CHAPTER 18: HYDROSPHERIC SCIENCES

THE BLUE PLANET
### TABLE 18.1. Water on Earth

<table>
<thead>
<tr>
<th></th>
<th>By surface area $^a$</th>
<th>By volume $^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>94.90</td>
<td>97.1</td>
</tr>
<tr>
<td>Rivers and lakes</td>
<td>0.40</td>
<td>0.02</td>
</tr>
<tr>
<td>Groundwater</td>
<td>—</td>
<td>0.60</td>
</tr>
<tr>
<td>Permanent ice cap</td>
<td>4.69</td>
<td>2.20</td>
</tr>
<tr>
<td>Earth’s atmosphere</td>
<td>—</td>
<td>0.001</td>
</tr>
</tbody>
</table>

*Note.* Calculated from values given by Nace (1967).

$^a$Percentage by area of earth’s total water surface.

$^b$Percentage by volume of earth’s water.
CHANGES IN DEPTH

AMOUNT OF TURBIDITY
BRIGHTNESS RANGE

WATER SURFACE CONDITIONS
BATHYMETRY

PROCESSES AFFECTING THE REMOTE SIGNAL
MAIN COMPONENTS ABSORBING LIGHT IN THE WATER COLUMN

INHERENT OPTICAL PROPERTIES

Pure Seawater

Phytoplankton

\[ b_{\text{w}} \] Morel (1974)
\[ a_{\text{w}} \] Pope and Fry (1997)

\[ b_{\text{chl}} \] Loisel and Morel (1998)
\[ a_{\text{chl}} \] Sathyendranath et al. (2001)
WATER COLUMN VARIABILITY

Three typical spectral shapes of remote sensing reflectance curves found in Mayagüez Bay.
TYPES OF WATERS

CASE 1 WATERS

1. Living algal cells
   - Variable concentration

2. Associate debris
   - Originating from grazing by zooplankton and natural decay

3. Dissolved organic matter
   - Liberated by algae and their debris [yellow substance]

CASE 2 WATERS

4. Resuspended sediments
   - From bottom along the coastline and in shallow areas

5. Terrigenous particles
   - River and glacial runoff

6. Dissolved organic matter
   - Land drainage [terrigenous yellow substance]

7. Anthropogenic influx
   - Particulate and dissolved materials
Why Study Ocean Color?

- Water Color Is Modified By The Presence Of Chlorophyll A In A Quantitative Relationship
- Chlorophyll Concentration Is Related To Carbon Fixation, Primary Productivity And The Carbon Cycle
- Carbon Fixation Is Related To Biogeochemical Cycles of Important Elements Like Nitrogen and Sulfur
- Chlorophyll Distributions Yield Information of Important Processes in The Ocean Like Currents, Upwelling, and Warm Core Rings
- Chlorophyll Distribution Is Important For Fisheries
- Images of Ocean Color Guide Ships To Important Study Areas

Trophic Relationships in a Simple Food Web
PHYTOPLANKTON

"Phytoplankton are the foundation of the marine food chain and they can influence Earth's climate."

Photosynthesis

Ocean Color
Different pigments absorb at different wavelengths

Absorption spectra of chlorophylls extracted in acetone. (Redrawn and adapted from Hall and Rao 1977.)

Room temperature (X00%) absorption spectrum of the $P_{m-m}$ chlorophyll of Gloeocapsa sp. (By permission, Petzold and Albrecht 1978.)
PHYTOPLANKTON ROLE IN THE CARBON CYCLE?
Morel and Prieur (1977)

\[ R_{\lambda} = \frac{E_{u(\lambda)}}{E_{d(\lambda)}} \]

Reflectance = \frac{\text{upwelling irradiance}}{\text{downwelling irradiance}}

This reflectance ratio is dependent on the:
- a) absorption coefficient (a)
- b) backscattering coefficient (b_b)

of the particles involved.

