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Long-Term Time Series of Remote Sensing Observations for Development of Regulatory Water Quality Standards

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Background

Water quality standards in the U.S. consist of:

- designated uses (the services that a water body provides; e.g., drinking water, aquatic life, harvestable species, recreation)
- criteria that define the environmental conditions that must be maintained to support the uses

For estuaries and coastal waters in the Gulf of Mexico, there are no numeric (quantitative) criteria to protect designated uses from effects of nutrients. This is largely due to the absence of adequate data that would quantitatively link biological conditions to nutrient concentrations. The Gulf of Mexico Alliance, an organization fostering collaboration between the Gulf States and U.S. Federal agencies, has identified the development of the numeric nutrient criteria as a major step leading to reduction in nutrient inputs to coastal ecosystems.

Nutrient enrichment in estuaries and coastal waters can be quantified based on response variables that measure phytoplankton biomass and water clarity. Long-term, spatially and temporally resolved measurements of chlorophyll *a* concentration, total concentration of suspended solids, and water clarity are needed to establish reference conditions and to quantify stressor-response relationships.

Approach

NASA remote sensing data are used to produce long-term time series of ocean color observations (from 1984 to present), using combined satellite measurements from the MODIS (Moderate Resolution Imaging Spectroradiometer) instruments on the Aqua and Terra spacecraft and from the TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus) instruments on the Landsat 5 and Landsat 7 spacecraft, respectively. MODIS instruments have provided data with near-daily coverage since 2000, while Landsat TM/ETM+ data, although available only every 16 days, extend back to 1984. Recent improvements in instrument calibration and data correction techniques enabled merging the time series of observations from MODIS and Landsat.

MODIS data are processed to retrieve inherent optical properties and water clarity parameters with spatial resolution of 250 m that enables measurements even for small estuaries. Landsat data are aggregated to comparable grid size to improve signal-to-noise ratio and radiometric resolution of the measurements.

Water clarity is defined here as light attenuation due to absorption and scattering by water and its suspended or dissolved constituents:

- chlorophyll *a* (in phytoplankton)
- total suspended solids (TSS), including suspended sediments and phytoplankton
- colored dissolved organic matter (CDOM)

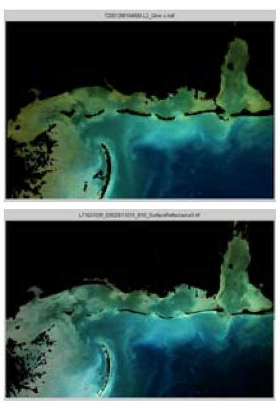


Figure 1. Atmospherically corrected, near-coincident images of Mobile Bay and Mississippi Sound acquired by the MODIS sensor on Terra satellite (top) and by the Landsat 7 satellite (bottom) on October 15, 2001.

Landsat pixels are aggregated from 30 m to 240 m. MODIS pixels are re-projected (nearest neighbor) to match the Landsat image.

MODIS 645-, 555-, and 469-nm bands, and Landsat bands 3 (630-690 nm), 2 (520-600 nm), and 1 (450-515 nm) are shown as the RGB colors.

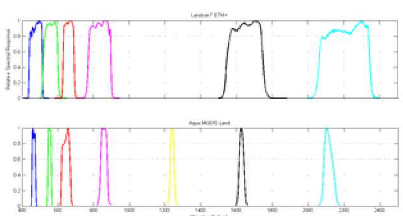


Figure 2. Spectral response functions of the Landsat 7 satellite sensor (top) and the MODIS instrument from the Aqua satellite (bottom); measured before launch.

