Satellite Remote Sensing of Ocean Color and Temperature

Bryan Franz

NASA Ocean Biology Processing Group
NASA's Goal

To make available the highest quality ocean color (and sst) data to the broadest user community in the most timely and efficient manner possible.
NASA Ocean Biology Processing Group

- Ocean Color

- Missions to Measurements
  - Sensor calibration/characterization
  - Product validation (SeaBASS MDB)
  - Algorithm development and evaluation (NOMAD)
  - User processing and display (SeaDAS)
  - User support (Ocean Color Forum)

- Global processing & distribution
  - SeaWiFS
  - MODIS
  - CZCS
  - OCTS

- SST processing for MODIS
My Background

Aeronautical Engineering
  aerodynamic design

Space Science
  interplanetary dust modeling
  instrument calibration

Earth Science
  atmospheric correction
  calibration & validation
  sensor intercomparison
What is ocean color?
Ocean color is the measurement of spectral distribution of radiance (or reflectance) upwelling from the ocean in the visible regime.

Marine Spectral Reflectance

Spectral Wavelength (\(\lambda\))
Quantifying Phytoplankton Processes Remotely

Chlorophyll-a

Marine Spectral Reflectance

Chlorophyll Algorithm

OC4 v4
Phytoplankton

the chlorophyll concentration that we observe is associated with the distribution of phytoplankton.

Phytoplankton are microscopic plants that represent the first link in the marine food chain.

The patterns of distribution are related to both physical and biological processes.

Phytoplankton require light, water, nutrients, and carbon dioxide to grow.
Global Carbon Budgets

Atmosphere
- 760 (+3.3/yr)
- 7.1 PgC/yr
- ~90 PgC flux
- ~2-3 PgC uptake

Ocean
- 38,000
- ~100 PgC flux
- ~2 PgC uptake

Land
- 2000
- ~120 PgC flux
- ~1.2 PgC uptake

Humans
- ~120 PgC
- ~120 PgC flux
- ~120 PgC uptake

Petagrams (Pg) of Carbon
Why measure phytoplankton from space?
The warm heart of the Gulf Stream is readily apparent in the top SST image. As the current flows toward the northeast it begins to meander and pinch off eddies that transport warm water northward and cold water southward. The current also divides the local ocean into a low-biomass region to the south and a higher-biomass region to the north.

The data were collected by MODIS aboard Aqua on April 18, 2005.
Impact to Human Health

A toxic bloom of the cyanobacteria nodularia spumigena was reported in the Baltic Sea. On 24 July 2003, SeaWiFS captured this view of the bloom.
Impact to Fisheries

Coccolithophore Bloom
Impact of Natural Disasters

Hurricane Floyd

- massive flooding
- rivers carried
  - sediment
  - sewage
- discharged into coastal areas
- resulted in anoxic conditions in bay

Sept. 23, 1999

Albemarle Sound

Cape Fear River

Pamlico Sound
SeaWiFS captures El Nino / La Nina transition

January 1998

SeaWiFS captures El Nino / La Nina transition

July 1998
Chronology of NASA’s Ocean Color Measurements

Sea Surface Temperature: AVHRR, MODIS, VIIRS, ...

Winds: SSMI, Nscat, Quikscat, SeaWinds, ...

Sea Surface Topography: TOPEX, Jason, Grace, OSTM, ...

Salinity: Aquarius
## 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&lt;sub&gt;typ&lt;/sub&gt;</th>
<th>L&lt;sub&gt;typ&lt;/sub&gt; mW cm&lt;sup&gt;-2&lt;/sup&gt; m&lt;sup&gt;-1&lt;/sup&gt; sr&lt;sup&gt;-1&lt;/sup&gt;</th>
<th>L&lt;sub&gt;max&lt;/sub&gt; mW cm&lt;sup&gt;-2&lt;/sup&gt; m&lt;sup&gt;-1&lt;/sup&gt; sr&lt;sup&gt;-1&lt;/sup&gt;</th>
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**VIS/NIR**

**Ocean Color**
Light Paths to the Sensor
Scattering and Attenuation of Reflected Solar Bands
Ocean Color from Space

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

- Gaseous absorption (ozone, water vapor, oxygen)
- Scattering by air molecules (Rayleigh)
- 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

\[ t_d(\lambda) \ L_w(\lambda) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - T L_g(\lambda) - t L_f(\lambda) - L_r(\lambda) - L_a(\lambda) \]

\[ n L_w(\lambda) = L_w(\lambda) fb(\lambda) / t_d(\lambda) \mu_0 \ f_0 \]

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

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

\[ L_a(\lambda=NIR) = L_t(\lambda) / t_g(\lambda) / f_p(\lambda) - T L_g(\lambda) - t L_f(\lambda) - L_r(\lambda) - t_d(\lambda) L_w(\lambda) \]
Aerosol Determination in Visible Wavelengths

