5.5. Coastal and inland waters
SeaWiFS and MODIS Experiences Show:

**High quality** ocean color products for the global **open oceans** (Case-1 waters).

**Significant efforts** are needed for improvements of water color products in the **inland & coastal regions**:

- **Turbid Waters**
  (violation of the NIR black ocean assumption)
- **Strongly-Absorbing Aerosols**
  (violation of non- or weakly absorbing aerosols)
Algorithm Developments for Productive/Turbid Waters

· **Arnone** et al. (1998) and **Siegel** et al. (2000) to account for the NIR ocean contributions for SeaWiFS and MODIS NIR bands.

· **Hu** et al. (1999) proposed an *adjacent pixel method*.

· **Gordon** et al. (1997) and **Chomko** et al. (2003) *the spectral optimization algorithm*.

· **Ruddick** et al. (2000) for regional Case-2 algorithm using the *spatial homogeneity of the aerosol* in a given area.

· **Lavender** et al. (2004) regional bio-optical model (suspended sediments) for SeaWiFS application.

· **Wang** and **Shi** (2005) derived NIR ocean contributions using the MODIS shortwave infrared (SWIR) bands.

· **Doerffer** et al. and others developed Artificial *Neural Network* for coastal Case-2 waters (implemented for MERIS data processing).

· **Wang** (2007) and **Wang & Shi** (2007) proposed the SWIR and NIR-SWIR atmospheric correction for the coastal waters.

· **Bailey** et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).

· **Wang** et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
The NIR Ocean Contribution Modeling (I)

Various investigators all sought to remove the NIR nL_w(\lambda) contributions from the TOA NIR radiances, so that a “black pixel” could be provided to the Gordon and Wang (1994) type atmospheric correction:

- **Siegel** et al. (2000) used chlorophyll estimate to determine the NIR nL_w(\lambda).
- **Lavender** et al. (2005) used a sediment estimate to determine the NIR nL_w(\lambda).
- **Ruddick** et al. (2000) fixed the aerosol and backscatter type and then solved for both the NIR nL_w(\lambda) and NIR aerosol reflectance simultaneously.
- **Arnone** et al. (1998) and **Stumpf** et al. (2003) used a bio-optical model for absorption coefficient at the red band and then used that with the red nL_w(\lambda) to find the NIR nL_w(\lambda).
- **Bailey** et al. (2010) developed an improved NIR model for the NASA standard ocean color data processing (SeaDAS).
- **Wang** et al. (2012) developed an NIR model for western Pacific regions (highly turbid) using the data from the SWIR algorithm for GOCI sensor.
The NIR Ocean Contributions Modeling (Example 1)
(Siegel et al., 2000)

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The NIR Ocean Contributions Modeling (Example 1)
(Siegel et al., 2000)

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The NIR Ocean Contributions Modeling (Example 2) (Lavender et al., 2000)

Note that the model is only applicable to the range $0.1 < \text{SPM} < 200 \text{ g m}^{-3}$.

$$a_{\text{SPM}}(\lambda) = a_{\text{SPM}}^0(\lambda) \text{SPM}^{0.32},$$

$$b_{\text{SPM}}(\lambda) = 0.85 \text{SPM} \left(\frac{\lambda}{670}\right)^{-0.9},$$

where the empirical constants are: $a_{\text{SPM}}^0(\lambda) = [0.65, 0.45, 0.12]$ for $\lambda = [670, 765, 865]$ respectively.

A radiative transfer model, Hydrolight (Mobley, 1995), was used to obtain water reflectance from these absorption and scattering values for various sun positions and satellite viewing geometries. Pure water absorption data were taken from Pope and Fry (1997) and Palmer and Williams (1974), water scattering data were taken from Morel (1974), and the SPM scattering phase function of Petzold (1972) was used. The model results are shown in Figs. 1 and 2. The results were incorporated into a look-up table for use in the BP atmospheric correction method.

2.3. The Bright Pixel inversion model

The method used to partition the Rayleigh-corrected reflectance into aerosol and water reflectance is similar to that employed by the European MERIS satellite sensor (Moore et al., 1999), see Fig. 3 for an overview of the scheme. The MERIS method uses the NIR bands centred on 705, 775 and 865 nm, whereas the SeaWiFS method described here uses the 670, 765 and 865 nm bands. The significance of this band change is considered later.