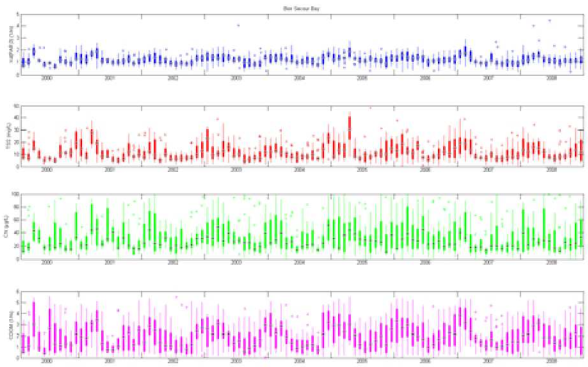


Figure 3. Time series of monthly statistics of water clarity parameters retrieved from MODIS remote sensing measurements for the Bon Secour Bay area in Mobile Bay (area averaged).

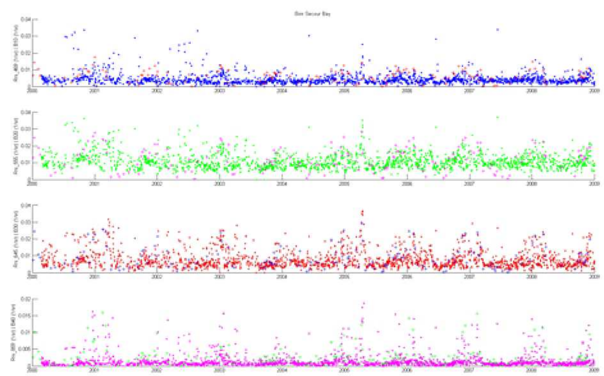


Figure 4. Comparison of time series of area-averaged remote sensing reflectance retrieved from MODIS (dots) and Landsat (crosses) data for the Bon Secour Bay area in Mobile Bay (starting in 2000 when MODIS data became available). Monthly statistics of water clarity parameters calculated from these MODIS data are shown in Figure 3.

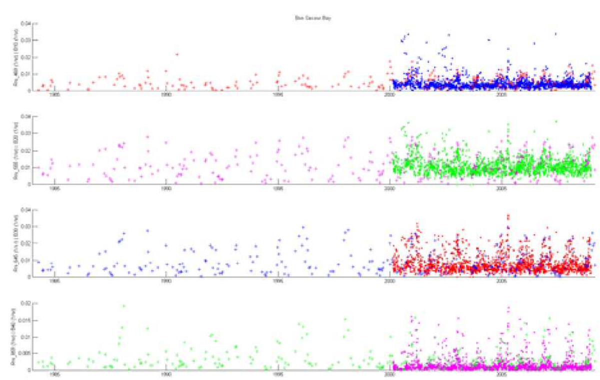
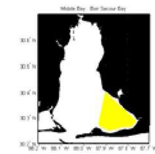


Figure 5. Comparison of time series of area-averaged remote sensing reflectance retrieved from MODIS (dots) and Landsat (crosses) data for the Bon Secour Bay area in Mobile Bay (full temporal extent provided by Landsat 5 and Landsat 7).

Figure 6. Map of the Mobile Bay with a yellow patch indicating the Bon Secour Bay area selected in this study for averaging water clarity parameters retrieved from MODIS datasets.



MODIS Products

Time series of water clarity parameters are created from the Level 1B MODIS data products obtained from the MODIS Adaptive Data Processing System/Level 1 and Atmosphere Archive and Distribution System (MODAPS/LAADS). The Level 1B calibrated radiance products are processed using the SeaDAS software (developed and maintained by the GSFC Ocean Biology Processing Group) to apply atmospheric correction (based on SWIR and NIR bands) and to retrieve inherent optical properties (IOPs) of coastal and estuarine waters. Based on SeaDAS quality flags generated for each pixel, water clarity parameters are not produced for pixels that are identified as (1) land, (2) cloud and/or ice, (3) affected by severe sun glint, and (4) acquired at high satellite zenith angle.

