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Use of Landsat data to track historical water quality changes in Florida Keys marine environments

Brian B. Barnes [a,*], Chuanmin Hu [a], Kara L. Holekamp [b,c], Slawomir Blonski [b,d], Bruce A. Spiering [e], David Palandro [f], Brian Lapointe [g]

[a] College of Marine Science, University of South Florida, 140 7th Ave South, St. Petersburg, FL 33701, USA
[b] Science Systems & Applications, Inc., Stennis Space Center, MS, USA
[c] Innovative Imaging & Research, Stennis Space Center, MS, USA
[d] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA
[e] NASA Applied Science & Technology Project Office, Stennis Space Center, MS, USA
[f] ExxonMobil Upstream Research Company, Houston, TX, USA
[g] Harbor Branch Oceanographic Institute, Florida Atlantic University, Fort Pierce, FL, USA

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A B S T R A C T

Satellite remote sensing has shown the advantage of water quality assessment at synoptic scales in coastal regions, yet modern sensors such as SeaWiFS or MODIS did not start until the late 1990s. For non-interrupted observations, only the Landsat series have the potential to detect major water quality events since the 1980s. However, such ability is hindered by the unknown data quality or consistency through time. Here, using the Florida Keys as a case study, we demonstrate an approach to identify historical water quality events through improved atmospheric correction of Landsat data and cross-validation with concurrent MODIS data. After aggregation of the Landsat-5 Thematic Mapper (TM) 30-m pixels to 240-m pixels (to increase the signal-to-noise ratio), a MODIS-like atmospheric correction approach using the Landsat shortwave-infrared (SWIR) bands was developed and applied to the entire Landsat-5 TM data series between 1985 and 2010. Remote sensing reflectance (R_{RS}) anomalies from Landsat (2 standard deviations from a pixel-specific monthly climatology) were found to detect MODIS R_{RS} anomalies with over 90% accuracy for all three bands for the same period of 2002–2010. Extending this analysis for the entire Landsat-5 time-series revealed R_{RS} anomaly events in the 1980s and 1990s, some of which are corroborated by known ecosystem changes due in part to changes in local freshwater flow. Indeed, TM R_{RS} anomalies were shown to be useful in detecting shifts in seagrass density, turbidity increases, black water events, and phytoplankton blooms. These findings have large implications for ongoing and future water quality assessment in the Florida Keys as well as in many other coastal regions.

1. Introduction

One of the challenges in remote sensing is placing measurements in the context of events before and after the life of an instrument. Several studies have compared the data of multiple satellite instruments in efforts to extend the time series of remotely sensed data (e.g., Maritorena & Siegel, 2005), occasionally finding significant disagreement in both time and space (e.g., Franz, 2003; Kwiatkowska, 2003). Even so, temporal gaps exist during which little to no satellite data are available. For ocean color remote sensing, which has been shown to be particularly useful in assessing optical water quality of coastal waters, such a data gap exists after the Coastal Zone Color Scanner (CZCS) stopped functioning in early 1986 and before the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was launched in late 1997.

Throughout this gap, however, satellites dedicated to land study continued to collect multi-spectral radiance data over coastal waters. The Landsat program began in 1972, and through eight satellites has maintained a nearly continuous record of satellite data for land and adjacent coastal waters. Landsat-5 (1984–2011) housed a Thematic Mapper (TM) sensor, which measured radiance with 30 m spatial resolution for 6 bands (three visible, three infrared), and thermal infrared (TIR) radiation at 120 m resolution. Each Landsat satellite has a polar earth orbit, crossing the equator at approximately 10:00 am local time with 185 km Earth-viewing swath width. As a result, repeat sampling for a particular location occurs at 16-day intervals. Although its primary purpose is for use over land, Landsat data collected over coastal and inland waters have been used with varying success to detect features including eddies (Ahlnäs, Royer, & George, 1987), phytoplankton blooms (Ekstrand, 1992), freshwater discharges (Lapointe, Matzie, & Clark, 1993), floating algae (Hu, 2009), cyanobacteria blooms (Vincent et al., 2004), water quality (Dekker & Peters, 1993; Giardino, Pepe, Brivio, Ghezzi, & Zilioli, 2001; Olmanson, Bauer, & Brezonik, 2008;

* Corresponding author. Tel.: +1 727 553 3952.
E-mail address: bbarnes4@mail.usf.edu (B.B. Barnes).

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Wang, Xia, Fu, & Sheng, 2004), sea surface temperatures (Thomas, Byrne, & Weatherbee, 2002), and coral community changes (Palandro, Andrefouet, Muller-Karger, & Dustan, 2001; Palandro et al., 2008), among others.

Since 2000 and 2002, respectively, the Moderate Resolution Imaging Spectroradiometers (MODIS) aboard the U.S. National Aeronautics and Space Administration (NASA)'s polar orbiting satellites Terra and Aqua (MODIST and MODISA) have provided near-daily measurements of radiance over the world's oceans after the CZCS (1978–1986) and SeaWiFS (1997–2010) eras. Most MODIS bands cover a spectral bandwidth of 10–20 nm with the spatial resolution of 250 m–1000 m. Aqua ascends across the equator at approximately 1:30 pm local time for daytime passes with a swath width of 2330 km, while Terra descends across the equator at 10:30 am local time with the same swath width.

