MODIS Ocean Data Processing

Bryan Franz

NASA Ocean Biology Processing Group

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## Operational MODIS Ocean Band Suite

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Wavelength (nm)</th>
<th>Band Width (nm)</th>
<th>Spatial Resolution (m)</th>
<th>SNR at ( L_{typ} ) (mW cm(^{-2}) m(^{-1}) sr(^{-1}))</th>
<th>( L_{typ} ) (mW cm(^{-2}) m(^{-1}) sr(^{-1}))</th>
<th>( L_{max} ) (mW cm(^{-2}) m(^{-1}) sr(^{-1}))</th>
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<tr>
<td>8</td>
<td>412</td>
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<td>1962</td>
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<td>1000</td>
<td>1112</td>
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</table>

### VIS/NIR

Ocean Color

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Wavelength (nm)</th>
<th>Band Width (nm)</th>
<th>Spatial Resolution (m)</th>
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<tr>
<td>22</td>
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<tr>
<td>31</td>
<td>11000</td>
<td>60</td>
<td>1000</td>
<td>0.05</td>
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<tr>
<td>32</td>
<td>12000</td>
<td>60</td>
<td>1000</td>
<td>0.05</td>
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</table>
Data Levels & Flow

- **Level 0**
  - raw digital counts
  - native binary format

- **Level 1A**
  - raw digital counts
  - HDF formatted

- **Level 1B**
  - calibrated reflectances
  - converted telemetry

- **Ancillary data**
  - wind speed
  - surface pressure
  - total ozone
  - Reynolds SST

- **ATT & EPH**
  - spacecraft attitude
  - spacecraft position

- **GEO**
  - geolocation
  - radiant path geometry

- **Level 2**
  - geolocated geophysical products for each pixel
Data Levels & Flow

- **Level 0**
  - raw digital counts
  - native binary format

- **Level 1A**
  - raw digital counts
  - HDF formatted

- **Level 1A Subset**
  - reduced to standard ocean bands only

- **Ancillary data**
  - wind speed
  - surface pressure
  - total ozone
  - Reynolds SST

- **ATT & EPH**
  - spacecraft attitude
  - spacecraft position

- **GEO**
  - geolocation
  - radiant path geometry

- **Level 1B**
  - calibrated reflectances
  - converted telemetry

- **Level 2**
  - geolocated geophysical products for each pixel
Level-3 Processing

- **Level 2**
  - geolocated geophysical products for each pixel

- **Level 3 binned**
  - geophysical products averaged spatially and/or temporally
  - sinusoidally distributed, equal area bins

- **Level 3 mapped**
  - images created by mapping and scaling binned products
  - user-friendly, cylindrical equiangular projection

---

**Standard Products**

- Bin resolution 4.6 x 4.6 km²

- Mapped resolution
  - 0.042-deg (4.6 km at equator)
  - 0.084-deg (9.2 km at equator)

- Composite Periods
  - Daily
  - 8-day
  - Monthly
  - Seasonal
  - Yearly
  - Mission
Level-3 Binned vs Mapped

*bin file grid*

- **bin files**
  - multiple products
  - stored as float
  - sampling statistics included

- **map files**
  - single product
  - stored as scaled integer

*map file grid*
Standard MODIS Ocean Products

- **Ocean Temperature**
  - Long-wave SST (11-12 μm), day and night
  - Short-wave SST (3.9 - 4.0 μm), night only
  - SST quality level (0-4)

- **Ocean Color (day only)**
  - Normalized water-leaving radiances, nLw(λ)
  - Chlorophyll, $C_a$
  - Diffuse attenuation, $K_d(490)$
  - Aerosol type and concentration
    - Optical thickness, $\tau_a$
    - Ångström exponent
    - Atmospheric epsilon
  - Processing flags
    - Cloud, land, glint, atmfail, atmwarn, chlfail, chlwarn, etc.
Non-standard MODIS Ocean Products

• Ocean Temperature
  – Brightness temperatures

• Ocean Color
  – Alternate $C_a$ and $K_d$ algorithms
  – Chlorophyll fluorescence, FLH
  – Particulate inorganic carbon, Calcite
  – Inherent optical properties (various bio-optical models)
    • absorption (total, phaeophytin, dissolved matter)
    • backscatter (total, particulate)
  – Photosynthetically active radiation, iPAR, PAR (coming)
  – Euphotic depth ($Z_{eu}$, $Z_{sd}$)
  – Subsurface PAR at 1st optical depth, $K_d$(PAR)
  – Intermediate atmospheric correction products
MSL12
Multi-Sensor Level-1 to Level-2

• Common software for Level-2 processing of MODIS, SeaWiFS and other sensors in a consistent manner.

