Ocean Color Products in the China East Coastal Regions Derived From MODIS Measurements

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Abstract

We report significant ocean near-infrared (NIR) contributions in the China east coastal regions from the Moderate Resolution Imaging Spectroradiometer (MODIS) measurements. The China east coastal regions present consistently the most turbid waters in the global coastal regions all year around. For the turbid waters, the standard MODIS data processing often produces significant errors in the derived ocean color products due to significant ocean water-leaving radiance contributions at the two NIR bands, i.e., the black ocean assumption in the NIR is invalid. In this presentation, we provide a new approach using the MODIS short wave infrared (SWIR) bands for atmospheric correction for deriving the ocean color products in the coastal regions. The ocean is still black at the SWIR bands even for the very turbid waters due to much stronger water absorptions at the SWIR wavelengths. The new approach has been tested and applied for various coastal regions (e.g., the U.S. and China east coastal regions) with the MODIS data. The *in situ* data collected along the China east coastal regions have been used to validate the algorithm performance. Using the MODIS Aqua measurements from July of 2002 to December of 2005, seasonal variations in the visible and the NIR ocean water-leaving radiances in the China east coastal regions are derived and analyzed. Very significant ocean NIR contributions along the various China east coastal regions (e.g., the Hangzhou Bay, the Yangtze River Estuary) are observed. The seasonal variations in the ocean NIR contributions (high in the winter and low in the summer) are related to the suspension and re-suspension of the sediment in the regions due to the seasonal monsoon winds and the ocean surface layer mixing effects.

MODIS Atmospheric Correction Algorithm for Turbid Waters

The main objective of the ocean color data processing is to derive the water-leaving reflectance $[\rho_w(\lambda)]_N$ by removing atmosphere and ocean surface effects (*Gordon and Wang*, 1994). One of main issues for the coastal regions ocean color remote sensing is the problem of the turbid waters, for which the ocean has significant radiance contributions at the near-infrared (NIR) bands (*Siegel, et al.*, 2000; *Wang and Shi*, 2005). The NIR black ocean assumption is invalid for the turbid waters, leading to significant errors in the MODIS derived ocean color products. Recently, *Wang and Shi* (2005) demonstrated an approach to derive the NIR ocean contributions using the MODIS short wave infrared (SWIR) bands for the turbid waters, and proposed the SWIR atmospheric correction for the ocean color remote sensing in the coastal regions.

At the SWIR wavelengths, the water has much stronger absorption than that at the NIR band, thus the black ocean assumption is generally valid at the SWIR bands even for very turbid ocean waters. The SWIR atmospheric correction approach has been developed and implemented in the MODIS ocean color data processing, and tested for the U.S. east and west coastal regions. The China east coastal region represents consistently the most turbid waters in the global coastal regions. Some *in situ* data collected along the China east coastal regions are provided for the purpose of algorithm validation

MODIS Aqua Data

Along the China east coastal regions, ocean waters are very turbid all the time. Significantly high concentrations of suspended sediment are consistently present along the various China east coastal regions, e.g., the Hangzhou Bay, the Yangtze River estuary, as well as their adjacent waters (*Chen, et al.*,2003).

Figure 1 provides examples of the true color images observed by MODIS Aqua along the China east coastal regions for various days representing different seasons. These images all show very turbid waters along the China east coastal regions, and demonstrate significantly large concentrations of suspended sediment in these regions (grayish-yellow ocean waters). Particularly, the China coastal regions along the Hangzhou Bay, the Yangtze River estuary, and the northern ocean region of the Yangtze River show extremely high sediment loadings (*Chen, et al.*, 2003) collected in the spring and fall of 2003.

In Fig. 1(c), four marked locations are corresponding to locations where *in situ* data were collected in the spring and fall of 2003.

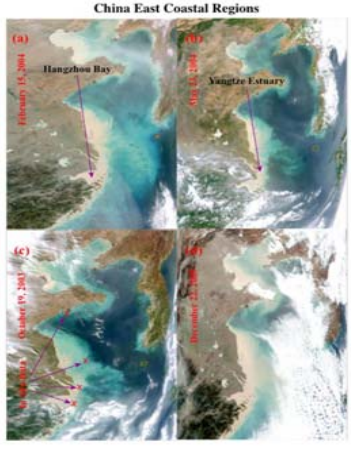

Figure 1. The MODIS Aqua true color images along the China east coastal regions acquired on (a) February 15, 2004, (b) May 23, 2004, (c) October 19, 2003, and (d) December 22, 2005, respectively.

MODIS Ocean Color Products

Figure 2 provides an example of the MODIS-derived ocean color products along the China east coastal regions. Figs. 2(a)-2(f) are images of the MODIS-derived chlorophyll-a and normalized water-leaving radiance $nLw(\lambda)$ at wavelengths 443, 488, 531, 748, and 869 nm, respectively. It is noted that, along the China east coastal regions, the MODIS normalized water-leaving radiance increases with increase of the wavelength from the blue to the green band, and $nLw(\lambda)$ values actually peaked at the red band (see results in Fig. 4). This is a typical characteristic of the sediment dominated waters. The NIR ocean contributions are very significant, e.g., at the Hangzhou Bay region the $nLw(\lambda)$ values in the winter can reach ~3 (mW cm^{-2}μ m^{-1} sr^{-1}) at 859 nm (see results in Fig. 4).