In Remote Sensing:

Radiance(L) = Radiant flux per solid angle per projected area (units: watts/meter^2*steradians).

\[ L = \frac{d^2\Phi}{d\Omega dA \cos \theta} \]

This is function of \( \lambda \).
# Spaceborne Ocean Color Instruments

1. Coastal Zone Color Scanner (CZCS)
2. Modular Optoelectronic Scanner (MOS)
3. Ocean Color and Temperature Scanner (OCTS)
4. Sea-viewing Wide Field-of-view Sensor (SeaWiFS)
5. Ocean Color Imager (OCI)
6. Moderate Resolution Imaging Spectroradiometer (MODIS)
7. Global Imager (GLI)
8. Medium Resolution Imaging Spectrometer (MERIS)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Satellite</th>
<th>Dates of Operation</th>
<th>Spatial Resolution</th>
<th>Swath Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>CZCS</td>
<td>Nimbus-7</td>
<td>10/24/78-6/22/86</td>
<td>825 m</td>
<td>1556 km</td>
</tr>
<tr>
<td>MOS</td>
<td>IRS P3</td>
<td>3/21/96-Present</td>
<td>520 m</td>
<td>200 km</td>
</tr>
<tr>
<td>MOS</td>
<td>Priroda</td>
<td>4/23/96-Present</td>
<td>650 m</td>
<td>85 km</td>
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<tr>
<td>OCTS</td>
<td>ADEOS</td>
<td>8/17/96-7/1/97</td>
<td>700 m</td>
<td>1400 km</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>Orbview-2</td>
<td>8/1/97-Present</td>
<td>1100 m</td>
<td>2800 km</td>
</tr>
<tr>
<td>OCI</td>
<td>ROCSAT-1</td>
<td>1/99-Present</td>
<td>800 m</td>
<td>690 km</td>
</tr>
<tr>
<td>MODIS</td>
<td>Terra/Aqua</td>
<td>12/18/99-Present</td>
<td>1000 m</td>
<td>2330 km</td>
</tr>
<tr>
<td>GLI</td>
<td>ADEOS-2</td>
<td>scheduled</td>
<td>1000 m</td>
<td>1600 km</td>
</tr>
<tr>
<td>MERIS</td>
<td>ENVISAT-1</td>
<td>scheduled</td>
<td>1200 m</td>
<td>1450 km</td>
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</table>
## Current Ocean-Colour Sensors

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>AGENCY</th>
<th>SATELLITE</th>
<th>LAUNCH DATE</th>
<th>SWATH (km)</th>
<th>RESOLUTION (m)</th>
<th>BANDS</th>
<th>SPECTRAL COVERAGE (nm)</th>
<th>ORBIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCTS</td>
<td>CNSA (China)</td>
<td>HY-1B (China)</td>
<td>11 Apr. 2007</td>
<td>1400</td>
<td>1100</td>
<td>10</td>
<td>402 - 12,500</td>
<td>Polar</td>
</tr>
<tr>
<td>CZI</td>
<td>CNSA (China)</td>
<td>HY-1B (China)</td>
<td>11 Apr. 2007</td>
<td>500</td>
<td>250</td>
<td>4</td>
<td>433 - 695</td>
<td>Polar</td>
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<tr>
<td>MERIS</td>
<td>ESA (Europe)</td>
<td>ENVISAT (Europe)</td>
<td>1 Mar. 2002</td>
<td>1150</td>
<td>300/1200</td>
<td>15</td>
<td>412-1050</td>
<td>Polar</td>
</tr>
<tr>
<td>MMRS</td>
<td>CNSA (China)</td>
<td>HY-1B (China)</td>
<td>11 Apr. 2007</td>
<td>360</td>
<td>175</td>
<td>5</td>
<td>480-1700</td>
<td>Polar</td>
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<tr>
<td>MODIS-Aqua</td>
<td>NASA (USA)</td>
<td>Aqua (EOS-PM1)</td>
<td>4 May 2002</td>
<td>2330</td>
<td>1000</td>
<td>36</td>
<td>405-14,385</td>
<td>Polar</td>
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<tr>
<td>MODIS-Terra</td>
<td>NASA (USA)</td>
<td>Terra (EOS-AM1)</td>
<td>18 Dec. 1999</td>
<td>2330</td>
<td>1000</td>
<td>36</td>
<td>405-14,385</td>
<td>Polar</td>
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<tr>
<td>OCM</td>
<td>ISRO (India)</td>
<td>IRS-P4 (India)</td>
<td>26 May 1999</td>
<td>1420</td>
<td>350</td>
<td>8</td>
<td>402-885</td>
<td>Polar</td>
</tr>
<tr>
<td>POLDER-3</td>
<td>CNES (France)</td>
<td>Parasol</td>
<td>18 Dec. 2004</td>
<td>2100</td>
<td>6000</td>
<td>9</td>
<td>443-1020</td>
<td>Polar</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>NASA (USA)</td>
<td>OrbView-2 (USA)</td>
<td>1 Aug. 1997</td>
<td>2806</td>
<td>1100</td>
<td>8</td>
<td>402-885</td>
<td>Polar</td>
</tr>
</tbody>
</table>