• Supports a multitude of product algorithms and processing methodologies.
  – standard and non-standard, validated and experimental
  – run-time selection of output product suite

• For MODIS, replaced:
  – PGE09, PGE10
  – products MOD18 - MOD28
  – file types MODOCL2A, MODOCL2B, MODOCQC, MOD28L2, MOD28QC
SeaDAS
SeaWiFS Data Processing, Analysis, and Display
MODIS Direct Broadcast Support

These images and histograms show pixel-for-pixel comparisons between MODIS/Aqua products generated from a Level-0 scene (UWisc DB station) using SeaDAS, and the overlapping 5-minute granule processed by the OBPG. Using SeaDAS, it is possible to exactly reproduce the standard products distributed by the OBPG, as well as a host of additional products.
Level-2 SST Processing

1 Convert observed radiances to brightness temperatures (BTs)

2 Apply empirical algorithm to relate brightness temperature in two wavelengths to SST

\[
sst = a_0 + a_1 \cdot BT_1 + a_2 \cdot (BT_2 - BT_1) + a_3 \cdot (1.0/\mu - 1.0)
\]

3 Assess quality (0=best, 4=not computed)
   - e.g., cloud or residual water vapor contamination
   - no specific “cloud mask”
Daytime SST Products

Longwave SST

Shortwave SST

Cloud

Sun glint
Nighttime SST Products

Shortwave SST

Longwave SST

Cloud
SST Quality Levels

Shortwave SST

Shortwave SST QL

QL=0
QL=1
QL=2
QL=3
QL=4
Light Paths to the Sensor
Scattering and Attenuation of Reflected Solar Bands
Ocean Color

1% error in instrument calibration or atmospheric model
~10% error in water-leaving radiance
Effects of the Atmosphere

- Gaseous absorption (ozone, water vapor, oxygen)
- Rayleigh scattering by air molecules
- Mie scattering and absorption by aerosols (haze, dust, pollution)
- Polarization (MODIS response varies with polarization of signal)

**Rayleigh (80-85% of total signal)**
- small molecules compared to nm wavelength, scattering efficiency decreases with wavelength as $\lambda^{-4}$
- reason for blue skies and red sunsets
- can be accurately approximated for a given atmospheric pressure and geometry (using a radiative transfer code)

**Aerosols (0-10% of total signal)**
- particles comparable in size to the wavelength of light, scattering is a complex function of particle size
- whitens or yellows the sky
- significantly varies and cannot be easily approximated
Surface Effects

Sun Glint

White Caps

Corrections based on statistical models (wind & geometry)
Atmospheric Correction

\[ t_d(\lambda) \ L_w(\lambda) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - TL_g(\lambda) - tL_f(\lambda) - L_r(\lambda) - L_a(\lambda) \]

\[ nL_w(\lambda) = L_w(\lambda) f_b(\lambda) / t_{d0}(\lambda) \mu_0 f_0 \]

But, we need aerosol to get \( L_w(\lambda) \)

\( L_w(\lambda=\text{NIR}) \approx 0 \) and can be estimated (model extrapolation from VIS) in waters where \( C_a \) is the primary driver of \( L_w(\lambda) \).

\[ L_a(\lambda=\text{NIR}) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - TL_g(\lambda) - tL_f(\lambda) - L_r(\lambda) - t_d(\lambda) L_w(\lambda) \]
Aerosol Determination in Visible Wavelengths

Given retrieved aerosol reflectance at two $\lambda$, and a set of aerosol models $fn(\theta, \theta_0, \phi)$.

$$\rho_a(748) \& \rho_a(869)$$

$$\rho_a(\text{NIR}) \Rightarrow \rho_{as}(\text{NIR})$$

$$\varepsilon(748, 869) = \frac{\rho_{as}(748)}{\rho_{as}(869)}$$

$$\varepsilon(\lambda, 869) = \frac{\rho_{as}(\lambda)}{\rho_{as}(869)}$$

$$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$$
Iterative Correction for Non-zero $L_w(NIR)$

1) Assume $L_w(NIR) = 0$
2) Compute $L_a(NIR)$
3) Compute $L_a(VIS)$ from $L_a(NIR)$
4) Compute $L_w(VIS)$
5) Estimate $L_w(NIR)$ from $L_w(VIS) + \text{model}$
6) Repeat until $L_w(NIR)$ stops changing

Iterating up to 10 times
Level-2 Ocean Color Processing

1. Determine atmospheric and surface contributions to total radiance at TOA and subtract, iterating as needed.

2. Normalize to the condition of Sun directly overhead at 1 AU and a non-attenuating atmosphere (nLw or Rrs = nLw/F₀).

3. Apply empirical or semi-analytical algorithms to relate the spectral distribution of nLw or Rrs to geophysical quantities.