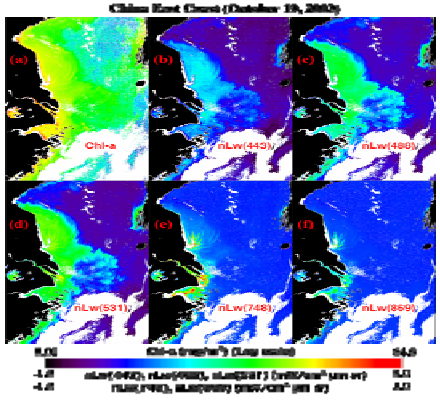

Figure 2. The MODIS-derived ocean color products along the China east coastal regions for (a) chlorophyll-a concentration and (b)-(f) $nLw(\lambda)$ at wavelengths 443, 488, 531, 748, and 869 nm, respectively. The MODIS data were acquired on October 19, 2003, corresponding to true color image in Fig. 1(c).

MODIS Data Compared with *In Situ* Measurements

During the spring and the fall of 2003, there have been extensive field campaigns along the China east coast and the Yellow Sea regions for collecting various physical, biological, and radiative ocean property data (*Tang, et al.*, 2004) .

Results in Fig. 3 show that the SWIR atmospheric correction performed reasonable well for these very turbid ocean waters. Indeed, both *in situ* and MODIS data show significantly high NIR ocean water-leaving reflectance values, i.e., the NIR $[\rho_w(\lambda)]_N$ values range from ~0.3%-1.0%. For these cases, the MODIS-derived normalized water-leaving reflectances at the visible bands compare quite well with the *in situ* measurements. The normalized water-leaving reflectance values in these cases have the maximums around green band. It is noted that, however, for these comparison cases (Fig. 3) the *in situ* data were collected in good environmental conditions (e.g., clear sky, low wind, *etc.*).

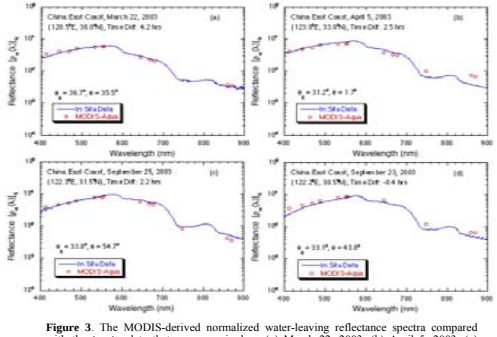

Figure 3. The MODIS-derived normalized water-leaving reflectance spectra compared with the *in situ* data that were acquired on (a) March 22, 2003, (b) April 5, 2003, (c) September 25, 2003, and (d) September 23, 2003. The locations of measurement are indicated in each plot and also shown in Fig. 1(c).

Seasonal Variation of *nLw* in the Hangzhou Bay Region

Figure 4 shows the MODIS monthly average $nLw(\lambda)$ values as a function of the wavelength for a location inside of the Hangzhou Bay (121.8°E and 30.5°N) (see Fig. 1(a)). The MODIS data were computed for the monthly average. Figure 4 plots four monthly curves corresponding to months of January, April, July, and October, respectively. Results in Fig. 4 show that in the Hangzhou Bay region the $nLw(\lambda)$ values peaked at the red band. The highest $nLw(\lambda)$ at the red and NIR bands are observed in the winter, while the lowest $nLw(\lambda)$ values at the red and NIR bands appeared in the summer. These results are consistent with other studies in which significantly higher suspended sediment concentration is observed in the winter than that in the summer season for the Hangzhou Bay region (Chen, *et al.*, 2003). High loading of the suspended sediment concentration leads to significantly large backscattering by suspended sediment particles, and thus the large water-leaving radiances. It is interesting to note that in the winter season the NIR $nLw(\lambda)$ value at 859 nm reaches ~3 (mW cm^{-2} μm^{-1} sr^{-1}), significantly larger than the $nLw(\lambda)$ values at the blue bands. In Fig. 4 , NIR $nLw(\lambda)$ at 748 and 869 are not shown due to sensor saturations at NIR bands in this region.

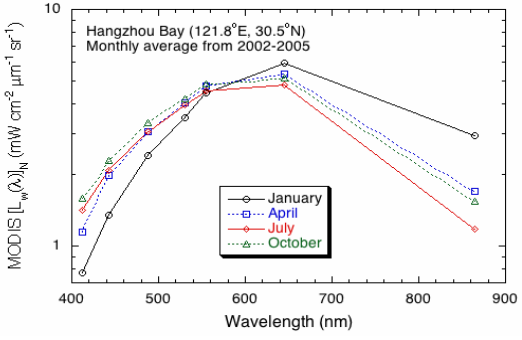

Figure 4. The MODIS monthly average of $nLw(\lambda)$ as a function of the wavelength for the location at the mouth of the Hangzhou Bay and for months of January, April, July, and October, respectively.

Summary and Remarks

The SWIR atmospheric correction algorithm is briefly described and used for the MODIS ocean color data processing for the China east coastal regions. In the China east coastal regions, oceans are consistently very turbid and have extremely larger NIR water-leaving radiances. Therefore, the standard MODIS data processing often fails to produce valid ocean color products in these regions. We have derived the MODIS ocean color products along the China east coastal regions using the SWIR atmospheric correction algorithm and compared the MODIS products with those from the *in situ* measurements. The validation results show a reasonably good agreement between satellite and *in situ* data. We demonstrated that the SWIR atmospheric correction approach can produce reasonably good quality ocean color products in the complicated and very turbid ocean waters

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