The following IOPs are retrieved using the Quasi-Analytical Algorithm and are used to produce the water clarity parameters using the formulae shown below:

- total absorption coefficient at 488 nm, $a(488)$
- total backscattering coefficients at 488 nm and 555 nm, $b_b(488)$ and $b_b(555)$
- phytoplankton absorption coefficient at 555 nm, $a_{ph}(555)$
- gelbstoff + detritus absorption coefficient at 412 nm, $a_{dg}(412)$

Diffuse attenuation coefficient for the photosynthetically active radiation:

$$K_d(PAR,z) = K_1 + \frac{K_2}{\sqrt{1+z}} \qquad K_d(PAR,0) = K_1 + K_2 \qquad K_1 \text{ and } K_2 \text{ calculated from } a(488) \text{ and } b_b(488)$$

- Z.-P. Lee, A. Weidemann, J. Kindle, R.A. Arnone, K.L. Carder, and C. Davis, "Euphotic zone depth: Its derivation and implication to ocean-color remote sensing," *J. Geophys. Res. (Oceans)*, vol. 112, p. 3009, March 2007

Total concentration of suspended solids:

$$TSS = 1.58153\,\frac{g}{m^2}\cdot b(555) \qquad b(555) = 40\,b_b(555)$$

- R.W. Gould, R.H. Stavn, M.S. Twardowski, and G.M. Lamela, "Partitioning optical properties into organic and inorganic components from ocean color imagery," *Proc. Ocean Optics XVI*, Santa Fe, NM, 2002

Chlorophyll *a* concentration:

$$Chl = \left[\frac{a_{ph}(555)}{A(555)}\right]^{\frac{1}{1-B(555)}}$$

- A. Bricaud, M. Babin, A. Morel, and H. Claustre, "Variability in the chlorophyll-specific absorption coefficients of natural phytoplankton: Analysis and parameterization," *J. Geophys. Res.*, vol. 100, pp. 13321-13332, July 1995

Light attenuation by CDOM (and detritus): $a_{dg}(412)$

- Z.-P. Lee, K.L. Carder, and R.A. Arnone, "Deriving inherent optical properties from water color: A multiband quasi-analytical algorithm for optically deep waters," *Appl. Opt.*, vol. 41, pp. 5755-5772, 2002

Landsat Products

After applying radiometric calibration, Landsat image pixels are converted to planetary reflectance and aggregated to pixel size of 240 m by averaging 8×8-pixel blocks. Similarly to the SeaDAS processing of MODIS data, Landsat atmospheric correction is based on an assumption of negligible water reflectance in the SWIR spectral bands (1.6 and 2.2 µm), which enables estimation of atmospheric path reflectance from image data in the SWIR bands. Separation of the atmospheric contribution into molecular (Rayleigh) and particulate (aerosol) scattering, scaling of aerosol reflectance in the SWIR bands to the visible and NIR bands, and estimation of diffuse atmospheric transmittance are accomplished by modeling atmospheric radiative transfer using the MODTRAN software developed by the U.S. Air Force Research Laboratory. MODTRAN calculations use the same or comparable meteorological data (pressure and humidity) and ozone data as the SeaDAS processing. Land mask and cloud mask are derived for each image from the 1.6-µm SWIR band.

Currently, SWIR-based atmospheric correction of MODIS data in SeaDAS is based on the 1.2-µm and 2.1-µm bands because of problems with data quality for the 1.6-µm MODIS band on the Aqua satellite. A recent study has shown that for highly turbid coastal waters, the 1.6-µm band provides a more accurate atmospheric correction than the 1.2-µm band.

Conclusions

Results shown in Figures 1 and 4 display good agreement between the time series of remote sensing reflectance measured by Landsat and MODIS in the Mobile Bay estuary, despite differences between spectral responses of the instruments.

These results validate the use of Landsat data products, aggregated to match the MODIS pixel size, to extend the high-resolution (250-m) MODIS time series of water clarity parameters back to 1984.

Combining MODIS and Landsat data enables creation of long-term time series of water clarity parameters derived from remote sensing observations that will support monitoring of coastal water quality and development of regulatory water quality standards, such as the quantitative nutrient criteria for coastal and estuarine waters.