4. Assess quality (set flags) at each step.
Level-2 Flags and Masking

RGB Image

Chlorophyll

Sediments

Glint

Cloud
Level-2 Flags and Masking

- Add masking for high glint
- Add masking for straylight
### Level-2 Ocean Color Flags

<table>
<thead>
<tr>
<th>BIT</th>
<th>NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>ATMFAIL</td>
<td>Atmospheric correction failure</td>
</tr>
<tr>
<td>02</td>
<td>LAND</td>
<td>Pixel is over land</td>
</tr>
<tr>
<td>03</td>
<td>BADANC</td>
<td>Reduced quality of ancillary data</td>
</tr>
<tr>
<td>04</td>
<td>HIGLINT</td>
<td>High sun glint</td>
</tr>
<tr>
<td>05</td>
<td>HILT</td>
<td>Observed radiance very high or saturated</td>
</tr>
<tr>
<td>06</td>
<td>HISATZEN</td>
<td>High sensor view zenith angle</td>
</tr>
<tr>
<td>07</td>
<td>COASTZ</td>
<td>Pixel is in shallow water</td>
</tr>
<tr>
<td>08</td>
<td>NEGLW</td>
<td>Negative water-leaving radiance retrieved</td>
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<tr>
<td>09</td>
<td>STRAYLIGHT</td>
<td>Straylight contamination is likely</td>
</tr>
<tr>
<td>10</td>
<td>CLDICE</td>
<td>Probable cloud or ice contamination</td>
</tr>
<tr>
<td>11</td>
<td>COCCOLITH</td>
<td>Coccolithophores detected</td>
</tr>
<tr>
<td>12</td>
<td>TURBIDW</td>
<td>Turbid water detected</td>
</tr>
<tr>
<td>13</td>
<td>HISOLZEN</td>
<td>High solar zenith</td>
</tr>
<tr>
<td>14</td>
<td>HITAU</td>
<td>High aerosol optical thickness</td>
</tr>
<tr>
<td>15</td>
<td>LOWLW</td>
<td>Very low water-leaving radiance (cloud shadow)</td>
</tr>
<tr>
<td>16</td>
<td>CHLFAIL</td>
<td>Derived product algorithm failure</td>
</tr>
<tr>
<td>17</td>
<td>NAVWARN</td>
<td>Navigation quality is reduced</td>
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<tr>
<td>18</td>
<td>ABSAER</td>
<td>possible absorbing aerosol</td>
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<tr>
<td>19</td>
<td>TRICHO</td>
<td>Possible trichodesmium contamination</td>
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<tr>
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<td>MAXAERITER</td>
<td>Aerosol iterations exceeded max</td>
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<td>21</td>
<td>MODGLINT</td>
<td>Moderate sun glint contamination</td>
</tr>
<tr>
<td>22</td>
<td>CHLWARN</td>
<td>Derived product quality is reduced</td>
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<tr>
<td>23</td>
<td>ATMWARN</td>
<td>Atmospheric correction is suspect</td>
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<tr>
<td>24</td>
<td>DARKPIXEL</td>
<td>Rayleigh-subtracted radiance is negative</td>
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<tr>
<td>25</td>
<td>SEAICE</td>
<td>Possible sea ice contamination</td>
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<tr>
<td>26</td>
<td>NAVFAIL</td>
<td>Bad navigation</td>
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<tr>
<td>27</td>
<td>FILTER</td>
<td>Pixel rejected by user-defined filter</td>
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<tr>
<td>28</td>
<td>SSTWARN</td>
<td>SST quality is reduced</td>
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<tr>
<td>29</td>
<td>SSTFAIL</td>
<td>SST quality is bad</td>
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<tr>
<td>30</td>
<td>HIPOL</td>
<td>High degree of polarization</td>
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<tr>
<td>31</td>
<td>spare</td>
<td>spare</td>
</tr>
<tr>
<td>32</td>
<td>OCEAN</td>
<td>not cloud or land</td>
</tr>
</tbody>
</table>