Neglecting the effects of phytoplankton and CDOM on NIR reflectance, Eqs (3) and (5) give:

$$\rho_a(\lambda) = \rho_a(\lambda) - \rho_s(\lambda) = \rho_a^0 + t(\lambda) f(\lambda, \text{SPM}, \theta_0, \theta, \phi).$$

Combining Eqs. (4) and (8) we can express the Rayleigh-corrected top-of-atmosphere reflectance ($\rho_o$) at 670 and 765 nm as two non-linear linked equations:

$$\rho_o(670) = \rho_a^0(865) \left(\frac{670}{865}\right)^n + t(670) f(670, \text{SPM}, \theta_0, \theta, \phi).$$
**Spectral Optimization Algorithm (II)**

- The **Spectral Optimization Algorithm (SOA)** (Chomko and Gordon, 1998) derives the properties of the ocean and atmosphere simultaneously using sensor-measured TOA radiance from the blue to NIR (entire radiance spectra from visible to NIR). However, the algorithm has no attempt to use realistic aerosol models.
  
  - Use a simple power-law size distribution aerosol model
  - Use the Garver-Siegel-Maritorena (GSM) ocean bio-optical model
  - Some studies with SeaWiFS data show improved results over the coastal productive waters (Kuchinke et al., 2009).

✓ The SOA approach with simultaneously ocean and atmosphere properties retrieval (one-step) requires **robust ocean bio-optical model** (e.g., over complex turbid waters).
Example Results of SOA (Chl-a) (Kuchinke et al., 2009)

Images Left to Right:

Menghua Wang, IOCCG Lecture Series 2
Atmospheric correction based on modelled radiance reflectances and artificial neural network

International Ocean Color Workshop Agenda
(23-24 April 2009, Hangzhou, China)

R. Doerffer, GKSS
Institute for Coastal Research
NN for atmospheric correction – 3rd version in C2R and Glint processor

Input

- RLtosa 12 bands
- Sun zenith
- View zenith
- Azimuth diff
- [Opt. Wind]

Output

- Tau_aerosol 412, 550, 778, 865
- Sun_glint ratio
- a_tot, b_tot
- MERIS band 1-9
  - Trans tosa-surface
  - Path radiance reflectance
  - RLw
  - errcode

\[ \text{RLw}(\theta,\phi) = \text{Lw}(\theta,\phi)/Ed \]
Atmospheric Correction: SWIR Bands

(Wang & Shi, 2005; Wang, 2007)

- At the shortwave IR (SWIR) wavelengths (>~1000 nm), ocean water has much strongly absorption and ocean contributions are significantly less. Thus, atmospheric correction can be carried out for coastal regions without using the bio-optical model.
- Water absorption for 869 nm, 1240 nm, 1640 nm, and 2130 nm are 5 m\(^{-1}\), 88 m\(^{-1}\), 498 m\(^{-1}\), and 2200 m\(^{-1}\), respectively.
- Examples using the MODIS Aqua 1240 and 2130 nm data to derive the ocean color products are provided.

- We use the SWIR band (1240 nm) for the cloud masking. This is necessary for coastal region waters.

- Require sufficient SNR characteristics for the SWIR bands and the SWIR atmospheric correction has slight larger noises at the short visible bands (compared with those from the NIR algorithm).
Black ocean at the SWIR bands: Absorption at the SWIR bands is at least an order larger than that at the 865 nm!
Aerosol Single-Scattering Epsilon ($\lambda_0 = 1240$ nm)

$\lambda_0 = 1240$ nm, $\theta_0 = 60^\circ$, $\theta = 45^\circ$, $\Delta \phi = 90^\circ$
Aerosol Single-Scattering Epsilon ($\lambda_0 = 1640$ nm)

$\lambda_0 = 1640$ nm, $\theta_0 = 60^\circ$, $\theta = 45^\circ$, $\Delta \phi = 90^\circ$
Aerosol Single-Scattering Epsilon ($\lambda_0 = 2130$ nm)

$\lambda_0 = 2130$ nm, $\theta_0 = 60^\circ$, $\theta = 20^\circ$, $\Delta \phi = 90^\circ$

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Data Processing (NOAA-MSL12) Using the SWIR Bands

Software Modifications:
- Atmospheric correction package has been significantly modified based on SeaDAS 4.6.
- Data structure and format of aerosol lookup tables and diffuse transmittance tables have been changed.
- With these changes, it is flexible now to run with different aerosol models (e.g., absorbing aerosols) and with various band combinations for atmospheric correction.