Updated 03/05/2008

## Comparison of Wavelength & Bandwidth for Spaceborne Ocean Color Instruments

![Comparison of Wavelength & Bandwidth for Spaceborne Ocean Color Instruments](image)
**COASTAL ZONE COLOR SCANNER (CZCS)**

* LAUNCHED ON OCTOBER 23, 1978

* SENSOR OPERATION FINISHED ON JUNE 22, 1986

* INSTANTANEOUS FIELD OF VIEW (Pixel)
  825 METERS AT NADIR

* SWATH WIDTH - 1636 Km

* ALTITUDE - 955 Km

* SUN-SYNCHRONOUS ORBIT (SOUTH TO NORTH)

* SCAN PLANE TILT - +20° to -20°
SCANNING GEOMETRY OF THE CZCS

The Nimbus-7 satellite with its various sensors (NASA PHOTO).
CZCS BANDS

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>WAVELENGTH (NM)</th>
<th>CENTER (NM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>455 - 455</td>
<td>445</td>
</tr>
<tr>
<td>2</td>
<td>510 - 530</td>
<td>520</td>
</tr>
<tr>
<td>3</td>
<td>540 - 560</td>
<td>550</td>
</tr>
<tr>
<td>4</td>
<td>660 - 680</td>
<td>670</td>
</tr>
<tr>
<td>5</td>
<td>700 - 800</td>
<td>750</td>
</tr>
<tr>
<td>6</td>
<td>10,500 - 12,500</td>
<td></td>
</tr>
</tbody>
</table>

Gordon et al. (1983)

\[ \text{Lt}(\lambda) = \text{Lr}(\lambda) + \text{La}(\lambda) + t(\lambda)\text{Lw}(\lambda) \]

Where:  
\( \text{Lt}(\lambda) = \text{Total Radiance} \)
\( \text{Lr}(\lambda) = \text{Rayleigh Scattering} \) 
(due to air molecules)
\( \text{La}(\lambda) = \text{Aerosol Scattering} \) 
(due to suspended particles)
\( \text{Lw}(\lambda) = \text{Water-leaving radiance} \) 
(transmitted through the atmosphere)
\( t(\lambda) = \text{diffuse transmittance} \) 
(of the atmosphere (small#))
\( \text{t}(\lambda) = \text{which absorbs part of the light} \)
The pigment concentration in the water affects the $L_w(\lambda)$. So, the biologists look for this value in the CZCS images.

Then, the atmospheric correction is a process of retrieval the $L_w(\lambda)$ from $L_t(\lambda)$. For this, $L_r(\lambda)$ and $L_a(\lambda)$ must be calculated.

$L_r(\lambda)$ : Is determined by analytic modeling.

$L_a(\lambda)$ : Is estimated from the 670 channel.