Level-2 flags used as masks in Level-3 processing
Are the results valid?
Available *In Situ* Match-Ups by Mission

MODIS/Aqua  
July 2002 - Present

SeaWiFS  
Sept 1997 - Present
Comparison of Water-Leaving Radiances to *In Situ*

### MODIS/Aqua vs SeaWiFS

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>MODIS # Matches</th>
<th>SeaWiFS # Matches</th>
<th>Mean Ratio*</th>
<th>% Difference**</th>
<th>r²</th>
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<tbody>
<tr>
<td>412</td>
<td>412</td>
<td>553</td>
<td>0.747</td>
<td>30.898</td>
<td>0.742</td>
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<tr>
<td>443</td>
<td>443</td>
<td>702</td>
<td>0.862</td>
<td>18.811</td>
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<tr>
<td>488</td>
<td>490</td>
<td>660</td>
<td>0.923</td>
<td>14.563</td>
<td>0.735</td>
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<tr>
<td>531</td>
<td>510</td>
<td>479</td>
<td>0.933</td>
<td>11.178</td>
<td>0.735</td>
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<tr>
<td>551</td>
<td>555</td>
<td>702</td>
<td>0.940</td>
<td>12.255</td>
<td>0.735</td>
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<tr>
<td>667</td>
<td>670</td>
<td>666</td>
<td>0.682</td>
<td>36.392</td>
<td>0.735</td>
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</table>
Comparison of Chlorophyll Retrievals to *In Situ*

<table>
<thead>
<tr>
<th>Sensor</th>
<th># Matches</th>
<th>Mean Ratio</th>
<th>% Diff</th>
<th>$r^2$</th>
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</thead>
<tbody>
<tr>
<td>SeaWiFS</td>
<td>1293</td>
<td>0.998</td>
<td>33.1</td>
<td>0.796</td>
</tr>
<tr>
<td>MODIS/Aqua</td>
<td>263</td>
<td>1.084</td>
<td>40.4</td>
<td>0.780</td>
</tr>
</tbody>
</table>
Definition of Trophic Subsets

Deep-Water (Depth > 1000m)

Oligotrophic (Chlorophyll < 0.1)

Mesotrophic (0.1 < Chlorophyll < 1)

Eutrophic (1 < Chlorophyll < 10)
Comparison of Relative Temporal Stability in nLw
Deep-Water, 8-Day Composites, Common Bins

MODIS/Aqua

SeaWiFS
MODIS/SeaWiFS Ratio Trends

Oligotrophic

Mesotrophic

Eutrophic
Seasonal Chlorophyll Images

MODIS/Aqua
Winter 2004
Summer 2004

SeaWiFS
Winter 2004
Summer 2004

0.01-64 mg m^-3
## SST Validation

### Buoy Measurements

<table>
<thead>
<tr>
<th>SST 11-12 μm</th>
<th>TERRA</th>
</tr>
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<tbody>
<tr>
<td>Year</td>
<td>day mean</td>
</tr>
<tr>
<td>2000</td>
<td>-0.139</td>
</tr>
<tr>
<td>2001</td>
<td>-0.262</td>
</tr>
<tr>
<td>2002</td>
<td>-0.135</td>
</tr>
<tr>
<td>2003</td>
<td>-0.086</td>
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<tr>
<td>2004</td>
<td>-0.068</td>
</tr>
<tr>
<td>2005</td>
<td>-0.110</td>
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<tr>
<td>2006</td>
<td>-0.105</td>
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<tr>
<td>all years</td>
<td>-0.108</td>
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<table>
<thead>
<tr>
<th>SST 11-12 μm</th>
<th>AQUA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>day mean</td>
</tr>
<tr>
<td>2002</td>
<td>-0.153</td>
</tr>
<tr>
<td>2003</td>
<td>-0.133</td>
</tr>
<tr>
<td>2004</td>
<td>-0.137</td>
</tr>
<tr>
<td>2005</td>
<td>-0.152</td>
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<td>2006</td>
<td>-0.135</td>
</tr>
<tr>
<td>all years</td>
<td>-0.142</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SST 4μm</th>
<th>TERRA</th>
<th>AQUA</th>
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<tbody>
<tr>
<td>Year</td>
<td>night mean</td>
<td>RMS</td>
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<tr>
<td>2000</td>
<td>-0.161</td>
<td>0.829</td>
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<tr>
<td>2001</td>
<td>-0.220</td>
<td>0.663</td>
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<td>2002</td>
<td>-0.191</td>
<td>0.528</td>
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<tr>
<td>2003</td>
<td>-0.176</td>
<td>0.500</td>
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<tr>
<td>2004</td>
<td>-0.178</td>
<td>0.493</td>
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<tr>
<td>2005</td>
<td>-0.178</td>
<td>0.471</td>
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<tr>
<td>2006</td>
<td>-0.174</td>
<td>0.473</td>
</tr>
<tr>
<td>all years</td>
<td>-0.179</td>
<td>0.505</td>
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</table>
Challenges to Remote Sensing of Coastal and Inland Waters

