal waters with varying suspended matter and CDOM concentrations. In *Remote Sensing of Aquatic Coastal Ecosystem Processes: Science and Management Applications*. L.L. Ricardson and E.F. LeDrew (Eds), pp. 27–80 (Dordrecht, The Netherlands: Springer).

Wang, H., Huang, W., Harwell, M.A., Edmiston, L., Johnson, E., Hsieh, P., Milla, K., Christensen, J., Stewart, J. and Liu, X., 2008, Modeling oyster growth rate by coupling oyster population and hydrodynamic models for Apalachicola Bay, Florida, USA. *Ecological Modeling*, **211**, pp. 77–89.

Wolfe, R.E., Roy, D.P. and Vermote, E., 1998, MODIS land data storage, gridding, and compositing methodology: Level 2 grid. *IEEE Transactions Geoscience and Remote Sensing*, **36**, 1324–1338.

Zhang, Y., Koponen, S.S., Pulliainen, J.T. and Halikainen, M.T., 2003, Application of empirical neural network to chlorophyll-*a* estimation in coastal waters using remote optosensors. *IEEE Sensors Journal*, **3**, pp. 376–382.

Zhu, L., Wang, S., Zhou, Y., Yann, F. and Zhou, W., 2004, Water quality monitoring in Taihu Lake using MODIS image data. In *Proceedings of the Geoscience and Remote Sensing Symposium (IGARSS'04)*, 20–24 September 2004, Anchorage, Alaska, pp. 2314–2317.

Zhu, L., Wang, S., Zhou, Y., Yang, F. and Wang, L., 2005, Determination of chlorophyll-a concentration changes in Taihu Lake, China using multi-temporal MODIS image data. In *Proceedings of the Geoscience and Remote Sensing Symposium (IGARSS'05)*, 25–29 July 2005, pp. 4535–4538.