<table>
<thead>
<tr>
<th>Rayleigh Model ($L_r$)</th>
<th>Aerosol Correction ($L_a$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This model depend on:</td>
<td>Assumption: At 670 band the water-leaving radiance is equal to zero ($L_w(\lambda) = 0$) in waters with low pigments concentrations. Then all radiance detected in this band is due to aerosols.</td>
</tr>
<tr>
<td>a) time of year</td>
<td>$L_a(670)$ is then calculated as the difference between $L_t(670)$ and $L_r(670)$ which was calculated from the Rayleigh Model:</td>
</tr>
<tr>
<td>b) time of day</td>
<td>$L_a(670) = L_t(670) - L_r(670)$</td>
</tr>
<tr>
<td>c) look angle of satellite view</td>
<td>The $L_a$ at the other wavelengths (i.e. 440, 528, 550 nm) is then related to $L_a(670)$ by a set of &quot;epison coefficients&quot; which are computed in base of aerosols type and distribution (Gordon et al., 1983).</td>
</tr>
</tbody>
</table>

Two Models:

1) **Single Scattering**: Valid for calculations within 55 degrees of the solar equator.

2) **Multiple Scattering**: Extends quantitative calculations out to 65 degrees of the solar equator and qualitative calculations within 75-80 degrees.

*Most of the calculations are based on the multiple scattering algorithm.*

This model uses tables which include:

- Sensor calibration and degradation
- Clear water radiance
- Instantaneous solar irradiance
- Ozone optical thickness
SOURCES OF ERROR

Atmospheric Correction

1) Suspended sediments may scatter at 670 wavelength, it is possible to overestimate \( \text{La} \) in coastal areas affected by river discharge and/or resuspension of sediments.

2) Another factor that could cause reflectance at \( \text{La}(670) \) is backscatter due to coccolithophores.

3) The method for atmospheric correction requires good sensor calibration. But, CZCS radiometric sensitivity decay with time (Gordon et al., 1983).

BIO-OPTICAL ALGORITHMS

Now we are ready to calculate the pigments concentration. To do this is necessary to consider few important assumptions.

ASSUMPTIONS

1) Phytoplankton absorption at 550 nm is minimal.
2) Phytoplankton degradation products covary with chlorophyll.
3) No red light is emitted from ocean \( (\text{Lw}670 = 0) \).
4) The refractive index of phytoplankton is identical for all species.
The algorithm used for estimating the pigments content of the ocean from CZCS measurements involves the use of radiance ratios. The general form of the equation is

$$\log(C) = a + b \log\left[\frac{L_{w(1)}}{L_{w(2)}}\right]$$

Where
- $C$ is the pigment concentration (mg/m^3)
- $a, b$ are regression coefficients
- $L_{w(1)}, L_{w(2)}$ are the atmospherically corrected radiances for a pair of CZCS channels

For CZCS pigments processing, these channel pairs are

- (443, 550 nm), for $C < 1.5$ mg/m^3
- (520, 550 nm), for $C > 1.5$ mg/m^3
Monthly Composite of CZCS During September 1979

Phytoplankton Pigment Concentration (mg/m³)

Sea-viewing Wide-Field-of view Sensor (SeaWiFS)
Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

<table>
<thead>
<tr>
<th>Band</th>
<th>Wavelength (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>412</td>
</tr>
<tr>
<td>2</td>
<td>443</td>
</tr>
<tr>
<td>3</td>
<td>490</td>
</tr>
<tr>
<td>4</td>
<td>510</td>
</tr>
<tr>
<td>5</td>
<td>555</td>
</tr>
<tr>
<td>6</td>
<td>670</td>
</tr>
<tr>
<td>7</td>
<td>765</td>
</tr>
<tr>
<td>8</td>
<td>865</td>
</tr>
</tbody>
</table>

CZCS BANDS

<table>
<thead>
<tr>
<th>CHANNEL</th>
<th>WAVELENGTH (nm)</th>
<th>CENTER (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>412 - 613</td>
<td>443</td>
</tr>
<tr>
<td>2</td>
<td>513 - 550</td>
<td>538</td>
</tr>
<tr>
<td>3</td>
<td>568 - 660</td>
<td>614</td>
</tr>
<tr>
<td>4</td>
<td>668 - 870</td>
<td>724</td>
</tr>
<tr>
<td>5</td>
<td>790 - 1200</td>
<td>967</td>
</tr>
</tbody>
</table>