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

$$\rho = \frac{\pi L}{F_0 \cdot \mu_0}$$

$$\begin{align*}
\rho_a(748) & \quad \rho_a(869) \\
\rho_a(\text{NIR}) & \Rightarrow \rho_{as}(\text{NIR}) \\
\varepsilon(748, 869) & = \frac{\rho_{as}(748)}{\rho_{as}(869)} \\
\varepsilon(\lambda, 869) & = \frac{\rho_{as}(\lambda)}{\rho_{as}(869)}
\end{align*}$$
Atmospheric Correction

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

\[ nL_w(\lambda) = L_w(\lambda) \ f_b(\lambda) / t_d0(\lambda) \ \mu_0 \ f_0 \]
Level-2 Ocean Color Processing

1. Determine atmospheric and surface contributions to total radiance at TOA and subtract.

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)
Calibration
Temporal Calibration

SeaWiFS Lunar Calibrations

<table>
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<th>SeaWiFS Band</th>
<th>SeaWiFS λ (nm)</th>
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</table>
MOBY is used to adjust prelaunch calibration for visible bands using satellite-buoy comparisons.
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

<table>
<thead>
<tr>
<th>Wavelength</th>
<th># Matches</th>
<th>Mean Ratio*</th>
<th>% Difference**</th>
<th>r²</th>
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#### SeaWiFS

<table>
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<th># Matches</th>
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<th>% Difference**</th>
<th>r²</th>
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Comparison of Chlorophyll Retrievals to *In Situ*

<table>
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<th>Sensor</th>
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<th>r²</th>
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<td>263</td>
<td>1.084</td>
<td>40.4</td>
<td>0.780</td>
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</table>

[Graphs showing comparisons of MODIS/Aqua and SeaWiFS with In Situ data]
Seasonal Chlorophyll Images

MODIS/Aqua

Winter 2004

Summer 2004

SeaWiFS

Winter 2004

Summer 2004

0.01-64 mg m^{-3}
Definition of Trophic Subsets

Deep-Water (Depth > 1000m)

Oligotrophic (Chlorophyll < 0.1)

Mesotrophic (0.1 < Chlorophyll < 1)

Eutrophic (1 < Chlorophyll < 10)
Comparison of Spectral Distribution Trends

MODIS & SeaWiFS Mean nLw

![Graph showing spectral distribution trends for oligotrophic, mesotrophic, and eutrophic conditions.](image)
Chlorophyll Comparisons

Oligotrophic

Mesotrophic

Eutrophic
Challenges to Remote Sensing of Coastal Waters

- Temporal and spatial variability
- Straylight contamination from land
- Non-maritime aerosols (dust, pollution)
  - Region-specific models required
  - Absorbing aerosols
- Anthropogenic emissions
- Suspended sediments and CDOM
  - Invalid estimation of $L_w$ (NIR), model not $f_n(C_a)$
  - Saturation of observed radiances
- Bottom reflectance
Correction for NO$_2$ Absorption

MODIS/Aqua RGB

OMI/Aura Tropospheric NO$_2$
Satellite vs In Situ

NIR

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

GWNIR oc3v5
- n = 77962
- med: 22.65
- mode: 22.39

GWSWIR oc3v5
- n = 49551
- med: 11.92
- mode: 7.94

Mid Bay, ALL
- in situ: n = 5814, med: 8.43, mode: 7.94
- color legend: in situ MODIS-Aqua

GWNIR oc3v5
- n = 281734
- med: 16.83
- mode: 15.85

GWSWIR oc3v5
- n = 225116
- med: 9.70
- mode: 6.51

Lower Bay, ALL
- in situ: n = 7204, med: 6.50, mode: 6.31
- color legend: in situ MODIS-Aqua

GWNIR oc3v5
- n = 193471
- med: 11.12
- mode: 7.94

GWSWIR oc3v5
- n = 166281
- med: 7.49
- mode: 5.62
MODIS Land/Cloud Bands of Interest

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength</th>
<th>Resolution</th>
<th>Potential Use</th>
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</thead>
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<tr>
<td>1</td>
<td>645 nm</td>
<td>250 m</td>
<td>sediments, turbidity, IOPs</td>
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<td>859</td>
<td>250</td>
<td>aerosols</td>
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<tr>
<td>3</td>
<td>469</td>
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<td>$Ca$, IOPs, CaCO$_3$</td>
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<td>500</td>
<td>$Ca$, IOPs, CaCO$_3$</td>
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<tr>
<td>7</td>
<td>2130</td>
<td>500</td>
<td>aerosols</td>
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</tbody>
</table>
RGB Image: 250-meter Resolution
nLw(645): 250-meter resolution
Data Products and Distribution
Standard Ocean Products

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

- **Ocean Color**
  - Normalized water-leaving radiances, nLw(λ)
  - Chlorophyll, \( C_a \)
  - Diffuse attenuation, \( K_d(490) \)
  - Aerosol type and concentration
  - Processing flags

- **Data Types**
  - Level-1: observed radiances (swath-based)
  - Level-2: retrieved geophysical parameters (swath-based)
  - Level-3: global gridded composites (daily, 8-day, monthly, merged)
SeaDAS
Data Processing, Analysis, and Display Software