Despite significant differences in the spectral and spatial resolutions as well as in the signal-to-noise ratios (SNR) between MODIS and TM (Hu et al., 2012), similarities in their spectral band positions indicate the potential for filling the 1986–1997 historical data gap using Landsat TM. The satellites housing these instruments all orbit at an altitude of 705 km with nearly identical inclination (98.20° for Landsat 5, 98.14° for Aqua). The TM visible band centers (485, 560, and 660 nm for bands 1, 2, and 3) roughly correspond to those of MODIS bands 10, 4, and 13 (centers at 488, 555, and 667 nm; Fig. 1). For simplicity, these corresponding bands for both sensors are termed 'blue', 'green' and 'red,' respectively. Despite these similar band centers, there are large differences in spectral resolution between these TM (~70 nm) and MODISA bands (10–20 nm).

The narrow swath width of the Landsat TM measurements (185 km) every 16 days and the much wider swath of MODIS measurements (2330 km) every 1–2 days mean that nearly every Landsat image has a corresponding MODIS image on the same day. Although Terra coincides more closely with Landsat overpass times, significant residual errors due to striping and scan mirror damage limit MODIST data applicability for ocean color research (Franz, Kwiatkowska, Meister, & McClain, 2008). However, MODISA has provided quality data since 2002. It is therefore desirable to validate the quality and accuracy of Landsat TM data using concurrent MODISA data so that water quality data derived from MODISA can be extended to the 1980s.

Our approach to fill the 1986–1997 satellite ocean color gap through cross-validation of TM and MODIS data was motivated by several factors. First, MODIS ocean color bands were designed for research of water targets, while TM was intended for land assessment. As a result, achieving MODIS-quality data from TM imagery (rather than simply using TM data) is preferable for ocean color research. Second, cross-validation of TM with MODISA data will provide high-frequency (albeit low resolution) continuation and supplementation of the Landsat dataset. At the time of this research, Landsat 5 was defunct, and Landsat 7 suffered a scan line corrector (SLC) failure. Although compromised Landsat 7 images can be used to measure water parameters (see Olmanson et al., 2008), the SLC failure effectively reduces repeat sampling frequency. Landsat 8 includes an ocean color band in the blue, but it was only launched recently and its data were not available until 2013. MODIS data could serve as a bridge between these three sensors, and the regular overlap between MODIS and Landsat allows opportunities to assess instrument drift. This is in contrast to the cross-calibration between Landsat sensors, which is completed over a very short time window during which the instruments are placed in parallel orbits (see Teillet et al., 2001). Finally, the high repeat sampling frequency of MODIS sensors allows for creation of monthly or seasonal climatologies, which can be used to compare water quality events to the average condition over the last decade. Alone, the Landsat dataset lacks capacity to place ephemeral water quality features in the context of climatological norms due to the 16 day repeat sampling frequency. Proper cross-validation of these two sensors, however, would allow such assessment of TM detected events, which would significantly enhance our ability to study historical water quality events in coastal waters.

Extending MODIS observations in the 2000s to the 1980s and 1990s using Landsat TM, however, is technically challenging because of the sensors' differences in 1) band width and band positions; 2) radiometric calibration; 3) solar and viewing geometry; 4) SNR; and 5) overpass time. Although one may assume that the difference in their overpass time (2–3 h) may not result in significant changes in either the atmospheric or the water properties, and that the lower SNR in Landsat TM data may be increased by pixel binning, the first three issues must be adequately addressed in order to use Landsat TM data in a similar fashion as with MODISA. Thus, in this study, an approach was developed to overcome the first three obstacles in order to make Landsat data comparable to MODIS and to subsequently assess historical water quality events. For demonstration of this application to use long-term Landsat TM data to study changes of the coastal ocean, we selected a delicate Florida Keys ecosystem that encompasses world renowned coral reefs, beaches, and seagrasses. Such analysis would provide information on the effects of Everglades water management and restoration practices on the water quality of downstream systems. Further, the ability to locate water quality events (in space and time) could provide a record of previous environmental stress and hint at resilience to future stressors for enduring organisms. Specifically, the study had the following objectives:

1) To develop a practical method to construct a long-term time series of atmospherically corrected Landsat TM data, validated for ocean color research;
2) To apply the dataset to identify historical water quality events in the Florida Keys ecosystem.

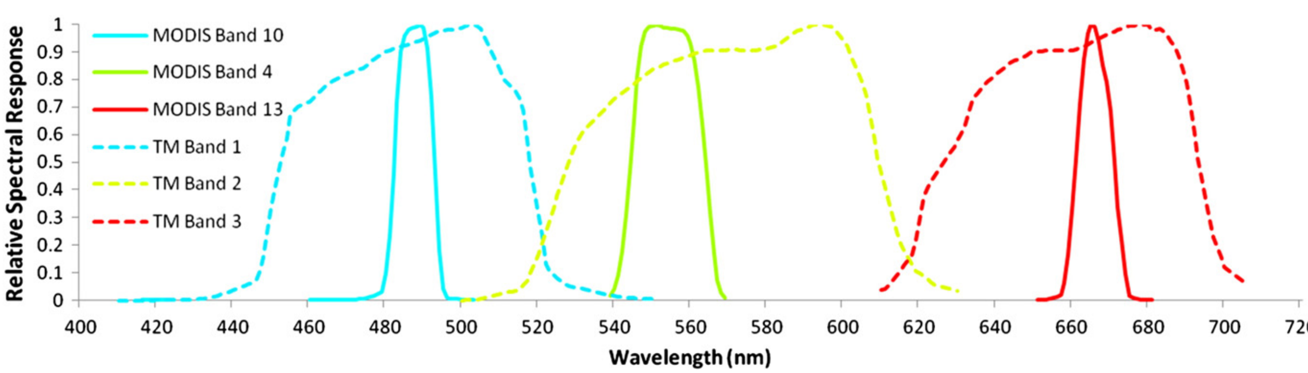

Fig. 1. Relative spectral response functions for Landsat TM bands (dashed) and MODISA bands (solid). Line color represents center wavelength for each band.