Phytoplankton Chl-a

Capability of ocean colour remote sensing

- Derive the depth-integrated chlorophyll a concentration in the range 0 - 60 mg l⁻¹
- Accuracy of about 35% in Case I oligotrophic open-ocean waters
- Much less in turbid coastal waters (Case II waters) because of suspended sediments and yellow substance
- Development of algorithms and methods for better estimation of Chlorophyll a in coastal waters is a key-point of present research
Chlorophyll a concentration Algorithms for SeaWiFS

Aiken [1995] algorithm for the North Sea (PML, UK)

Chl-a = exp[0.464 - 1.989 * ln(bw490/bw555)] if < 2.0 \mu g.l^{-1}

Chl-a = \frac{f(bw490/bw555) - 5.290}{[0.719 - 4.230 \times (bw490/bw555)]} \text{ otherwise}

bw is the measured radiance corrected from atmospheric effects, namely the water leaving radiance

The NASA algorithm (Case I waters only)

Chl-a = -0.04 + a_{\log}(0.341 - 3.001 \times R + 2.811 \times R^2 - 2.041 \times R^3)

where

R = \log_{10}(\frac{R_{\text{rs}}(490)}{R_{\text{rs}}(550)})

R is the remote sensing reflectance: measured radiance corrected from atmospheric effects and normalized for the sun position

SeaWiFS ALGORITHMS

OC2 Chlorophyll Algorithm:

C = 10^{(a_0 + a_1 \times R + a_2 \times R^2 + a_3 \times R^3)} + a_4

R = \frac{R_{\text{rs}}(490)}{R_{\text{rs}}(555)}

a = [0.3410, -3.0010, 2.8110, -2.0410, -0.0400]

OC4 Chlorophyll Algorithm:

C = 10^{(a_0 + a_1 \times R + a_2 \times R^2 + a_3 \times R^3)} + a_4

R = \log(\max(R_{\text{rs}}(443), R_{\text{rs}}(490), R_{\text{rs}}(510)/R_{\text{rs}}555))

a = [0.4708, -3.8469, 4.5338, -2.4434, -0.0414]
GLOBAL ESTIMATION OF PHYTOPLANKTON CHLOROPHYLL-A USING SEAWIFS DATA

RECEIVING CAPABILITIES OF SeaWiFS AT UPRM

L-BAND ANTENNA
COASTAL UPWELLING IN THE CARIBBEAN SEA

AVHRR
Sea Surface Temperature

SeaWiFS
Chlorophyll-a

SeaWiFS Image
Mt. Etna Eruption - 30 October 2002

Mt. Etna on the island of Sicily erupting. The above SeaWiFS image of the eruption plume was captured on Wednesday, 30 October 2002 at 11:07 GMT.
Moderate Resolution Imaging Spectroradiometer (MODIS)

Launched on December 18, 1999

Launched on May 4, 2002
MODIS Technical Specifications

Orbit: 705 km, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (Aqua), sun-synchronous, near-polar, circular

Scan Rate: 20.3 rpm, cross track

Swath Dimensions: 2330 km (cross track) by 10 km (along track at nadir)

Telescope: 17.78 cm diam. off-axis, afocal (collimated), with intermediate field stop

Size: 1.0 x 1.6 x 1.0 m

Weight: 228.7 kg

Power: 162.5 W (single orbit average)

Data Rate: 10.6 Mbps (peak daytime); 6.1 Mbps (orbital average)

Quantization: 12 bits

Spatial Resolution: 250 m (bands 1-2)
Resolution: 500 m (bands 3-7)
1000 m (bands 8-36)

Design Life: 6 years
### MODIS BANDS

#### Land/Cloud/Aerosols Boundaries
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>620 - 670</td>
<td>21.8</td>
<td>126</td>
</tr>
<tr>
<td>2</td>
<td>841 - 876</td>
<td>24.7</td>
<td>201</td>
</tr>
</tbody>
</table>