Lookup Tables Generation and Implementation:
- Rayleigh lookup tables for the SWIR bands (for all MODIS 16 bands).
- Aerosol optical property data (scattering phase function, single scattering albedo, extinction coefficients) for the SWIR bands (12 models).
- Aerosol radiance lookup tables (12 aerosol models) for the SWIR bands (for all MODIS 16 bands). Vector RTE (with polarization) were used for aerosol LUTs generation.

Data Processing:
- Regenerated MODIS L1B data including all SWIR band data (for SeaDAS).
- Developed cloud masking using the MODIS SWIR 1240 nm band.
- For MODIS Aqua, atmospheric correction can be operated using 1240/2130 nm bands, 1640/2130 nm bands.

Vicarious calibration:
- SWIR and NIR-SWIR algorithms (data processing systems) have been vicariously calibrated to produce consistent ocean color products.
5.6. Examples from MODIS-Aqua measurements
Results from SWIR Atmospheric Correction for turbid ocean waters in US east coastal

MODIS-Aqua True Color Image

U.S. East Coastal

April 6, 2004
Ocean Spectra from Visible to NIR for Various Ocean Waters

U.S. East Coast, April 6, 2006
SWIR Bands Method

\( nLw(645) \)

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\( \tau_a(869) \sim 0.3 \)
Comparisons of MODIS Ocean Color Products from NIR, SWIR, and NIR-SWIR Combined Methods

Example: U.S. East Coast


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Results from MODIS-Aqua Measurements (Chesapeake Bay)

Chesapeake Bay Region
λ = 412 nm
Mean Ratio = 1.29 (a)

Chesapeake Bay Region
λ = 443 nm
Mean Ratio = 1.09 (b)

Chesapeake Bay Region
λ = 488 nm
Mean Ratio = 1.00 (c)

Chesapeake Bay Region
λ = 531 nm
Mean Ratio = 0.95 (d)

Number of Data = 647

Mean Ratio = 1.06
Median Ratio = 0.97
STD = 0.48
Results from MODIS-Aqua Measurements

(China East Coast)

Lake Taihu

China East Coast (October 19, 2003)

(a) 

(b) 

(c) 

Hangzhou Bay

Yangtze Estuary

(f)

In Situ Data

MODIS-Aqua

Reflectance \( \rho_w(\lambda) \)

Wavelength (nm)

400 500 600 700 800 900

Reflectance \( \rho_w(\lambda) \)

Wavelength (nm)

March 22, 2003

April 5, 2003

(120.5°E, 36.0°N)

(123.0°E, 33.0°N)

\( \theta_0 = 36.7°, \theta = 35.5° \)

\( \theta_0 = 31.2°, \theta = 1.7° \)

Time Diff: 4.2 hrs

Time Diff: 2.5 hrs

(b) 

(c)

θ₀ = 33.8°, θ = 54.7°

θ₀ = 33.1°, θ = 43.8°

Time Diff: 2.2 hrs

Time Diff: -0.4 hrs

China East Coast

China East Coast

(d)

(e)

nLw(443)

nLw(531)

nLw(689) ~ 0

nLw(869)

τₐ(689)

Chlorophyll-a (mg/m³) (Log scale)

0.0

0.1

0.3

32.0

nLw(443), nLw(531) (mW/cm² μm sr)

nLw(689) (mW/cm² μm sr)

0.0

2.0

-1.0

-0.5

September 23, 2003 (d)

September 25, 2003

(122.3°E, 31.5°N)

(122.2°E, 30.5°N)

Time Diff: -0.4 hrs

Time Diff: 2.2 hrs

θ₀ = 33.1°, θ = 43.8°

θ₀ = 33.8°, θ = 54.7°
### Validation Results (3)

China East Coast  
March 22-April 6 & Sep. 19-26, 2003

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Slope</th>
<th>Int</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>443</td>
<td>0.712</td>
<td>0.012</td>
<td>0.858</td>
</tr>
<tr>
<td>488</td>
<td>0.798</td>
<td>0.011</td>
<td>0.928</td>
</tr>
<tr>
<td>531</td>
<td>0.907</td>
<td>0.006</td>
<td>0.958</td>
</tr>
<tr>
<td>645</td>
<td>0.873</td>
<td>0.003</td>
<td>0.949</td>
</tr>
<tr>
<td>859</td>
<td>0.991</td>
<td>0.002</td>
<td>0.968</td>
</tr>
<tr>
<td>ALL</td>
<td>0.896</td>
<td>0.005</td>
<td>0.951</td>
</tr>
</tbody>
</table>