• Temporal and spatial variability
  – Limitations of satellite sensor resolution and repeat frequency
  – Validity of ancillary data (reference SST, wind)

• Straylight contamination from land

• Non-maritime aerosols (dust, pollution)
  – Region-specific models required
  – Absorbing aerosols

• Anthropogenic emissions (NO$_2$ absorption)

• Suspended sediments and CDOM
  – Invalid estimation of Lw(NIR), model not fn(C$_a$)
  – Saturation of observed radiances
Correction for NO$_2$ Absorption

OMI/Aura Tropospheric NO$_2$

20% increase in nLw(412)
MODIS Land/Atmosphere Bands
Application to Ocean Remote Sensing

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength</th>
<th>Resolution</th>
<th>Potential Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>645 nm</td>
<td>250 m</td>
<td>sediments, turbidity, IOPs</td>
</tr>
<tr>
<td>2</td>
<td>859</td>
<td>250</td>
<td>aerosols</td>
</tr>
<tr>
<td>3</td>
<td>469</td>
<td>500</td>
<td>$Ca$, IOPs, CaCO$_3$</td>
</tr>
<tr>
<td>4</td>
<td>555</td>
<td>500</td>
<td>$Ca$, IOPs, CaCO$_3$</td>
</tr>
<tr>
<td>5</td>
<td>1240</td>
<td>500</td>
<td>aerosols</td>
</tr>
<tr>
<td>6</td>
<td>1640</td>
<td>500</td>
<td>aerosols</td>
</tr>
<tr>
<td>7</td>
<td>2130</td>
<td>500</td>
<td>aerosols</td>
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</tbody>
</table>
## Expanded MODIS Ocean Band Suite

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Wavelength (nm)</th>
<th>Band Width (nm)</th>
<th>Spatial Resolution (m)</th>
<th>SNR at ( L_{typ} )</th>
<th>( L_{typ} ) ( \text{mW cm}^{-2} \mu \text{m}^{-1} \text{sr}^{-1} )</th>
<th>( L_{max} ) ( \text{mW cm}^{-2} \mu \text{m}^{-1} \text{sr}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
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Use of MODIS SWIR bands in coastal waters
(Wang and Shi, 2005)

- In the SWIR range water has more than one order of magnitude stronger absorption than that at the NIR
- In SWIR ocean is black even in turbid waters, $L_w(\text{SWIR}) = 0$
Improved Chlorophyll Retrievals using SWIR bands

NIR-based Aerosols

SWIR-based Aerosols
Satellite vs In Situ

NIR

Upper Bay, ALL  in situ n = 3663, med: 10.52, mode: 10.00
color legend: in situ MODIS--Aqua

Middle Bay, ALL  in situ n = 5314, med: 9.43, mode: 7.94

Lower Bay, ALL  in situ n = 7204, med: 6.50, mode: 6.31

SWIR

GWNIR oc3v5

GWSWIR oc3v5

GWNIR oc3v5

GWSWIR oc3v5

GWNIR oc3v5

GWSWIR oc3v5

Satellite vs In Situ

upper

middle

lower
showing river sediments
RGB Image: 250-meter Resolution
nLw(645): 250-meter resolution
Thank You!
Back-up Slides
### SST Quality Tests

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<td>Brightness temperatures are out-of-range</td>
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<td>BTDIFF</td>
<td>Brightness temperatures are too different</td>
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<td>Brightness temperatures are spatially non-uniform</td>
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<td>Sensor zenith angle very high</td>
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### SST Quality Levels

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Direct Comparison of Satellite nLw Retrievals
Deep-Water, 8-Day Composites, Common Bins

SeaWiFS & MODIS

MODIS / SeaWiFS
Coastal waters

- In case-2 waters (colored dissolved organic matter and suspended particles: sediments and phytoplankton), there can be a substantial water-leaving radiance in the NIR