#### Land/Cloud/Aerosols Properties
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>459 - 479</td>
<td>35.3</td>
<td>243</td>
</tr>
<tr>
<td>4</td>
<td>545 - 565</td>
<td>29.0</td>
<td>228</td>
</tr>
<tr>
<td>5</td>
<td>1230 - 1250</td>
<td>5.4</td>
<td>74</td>
</tr>
<tr>
<td>6</td>
<td>1628 - 1652</td>
<td>7.3</td>
<td>275</td>
</tr>
<tr>
<td>7</td>
<td>2105 - 2155</td>
<td>1.0</td>
<td>110</td>
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</tbody>
</table>

#### Ocean Color/Phytoplankton/Biogeochemistry
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
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</thead>
<tbody>
<tr>
<td>8</td>
<td>405 - 420</td>
<td>44.9</td>
<td>880</td>
</tr>
<tr>
<td>9</td>
<td>438 - 448</td>
<td>41.9</td>
<td>838</td>
</tr>
<tr>
<td>10</td>
<td>483 - 493</td>
<td>32.1</td>
<td>801</td>
</tr>
<tr>
<td>11</td>
<td>526 - 536</td>
<td>27.9</td>
<td>754</td>
</tr>
<tr>
<td>12</td>
<td>546 - 556</td>
<td>21.0</td>
<td>750</td>
</tr>
<tr>
<td>13</td>
<td>662 - 672</td>
<td>9.5</td>
<td>910</td>
</tr>
<tr>
<td>14</td>
<td>673 - 683</td>
<td>8.7</td>
<td>1087</td>
</tr>
<tr>
<td>15</td>
<td>743 - 753</td>
<td>10.2</td>
<td>586</td>
</tr>
<tr>
<td>16</td>
<td>852 - 877</td>
<td>6.2</td>
<td>516</td>
</tr>
</tbody>
</table>

#### Atmospheric Water Vapor
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>890 - 920</td>
<td>10.0</td>
<td>167</td>
</tr>
<tr>
<td>18</td>
<td>931 - 941</td>
<td>3.6</td>
<td>57</td>
</tr>
<tr>
<td>19</td>
<td>915 - 965</td>
<td>15.0</td>
<td>250</td>
</tr>
</tbody>
</table>

### MODIS BANDS

#### Surface/Cloud Temperature
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.660 - 3.840</td>
<td>0.45(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td>21</td>
<td>3.929 - 3.989</td>
<td>2.38(335K)</td>
<td>2.00</td>
</tr>
<tr>
<td>22</td>
<td>3.929 - 3.989</td>
<td>0.67(300K)</td>
<td>0.07</td>
</tr>
<tr>
<td>23</td>
<td>4.020 - 4.080</td>
<td>0.79(300K)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

#### Atmospheric Temperature
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>4.433 - 4.498</td>
<td>0.17(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td>25</td>
<td>4.482 - 4.549</td>
<td>0.59(275K)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### Cirrus Clouds Water Vapor
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>1.360 - 1.390</td>
<td>6.00(300K)</td>
<td>0.25</td>
</tr>
<tr>
<td>27</td>
<td>6.535 - 6.895</td>
<td>1.16(240K)</td>
<td>0.25</td>
</tr>
<tr>
<td>28</td>
<td>7.175 - 7.475</td>
<td>2.18(250K)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### Cloud Properties
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>8.400 - 8.700</td>
<td>9.58(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td>30</td>
<td>9.580 - 9.880</td>
<td>3.69(250K)</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### Surface/Cloud Temperature
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>10.780 - 11.280</td>
<td>9.55(300K)</td>
<td>0.05</td>
</tr>
<tr>
<td>32</td>
<td>11.770 - 12.270</td>
<td>8.94(300K)</td>
<td>0.05</td>
</tr>
</tbody>
</table>