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Water-leaving Radiance Spectra in Hangzhou Bay

Hangzhou Bay (30.5°N, 121.8°E)
Average from 2002-2005

Average aerosol optical thickness at 859 nm:

<table>
<thead>
<tr>
<th>Season</th>
<th>$\tau_a$ (859)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>0.240</td>
</tr>
<tr>
<td>Spring</td>
<td>0.275</td>
</tr>
<tr>
<td>Summer</td>
<td>0.226</td>
</tr>
<tr>
<td>Fall</td>
<td>0.230</td>
</tr>
</tbody>
</table>

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$nL_w(443)$
Scale: 0.-3.0
(mW/cm$^2$ $\mu$m sr)

Chlorophyll-a
0.01-10 (mg/m$^3$)
(Log scale)


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The SWIR 1240 nm band is not black for extremely turbid waters in Hangzhou Bay (Shi & Wang, 2009)
The SWIR 1240 nm band is not black for extremely turbid waters in La Plata Estuary (Shi & Wang, 2009)
The SWIR-Derived Ocean Radiance Relationships (Shi & Wang, 2009)

(a) China East Coastal Region
nLw(859) vs. nLw(645)
Data Processed Using:
MODIS 1640 & 2130 nm Bands

(b) China East Coastal Region
nLw(859) vs. nLw(1240)
Data Processed Using:
MODIS 1640 & 2130 nm Bands

(c) La Plata Estuary
nLw(859) vs. nLw(645)
Data Processed Using:
MODIS 1640 & 2130 nm Bands

(d) La Plata Estuary
nLw(859) vs. nLw(1240)
Data Processed Using:
MODIS 1640 & 2130 nm Bands

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Blue-Green Algae (Microcystis) Bloom Crisis in Lake Taihu (Spring 2007)
Results from Inland Lake Taihu

Using the SWIR algorithm, we have derived the water optical properties over the Lake Taihu using the MODIS-Aqua measurements during the spring of 2007 for monitoring a massive blue-green algae bloom, which was a major natural disaster affecting several millions residents in nearby Wuxi city.


➢ The work was featured in the NASA 2008 Sensing Our Planet (http://nasadaacs.eos.nasa.gov/articles/2008/2008_algae.html)

Acknowledgements

In situ data from Lake Taihu from J. Tang and Y. Zhang.
The third largest fresh inland lake in China (~2,250 km²).
Located in one of the world’s most urbanized and heavily populated areas.
Provide water resource for several million residents in nearby Wuxi city.

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The SWIR atmospheric correction algorithm (Wang, 2007; Wang & Shi, 2005) is used for the water property data processing.

Since MODIS 1240 nm band is not always black for the entire Lake Taihu, we have developed three-step method in the data processing for each MODIS-Aqua data file:

- First, regions for the black of 1240 nm band are determined using the SWIR data processing.
- Second, a dominant aerosol model from the region with black of 1240 nm band is obtained, and
- Finally, with the derived aerosol model, the SWIR atmospheric correction algorithm is run using only 2130 nm band (with fixed aerosol model).

The Lake Taihu water property data are then derived.


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March 29, 2007

(a) True Color Image

(b) Chlorophyll-a

(c) nLw(443)

Lake Taihu

Meiliang Bay

Gonghu Bay

Zhushan Bay

May 7, 2007

(d) True Color Image

(e) Chlorophyll-a

(f) nLw(443)

Bloom Location

Central Lake

nLw(443) (mW/cm² μm sr)

Chlorophyll-a Concentration (mg/m³)

0.0

1.0

5.0

32.0

(Wang and Shi, 2008)
Time Series of Chlorophyll-a (index) and $nLw(443)$ at Wuxi Station (bloom) and Central Lake (non-bloom)

- Normalized Water-leaving Radiance at 443 nm
- Chlorophyll-a

Date (2007):
- March 21
- April 10
- April 30
- May 20
- June 9

Chlorophyll-a (mg m$^{-3}$)