- \( L_w(\text{NIR}) \neq 0 \)

- With standard processing, excess NIR radiance is wrongly attributed to the atmosphere

- Overestimation of \( L_a \) causes underestimation of \( L_w \) and elevated chlorophyll levels
Aerosol Determination in High Chlorophyll

- High chlorophyll waters (or turbid coastal water) may contain significant \( L_w \) contribution in the NIR

- Atmospheric correction is applied iteratively using NIR reflectance modeling based on consecutive chlorophyll and reflectance retrievals (green & red)

- The modeling assumes
  - NIR absorption to be due to water only, and
  - NIR backscatter to be a function of particulates, colored dissolved organic matter, and detritus
Short-wave SST

\[ \text{sst4} = a_0 + a_1 \cdot \text{BT39} + a_2 \cdot \text{dT} + a_3 \cdot (1.0/\mu - 1.0) \]

where:
BT39 = brightness temperature at 3.959 um, in deg-C
BT40 = brightness temperature at 4.050 um, in deg-C
\( \mu \) = cosine of sensor zenith angle
dBT = BT39 - BT40

a0, a1, a2, a3 - fit coefficients derived
derived by regression of MODIS BTs with \textit{in situ} buoys
vary seasonally (probably due to residual water-vapor effects)
determined by science team PI (Peter Minnett and Univ. Miami staff)
Long-wave SST

\[ \text{dBt} \leq 0.5 \]
\[ \text{sst} = a_{00} + a_{01} \times \text{BT}_{11} + a_{02} \times \text{dBt} \times \text{bsst} + a_{03} \times \text{dBt} \times (1.0 / \mu - 1.0) \]

\[ \text{dBt} \geq 0.9 \]
\[ \text{sst} = a_{10} + a_{11} \times \text{BT}_{11} + a_{12} \times \text{dBt} \times \text{bsst} + a_{13} \times \text{dBt} \times (1.0 / \mu - 1.0) \]

\[ 0.5 < \text{dBt} < 0.9 \]
\[ \text{sstlo} = a_{00} + a_{01} \times \text{BT}_{11} + a_{02} \times \text{dBt} \times \text{bsst} + a_{03} \times \text{dBt} \times (1.0 / \mu - 1.0) \]
\[ \text{ssthi} = a_{10} + a_{11} \times \text{BT}_{11} + a_{12} \times \text{dBt} \times \text{bsst} + a_{13} \times \text{dBt} \times (1.0 / \mu - 1.0) \]
\[ \text{sst} = \text{sstlo} + (\text{dBt} - 0.5) / (0.9 - 0.5) \times (\text{ssthi} - \text{sstlo}) \]

where:
- \( \text{BT}_{11} \) = brightness temperature at 11 um, in deg-C
- \( \text{BT}_{12} \) = brightness temperature at 12 um, in deg-C
- \( \text{bsst} \) = baseline SST, which is either \( \text{sst}_{4} \) (if valid) or \( \text{sst}_{\text{ref}} \) (from oisst)
- \( \text{dBt} \) = \( \text{BT}_{11} - \text{BT}_{12} \)
- \( \mu \) = cosine of sensor zenith angle
Gaseous Absorption

Transparency Windows

Transmittance due to O₂ and Water–Vapor

Wavelength (nm)

Transmittance
Atmospheric Correction Equation

\[ L_t = L_r + (L_a + L_{ra}) + tL_{wc} + TL_g + t L_w \]

- \( L_w \) is the quantity we wish to retrieve at each wavelength.
- \( TL_g \) is Sun glint, the direct reflectance of the solar radiance from the sea surface. Function of geometry and wind.
- \( tL_{wc} \) is the contribution due to "white"-capping, estimated from statistical relationship with wind speed.
- \( L_r \) is the contribution due to molecular (Rayleigh) scattering, which can be accurately computed.
- \( L_a + L_{ra} \) is the contribution due to aerosol and Rayleigh-aerosol scattering, estimated in NIR from measured radiances and extrapolated to visible using aerosol models.
Revised Temporal Calibration
Reflected Solar Bands

• In collaboration with MCST

• Reanalyzed Onboard Calibration (OBC) Data (solar, lunar)

• Removed residual correlations with diffuser screen geometry

• Refit solar diffuser trends to double exponential model

• Improved LUT extrapolation
Multi-Mission Approach

• Common software for Level-1 through Level-3
  – reduces potential for algorithm and implementation differences
  – sensor-specific issues consolidated in i/o function and external tables

