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Remote sensing of water clarity in Tampa Bay

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Abstract

We examined the spatial and temporal variability of the Secchi Disk Depth (SDD) within Tampa Bay, Florida, using the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) satellite imagery collected from September 1997 to December 2005. SDD was computed using a two-step process, first estimating the diffuse light attenuation coefficient at 490 nm, $K_d(490)$, using a semi-analytical algorithm and then SDD using an empirical relationship with $K_d(490)$. The empirical SDD algorithm ($SDD=1.04 \times K_d(490)^{-0.82}$, $0.9<SDD<8.0$ m, $r^2=0.67$, $n=80$) is based on historical SDD observations collected by the Environmental Protection Commission of Hillsborough County (EPCHC) in Tampa Bay. SeaWiFS derived SDD showed distinctive seasonal variability, attributed primarily to chlorophyll concentrations and color in the rainy season and to turbidity in the dry season, which are in turn controlled by river runoff and winds or wind-induced sediment resuspension, respectively. The Bay also experienced strong interannual variability, mainly related to river runoff variability. As compared to *in situ* single measurements, the SeaWiFS data provide improved estimates of the "mean" water clarity conditions in this estuary because of the robust, frequent, and synoptic coverage. Therefore we recommend incorporation of this technique for routine monitoring of water quality in coastal and large estuarine waters like Tampa Bay.

Keywords: Remote sensing; Light attenuation coefficient; Water clarity; Secchi disk depth; Bio-optical algorithm; SeaWiFS; Tampa Bay estuary

1. Introduction

Tampa Bay is the largest open-water estuary in Florida, U.S.A., with a surface area of ~1000 km^2. It is traditionally divided into four main sub-segments, namely Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), and Lower Tampa Bay (LTM) (Fig. 1). Tampa Bay is a diverse and productive natural system that provides a vital habitat for crustaceans, fish, shellfish and a variety of marine mammals, reptiles and birds (Harwell et al., 1995), which contributes over $5 billion annually to the economy of the state from trade, tourism, development, and fishing (FDCA, 1996). It is therefore critical that the development of the Bay area be conducted in an environmentally sound way to sustain a healthy system.

In the decades prior to the 1980's, Tampa Bay was heavily polluted by nutrient loadings from sources like sewage and other wastewater. This led to sustained phytoplankton blooms that reduced the water clarity, which in turn is considered as the cause of the substantial losses of seagrass coverage (Lewis et al., 1998; Tomasko et al., 2005). Since then, significant ecosystem restoration efforts have been under way. In 1990, the Tampa Bay National Estuary Program (TBNEP) was established to coordinate and integrate efforts to restore and protect the Bay. In 1996, the TBNEP developed a Comprehensive Conservation and Management Plan (CCMP), which focused on restoration of seagrass to levels similar to those observed in the 1950s by reducing nutrient (primary nitrogen) inputs into the Bay (Janicki & Wade, 1996). Water quality of the Bay has gradually improved, and some of the seagrass has recovered (Johansson, 2000; Tomasko et al., 2005). Thus water clarity in Tampa Bay has been monitored as a measure of the impact of nutrient load on phytoplankton concentrations, and is a key parameter used in riverine nutrient input management (Janicki et al., 2001).

Water clarity in Tampa Bay has been measured with a Secchi disk once per month at established stations (Janicki & Wade,

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1996; Fig. 1), as done in many coastal environmental monitoring programs. A white disk (sometimes also painted in black/white quarters), usually ~20 cm in diameter, is lowered into the water and the depth at which the disk is no longer visible is recorded as the Secchi Disk Depth (SDD, in units of meters). SDD provides a simple, inexpensive measurement of the rate at which light is attenuated with depth. Due to the size of Tampa Bay and logistical limitations, it usually takes three weeks to conduct bay-wide SDD observations at a series of pre-established historical stations (Fig. 1). Clearly this sampling program is not synoptic, so a natural question is whether this monitoring strategy is sufficient to help assess the mean and variability in water clarity in time over the extent of Tampa Bay, the extent and changes in eutrophication due to anthropogenic nutrient inputs, and the impact on areas where seagrass re-growth is desired.

Water clarity or specifically light attenuation coefficients have also been estimated for coastal and open ocean waters using satellite ocean color measurements drawing upon the repeated and synoptic sampling capability. However, previous applications frequently used site- and/or time-specific empirical algorithms (Austin & Petzold, 1981; Mueller, 2000; Prasad et al., 1998; Stumpf & Pennock, 1991). For example, the standard empirical algorithm used to estimate the diffuse light attenuation coefficient at 490 nm, $K_d(490)$ (m^{-1}), from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) data was developed based largely on open ocean observations where most $K_d(490) < 0.15$ m^{-1} (Mueller, 2000). Thus the previous empirical algorithms are prone to generate large errors when applied to coastal and estuarine waters where the optical properties are different from those waters for algorithm development (Lee et al., 2005b). More recently, improved light attenuation coefficient estimates for coastal waters have been possible by application of a semi-analytical algorithm to *in situ* collected data (Lee et al., 2005a,b). However the accuracy of estimates based on space-based observations remains unknown, because satellite-derived reflectance contains uncertainties over coastal and estuarine zones due to non-zero remote sensing reflectance (R_{rs}) in the near-infrared in some turbid waters, and/or due to high concentrations of blue-absorbing aerosols in some near-shore atmosphere (Harding et al., 2005; Hu et al., 2000).