Bloom Location
Central Lake

$nLw(\lambda)$ (mW cm$^{-2}$ m$^{-2}$ sr)$^{-1}$
Validation Results for MODIS-derived Water-leaving Radiance Spectra

Lake Taihu in China, June 10, 2007

Location: (120.20°E, 31.43°N)

Lake Taihu in China, June 12, 2007

Location: (120.29°E, 31.27°N)

Lake Taihu in China, June 17, 2007

Location: (120.31°E, 30.95°N)

Lake Taihu in China, June 18, 2007

Location: (120.30°E, 30.94°N)
Black pixel assumption at the SWIR 1640 and 2130 nm is generally valid for Lake Taihu.

The SWIR atmospheric correction algorithm using bands 1640 and 2130 nm (Wang, 2007) can be used for the water property data processing.

However, for MODIS-Aqua, four out of ten detectors for the SWIR 1640 nm band are inoperable (dysfunctional).

We focus on deriving seasonal results for the lake using the SWIR 1640 and 2130 nm atmospheric correction algorithm.

More in situ data (five seasonal cruises in 2006-2007 in the lake) are also available to us now.
Validation Results for MODIS-derived Water-leaving Radiance Spectra

Lake Taihu in China, January 9, 2006

Lake Taihu in China, July 30, 2006

Lake Taihu in China, July 30, 2006

Lake Taihu in China, October 15, 2006
Validation Results in Lake Taihu (Method 2)

5x5 with >12 valid pixels

Lake Taihu in China
1640 & 2130 nm Method

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>Ratio</th>
<th>Std</th>
</tr>
</thead>
<tbody>
<tr>
<td>412</td>
<td>1.068</td>
<td>0.132</td>
</tr>
<tr>
<td>443</td>
<td>1.033</td>
<td>0.119</td>
</tr>
<tr>
<td>488</td>
<td>1.038</td>
<td>0.161</td>
</tr>
<tr>
<td>555</td>
<td>0.946</td>
<td>0.128</td>
</tr>
<tr>
<td>645</td>
<td>0.942</td>
<td>0.180</td>
</tr>
<tr>
<td>859</td>
<td>1.381</td>
<td>0.456</td>
</tr>
<tr>
<td>1240</td>
<td>0.913</td>
<td>2.903</td>
</tr>
</tbody>
</table>

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Seasonal Histograms in $nL_w(1240)$

Lake Taihu in China
MODIS-Aqua (2002-2010)

TOA Radiance at 1240 nm
~ 0.1 mW cm$^{-2}$ um$^{-1}$ sr$^{-1}$

(a)

Histogram (%)

Histograms for different seasons:
- Winter
- Spring
- Summer
- Fall

$nL_w(1240)$ (mW cm$^{-2}$ tm$^{-1}$ sr$^{-1}$)

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Climatology Histogram in $nL_w(1240)$

Lake Taihu in China
MODIS-Aqua (2002-2010)
All Data

Total # of In Situ Data: 135

MODIS-Aqua

In Situ Data

TOA Radiance at 1240 nm
$\sim 0.1$ mW cm$^{-2}$ um$^{-1}$ sr$^{-1}$

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MODIS-Measured Climatology Water Optical Property for Lake Taihu

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MODIS-Aqua-Derived (2002-2010)
Various Water-leaving Radiance Relationships

Lake Taihu in China
Radiance Saturation

\[ nL_w(\lambda) \sim b_b(\lambda) / [a(\lambda) + b_b(\lambda)] \]

Radiance saturation phenomenon is attributed to the dominance of \( b_b(\lambda) \) for extremely turbid waters, i.e., \( b_b(\lambda) \gg a(\lambda) \)!
Adjacent Effects on the Ocean Color Products

MODIS-Aqua Mapped Chl-a image in the Chesapeake Bay (Oct. 7, 2004)

A200402811815.L2_LAC
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At line 37°N

At line 35°N

MODIS-NIR

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MODIS-Aqua L2 Chl-a image in the Gulf of Maine (Feb. 5, 2005)

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The SWIR Algorithm Related Publications (1)
(Algorithms and Validations)


Menghua Wang, IOCCG Lecture Series 2014--Atmospheric Correction
The SWIR Algorithm Related Publications (2)
(Various Applications)


Menghua Wang, IOCCG Lecture Series 2014--Atmospheric Correction
Questions?