• Mission-independent, distributed processing system
  – controls staging/sequencing of processing jobs for max through-put
  – 150x global reprocessing for MODIS, 1600x for SeaWiFS

• Standard procedures for calibration and validation
  – temporal calibration via On-Board Calibration system (OBC)
  – vicarious calibration to MOBY (instrument + algorithm calibration)
  – validation against SeaBASS in situ archive
  – temporal trending analysis of Level-3 products
Aerosol modeling

• Shettle and Fenn (1979) introduced a set of basic aerosol models
  – tropospheric
  – coastal
  – maritime, and
  – urban
• Each model consists of a mixture of dry aerosol particles that will grow when exposed to a humid environment
• Tropospheric, coastal, and maritime models defined for different humidity ranges are used in ocean color atmospheric correction
Operational aerosol models
(Gordon and Wang, 1994)

- There are 12 aerosol models used in the current atmospheric correction
  - The models are tabulated per sensor wavelength
    - albedo
    - extinction coefficient
    - phase function value per scattering angles
    - quadratic equation coefficients per $\theta_0$, $\theta$, $\phi$ for conversion from single scattering to multiple scattering reflectance
    - Rayleigh-aerosol diffuse transmittance coefficients, a and b

<table>
<thead>
<tr>
<th>AEROSOL MODELS</th>
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<tbody>
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<td>1  O99</td>
<td>oceanic 99% humidity</td>
</tr>
<tr>
<td>2  M50</td>
<td>maritime 50% humidity</td>
</tr>
<tr>
<td>3  M70</td>
<td>maritime 70% humidity</td>
</tr>
<tr>
<td>4  M90</td>
<td>maritime 90% humidity</td>
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<td>5  M99</td>
<td>maritime 99% humidity</td>
</tr>
<tr>
<td>6  C50</td>
<td>coastal 50% humidity</td>
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<tr>
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</tr>
<tr>
<td>12 T99</td>
<td>tropospheric 99% humidity</td>
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</table>
\[ \alpha = \ln \left( \frac{\tau(\lambda)}{\tau(865)} \right) / \ln \left( \frac{865}{\lambda} \right) \]

Single scattering reflectance ratio

\[ \epsilon(\lambda, 865) = \frac{\rho_{as}(\lambda)}{\rho_{as}(865)} \]

Ångström exponent

flat slope ⇒ weak wavelength dependence ⇒ large particles
Sequence of operations
(Gordon and Wang, 1994)

- Obtain $L_a$ from the top-of-the-atmosphere NIR radiances
  $$L_a = \frac{[(L_t - tL_{wc}) / t_{oz\_sol} / t_{oz\_sen} / polcor - L_r]}{t_{o2} - TL_g}$$

- Select the tabulated aerosol model which two-band relative NIR reflectances are the closest to satellite-derived reflectances
- Using this aerosol model estimate aerosol contribution in the visible bands
- Remove aerosol radiance in the visible bands
- Calculate VIS water-leaving radiances

<table>
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<tr>
<th>SeaWiFS Band</th>
<th>SeaWiFS $\lambda$ (nm)</th>
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<td>555</td>
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<td>7</td>
<td>765</td>
</tr>
<tr>
<td>8</td>
<td>865</td>
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</table>
Use of $\varepsilon$ in atmospheric correction

- $\varepsilon$ is used in selection of aerosol models and in propagating model reflectance from the NIR to VIS wavelengths.
- $\varepsilon$ is a ratio of single scattering aerosol reflectance.

\[
\varepsilon(\lambda, 865) = \frac{\rho_{\text{as}}(\lambda)}{\rho_{\text{as}}(865)}, \quad \text{where } \rho = \frac{\pi L}{F_0 \cdot \mu_0}
\]

- $\varepsilon$ is assumed known for any type of aerosol and geometry.