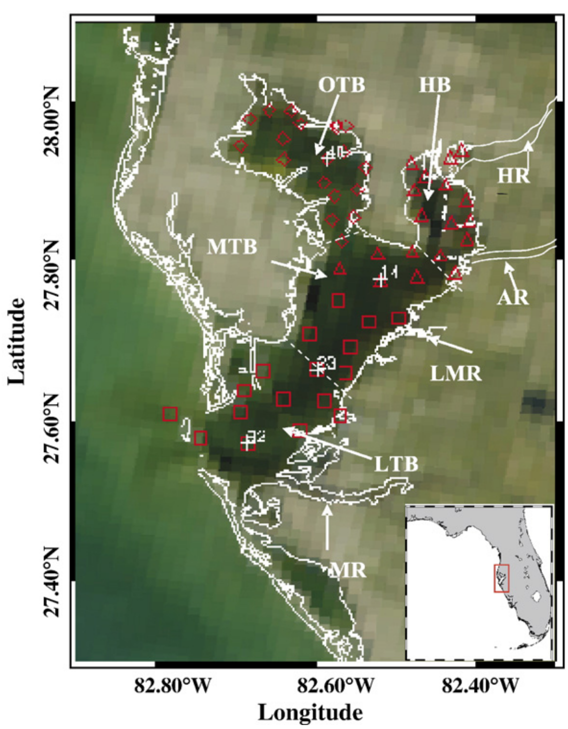

Fig. 1. SeaWiFS true-color (Red–Green–Blue) satellite image of Tampa Bay, U.S.A., with an inset showing the location of this estuary in the state of Florida. The four main sub-segments of the bay are Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), and Lower Tampa Bay (LTB). Major rivers are the Hillsborough River (HR), Alafia River (AR), Little Manatee River (LMR), and Manatee River (MR). Environmental Protection Commission of Hillsborough County's (EPCHC) water quality monitoring stations are shown using different symbols to indicate monthly sampling times: diamonds (OTB) are generally sampled the first week of the month, triangles (HB) the second week, and squares (MTB and LTB) in the third or fourth weeks. Time-series data were extracted for this study at four stations (92, 23, 14, and 40, crosses).

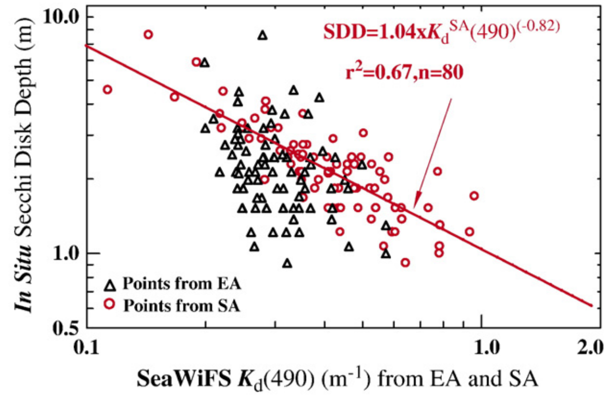

Fig. 2. Light attenuation coefficient at 490 nm ($K_d(490)$, m^{-1}) derived from SeaWiFS vs. *in situ* Secchi disk depth (SDD, m). $K_d(490)$ was estimated using (1) the empirical band-ratio algorithm (EA) (triangles, updated Mueller's (2000) algorithm) and (2) the semi-analytical algorithm(SA) (circles, Lee et al., 2005a).

Here, we used a two-step transformation of SeaWiFS imagery to estimate water clarity in Tampa Bay between September 1997 and December 2005. We first we estimated $K_d(490)$ based on the semi-analytical method of Lee et al. (2005a). The $K_d(490)$ estimates were closely related to SDD observations collected by the Environmental Protection Commission of Hillsborough County (EPCHC). This allowed us to examine the temporal and spatial variability of SDD in Tampa Bay using the satellite data, by computing SDD based on the remotely-sensed $K_d(490)$. Based on our results, we further provide recommendations for improving the water quality monitoring program of Tampa Bay and similar programs in other estuaries.

2. Methods and materials

2.1. Satellite data

SeaWiFS "merged local area coverage" (MLAC) Level-1A data (nominal spatial resolution of ~1 km) were downloaded from the NASA Goddard Space Flight Center (GSFC, http://