- free
- multi-mission
- display tools
- analysis tools
- processing
- open source
Examples of Non-standard Ocean Products

• 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)

• Euphotic depth ($Z_{eu}$, $Z_{sd}$)

• Spectrally integrated diffuse attenuation, $K_d$(PAR)
Data Distribution

• Free and open data distribution policy
  – Level-1, Level-2, and Level-3
  – ocean color and SST
  – CZCS, OCTS, SeaWiFS, MODIS

• Web-based browsing and direct ftp access

• Automated ordering system

• Subscription services

• Geographic and parameter sub-setting
Remote Sensing of Coral Reefs

http://oceancolor.gsfc.nasa.gov/cgi/reefs.pl
Water Depth Classification from SeaWiFS
http://oceancolor.gsfc.nasa.gov/
Acknowledgements

- Scarla Weeks and the CMS
  thanks for the invite

- Chuck McClain and Gene Feldman of NASA
  thanks for paying the bill

- The Ocean Biology Processing Group
  thanks for doing all the work
Thank You!
Thank You!
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
## Expanded MODIS Ocean Band Suite

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Diversity

Chlorophytes

Euglenophytes

Haptophytes

Glaucophytes

Bacillariophytes

Pyrrophytes (dinoflagellates)
Green color of plants, including phytoplankton, is a result of plant pigments, primarily chlorophyll a.

Phytoplankton – the principal source of organic matter in the oceans which sustains the marine food chain, a biological pump which sequesters carbon dioxide from the atmosphere into the deep ocean.
Algal Blooms

Feb. 25, 1999
Sea-viewing Wide Field-of-view (SeaWiFS) images of the Galapagos islands and surrounding waters from May 9, 1998 (top) and May 24, 1998 (bottom). The equatorial current shut down by El Niño reappeared over a period of days, indicated by the high concentrations of phytoplankton chlorophyll streaming to the west in the later image.
On November 26, 2002, SeaWiFS captured this relatively clear view of southern Africa and the seas around it. Phytoplankton distributions that are barely discernible in the quasi-true-color image become much clearer in the image of computed chlorophyll concentrations. In the second image, the lower chlorophyll concentrations associated with the Agulhas Current are visible along the southeastern coast of the continent. When this current meets the Antarctic Circumpolar Current, it gets retroflexed back towards the east and forms the meanders and eddies visible in the lower right quadrant of the image. Higher chlorophyll concentrations along the west coast of Africa result from upwelling associated with the Benguela Current which flows northward along the western edge of the continent.
Level-2 Flags and Masking

RGB Image

Chlorophyll

Sediments

Glint

Cloud
Level-2 Flags and Masking

- RGB Image
- nLw (443)
- Add masking for high glint
- Add masking for straylight

- Sediments
- Glint
- Cloud
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

8.7 mg/m$^3$
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) + model
6) Repeat until $L_w$(NIR) stops changing

Iterating up to 10 times
## MODIS Land/Cloud Bands of Interest

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<th>Wavelength</th>
<th>Resolution</th>
<th>Potential Use</th>
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Retrieval Coverage Differences Between SST and OC

RGB Image

SST

Chlorophyll

Sun glint

Sun glint
Change in Chlorophyll Retrieval with Alternate Aerosol Determination Methods

NIR-based Aerosols

SWIR-based Aerosols
Comparison of Relative Temporal Stability in nLw
Deep-Water, 8-Day Composites, Common Bins

MODIS/Aqua

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

SeaWiFS & MODIS

MODIS / SeaWiFS
MODIS Land/Cloud Bands of Interest

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<td>7</td>
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<td>500</td>
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spatial resolution and expanded dynamic range come at the cost of increased digitization error (reduced sensitivity at ocean radiances) and reduced signal to noise
SST Quality Levels

Shortwave SST

Shortwave SST QL

QL=0

QL=1

QL=2

QL=3

QL=4
Sea Surface Temperature
### Operational MODIS Ocean Band Suite

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<th>Band Width (nm)</th>
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<th>( L_{\text{typ}} ) mW cm(^{-2}) (\mu\text{m}^{-1}) sr(^{-1})</th>
<th>( L_{\text{max}} ) mW cm(^{-2}) (\mu\text{m}^{-1}) sr(^{-1})</th>
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#### VIS/NIR Ocean Color

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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 (regression against in situ buoy data)

\[
\text{sst} = a_0 + a_1 \cdot \text{BT}_1 + a_2 \cdot (\text{BT}_2 - \text{BT}_1) + a_3 \cdot (1.0/\mu - 1.0)
\]

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

Shortwave SST

Longwave SST

Cloud
## SST Validation
### Buoy Measurements

### SST 11-12 μm TERRA

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<th>Year</th>
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<th>RMS</th>
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### SST 11-12 μm AQUA

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http://oceancolor.gsfc.nasa.gov/
### Ocean Color Forum

Welcome, gene

**Forum**

- Mark Old
- Mark Read
- New
- Unread
- Replies
- ToDo
- Feeds
- Info

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