- Find two aerosol models which theoretical $\varepsilon$ brackets the $\varepsilon$ calculated from the data.
- Get modeled $\varepsilon$ for the two models for VIS wavelengths.
- Extrapolate $\rho_{\text{as}}$ to VIS for the two models.

\[
\rho_{\text{as}}(\lambda) = \rho_{\text{as}}(865) \cdot \varepsilon(\lambda, 865)
\]

- $\rho_{\text{as}}(\lambda) \Rightarrow \rho_{\text{a}}(\lambda)$
- Average $\rho_{\text{a}}(\lambda)$ between the two models $\Rightarrow L_{\text{a}}(\lambda) \Rightarrow tL_{\text{w}}(\lambda)$
nLw calculation

- \( nL_w = \frac{L_w \cdot brdf}{t_{sol} \cdot t_{oz\_sol} \cdot \mu_0 \cdot f_{sol}} \)

- \( nL_w \) - the radiance that would be measured exiting the flat surface of the ocean with the Sun at zenith (directly overhead) and with the atmosphere absent

- \( nL_w(VIS) \Rightarrow nL_w(VIS_{10nm}) \)

- correction of the retrieved \( nL_w \) from the full bandpass averaged value to a 10-nm square bandpass centered on the sensor nominal wavelength

\( \theta_0 \) – solar zenith angle, \( \theta \) – sensor zenith, \( \phi \) – relative azimuth

\( \mu_0 = \cos(\theta_0) \), \( \mu = \cos(\theta) \)

\( f_{sol} \) – solar distance correction factor

\( t_{oz\_sen} \) – diffuse transmittance from surface to sensor through ozone layer

\( t_{oz\_sen} \) – diffuse transmittance from Sun to surface through ozone layer

\( brdf \) – bidirectional reflectance correction at surface
Chlorophyll algorithms

• Each sensor has a default empirical chlorophyll algorithm
  – MODIS-Aqua default, OC3 algorithm
  – SeaWiFS default, OC4 algorithm

\[
C_a = 10^{0.283-2.753R+1.457R^2+0.659R^3-1.403R^4}, \text{ where } R = \log_{10}\left(\frac{R_{rs443} > R_{rs488}}{R_{rs551}}\right)
\]

\[
C_a = 10^{0.366-3.067R+1.930R^2+0.649R^3-1.532R^4}, \text{ where } R = \log_{10}\left(\frac{R_{rs443} > R_{rs490} > R_{rs510}}{R_{rs555}}\right)
\]

• There are other optional empirical and semi-analytical algorithms (inversion of \(R_{rs} = \)), e.g. Garver, Siegel, Maritorena, 2001
• There are optional IOP algorithms, e.g. Z.P. Lee, J. Carder

remote sensing reflectance \(R_{rs} = nL_w / F_0\), w – water, ph – phytoplankton, d – suspended particulate matter, g – colored dissolved organic matter
Uncertainties in the operational atmospheric correction
Coastal waters

- In case-2 waters (colored dissolved organic matter and suspended particles: sediments and phytoplankton), there can be a substantial water-leaving radiance in the NIR

- \( L_w(\text{NIR}) \neq 0 \)

- With standard processing, excess NIR radiance is wrongly attributed to the atmosphere
- Overestimation of \( L_a \) causes underestimation of \( L_w \) and elevated chlorophyll levels

Radiance in case-2 waters:
- absorption by CDOM in the blue
- reflectance by sediments in the NIR
- Chesapeake Bay

Radiance in clear waters:
- phytoplankton only
- around MOBY
MOBY used to adjust prelaunch calibration gains for visible bands using satellite-buoy comparisons.
Summary Statistics for Global Trend Comparisons
Water-Leaving Radiances

MODIS & SeaWiFS Mean $nL_w$

MODIS & SeaWiFS Std. Dev $nL_w$
Chlorophyll Comparisons

- Oligotrophic
- Mesotrophic
- Eutrophic
Residual Detector Striping

nLw(412) Before Correction

nLw(412) After Correction
Bidirectional Reflectance at Surface

- Each sensor views the same location on earth from different view angle and at different time of day (solar angle).
- The angular distribution of upwelling radiance varies with solar illumination angle and the scattering properties of the water body.
- A. Morel developed a correction for this effect, which was incorporated into the common processing software for both sensors.

Residual Scan Dependence in MODIS nLw(443)

Before BRDF

After BRDF
Artifacts and Issues
## Operational MODIS Ocean Band Suite

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<thead>
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<th>Band Number</th>
<th>Wavelength (nm)</th>
<th>Band Width (nm)</th>
<th>Spatial Resolution (m)</th>
<th>SNR at $L_{typ}$</th>
<th>$L_{typ}$</th>
<th>$L_{max}$</th>
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nLw(412) versus \textit{In Situ} for Common Match-ups

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<td>SeaWiFS</td>
<td>0.756</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>1.01</td>
</tr>
</tbody>
</table>
Deep-Water (Depth > 1000m)