#### Cloud Top Altitude
<table>
<thead>
<tr>
<th>Band</th>
<th>Bandwidth</th>
<th>Spectral Radiance</th>
<th>Required NE[delta]T(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>13.165 - 13.485</td>
<td>4.52(260K)</td>
<td>0.25</td>
</tr>
<tr>
<td>34</td>
<td>13.485 - 13.785</td>
<td>3.76(250K)</td>
<td>0.25</td>
</tr>
<tr>
<td>35</td>
<td>13.785 - 14.085</td>
<td>3.11(240K)</td>
<td>0.25</td>
</tr>
<tr>
<td>36</td>
<td>14.085 - 14.385</td>
<td>2.08(220K)</td>
<td>0.35</td>
</tr>
</tbody>
</table>
Sea Surface Temperature (Celsius Degree)

Phytoplankton Chlorophyll-a (mg m\(^3\))

Weekly MODIS Chlorophyll
March 6 - 13, 2001
Weekly Ocean Net Primary Productivity

Challenges and Opportunities of Remote Sensing in Coastal Waters

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University of Puerto Rico at Mayagüez
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Objectives of this presentation

✓ Discuss the potential and limitations for remote sensing of ocean color and coral reefs monitoring in Caribbean coastal waters.

✓ Demonstrate the regional capabilities to develop very strong educational, research, and monitoring programs using remote sensing.

✓ Emphasize that new satellite sensors and image processing techniques are needed for the Caribbean.

✓ Show that a multi-sensor and multi-disciplinary approach is required to understand Caribbean coastal waters.

✓ Establish the importance of land-sea interactions studies for future Caribbean OOS.

Challenges for Ocean Color in Caribbean Coastal Waters
Global problems for ocean color remote sensing are also present in the Caribbean

- Better understanding of the temporal and spatial variability of inherent and apparent optical properties is needed.
- Site-specific bio-optical algorithms are required to better estimates the concentration of Chlorophyll-a and Suspended Sediments.
- CDOM and suspended sediments are seasonally produced by rivers discharge and their correlation controls the bio-optical variability.
- Photosynthetic picoplankton, like cyanobacteria, are competing with large phytoplankton for the quality and quantity of light.
- Current satellite sensors do not provide accurate estimates of water quality parameters in coastal areas due to all the above problems.

But, three unique challenges for remote sensing are also found in Caribbean coastal waters

1. **Size of the coastal regions**-requires sensors with very high spatial resolution.
2. **Low concentration of the parameters**-requires sensors with very high S/N ratio.
3. **Short-term effects of dramatic seasonal events, like hurricanes, on land-sea interactions**-requires sensors with high temporal resolution.
PHYTOPLANKTON DYNAMICS AFFECTED BY LARGE REGIONAL RIVERS AS DETECTED BY SEAWIFS

But, SeaWiFS images fail in coastal waters with local rivers
Low Chl for developing bio-optical algorithms
(also the number of data points are limited)

\[
y = -0.4212x + 1.8219
\]
\[
R^2 = 0.7436
\]

Low reflectance signal and no fluorescence peak
PHYTOPLANKTON DYNAMICS AFFECTED BY HURRICANES

Opportunities for Ocean Color in Caribbean Coastal Waters
Easy access to coastal waters
Mayaguez Bay at Western P.R.

- It is an accessible natural laboratory with large spatial and temporal variations.
- It is affected by rivers discharge and anthropogenic effects.
- Past and current research has provided excellent background information.
- It is an ideal place to develop and test remote sensing techniques for coastal waters.

Good sampling equipment for sensors validation and algorithms development
New algorithms for MODIS

-Chlorophyll-a = Empirical algorithm
500 m resolution
\[ [\text{Chl-a}] = -42.12 \times (B3/B4) + 1.8219 \]

-Chlorophyll-a = OC3 MODIS algorithm
1 km resolution

SATELLITE DATA COLLECTION
BY THE UPRM-TCESS
SPACE INFORMATION LABORATORY
UPRM Station Viewing Area

PHYTOPLANKTON DYNAMICS AFFECTED BY COASTAL UPWELLING

AVHRR
Sea Surface Temperature

SeaWiFS
Chlorophyll-a
Empirical Algorithm to estimate Suspended Sediments in Mayaguez Bay using AVIRIS

\[
SS \text{ (mg/l)} = 0.0829 \times R_{777} + 0.0325
\]

Where \( R_{777} \) = AVIRIS Reflectance at 777 nm
Sensors with high spatial resolution

Challenges for monitoring benthic habitats in Caribbean Coastal Waters
Issues in benthic habitat mapping

1. Sensor Characteristics:
   - Signal to Noise (S/N) Ratio
   - Spatial and Spectral Resolution

2. Atmospheric Conditions:
   - Scattering and Absorption
   - Gases and Aerosols

3. Signal from the Water Column:
   - Surface Conditions
   - Light Penetration
   - Bio-Optical Properties

4. Signal from the Bottom:
   - Water Depth
   - Bottom Type
   - Size of the Community

5. Signal Processing

Scientific Issues

- Identify capabilities for subsurface aquatic analysis using passive optical remote sensing.

- Develop, implement and evaluate classification and detection algorithms.

- Analyze spectral interaction between bottom material and water column under natural and controlled conditions.

- Examine temporal changes in the spectral signal at both the field and image level.

- Assess performance of change detection algorithms.
Primary Study Area

Enrique Reef

Puerto Rico

WHAT IS THE BEST RESOLUTION?

EVALUATE THE SPECTRAL VS SPATIAL RESOLUTION

<table>
<thead>
<tr>
<th>SENSOR</th>
<th>BANDS</th>
<th>SPECTRAL RANGE (µm)</th>
<th>PIXEL SIZE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKONOS</td>
<td>4 PAN</td>
<td>0.45-0.90</td>
<td>4</td>
</tr>
<tr>
<td>HYPERION</td>
<td>220</td>
<td>0.4-2.35</td>
<td>30</td>
</tr>
</tbody>
</table>
Image interpretation and classification

**Change Detection**

\[ B(x) = \begin{cases} 
1 & \text{if pixel } x \text{ has significant change from } I_1(x) \text{ to } I_2(x) \\
0 & \text{Otherwise} 
\end{cases} \]

Work by Vanessa Ortiz Rivera, UPRM
Spectral Unmixing

2002 HYPERION

Unconstrained

Sum To One

Unconstrained Non-Negative

Sum Less Than or Equal to One Non-Negative

Work by Samuel Rosario, UPRM

Opportunities for monitoring benthic habitats in Caribbean Coastal Waters
Field Data

Field Measurements:
- Aquatic optical properties
- Georeferenced benthic reflectance
- Spectral library (species)
- Benthic Composition
- Detailed habitat map

Multi-Sensors Data

HYPERION:
- August 15, 2002
- January 15, 2003
- March 13, 2004
- March 29, 2004
- September 5, 2004

Multi/Hyperspectral Data:
- IKONOS
- HYPERION
- AVIRIS
- HyMap

IKONOS:
- 2002
- 2004
- 2006

AVIRIS: August 19, 2004

Coral: Porites compressa
Spectral Unmixing

AVIRIS Color Composite

Benthic Habitat Composition

Work by James Goodman, UPRM

Studying deep corals using an AUV
Coral Reef Images and Results

Work by Roy Armstrong, UPRM

Multi-modal/Multi-platform Approach

To meet scientific objectives modal/multiplatform capability is needed

Shallow Reefs <30m

Deep Reefs SeaBED AUV

Spaceborne Hyperspectral Imager
In summary…
what are the major challenges?

- Higher spectral, spatial, temporal, and radiometric resolutions in future sensors.
- Multi-modalities approaches.
- More site-specific algorithms instead of global algorithms.
- Integrate current diverse capabilities in future OOS.
- Develop a better knowledge of land-sea interactions.

In summary…
what are the major opportunities?

- The region has the people with the appropriate expertise to overcome the challenges.
- Required infrastructure for remote sensing, like optical instruments and satellite receiving station, is already on place.
- Past and present data provide a good baseline for future work.
A Caribbean OOS should monitor the Land-Sea Interactions by combining multiple sensors data

Assignment

Read Chapter 19 and answer the review questions 1, 4, and 9 (at the end of the chapter).