SCIENCE FOCUS: Turbidity

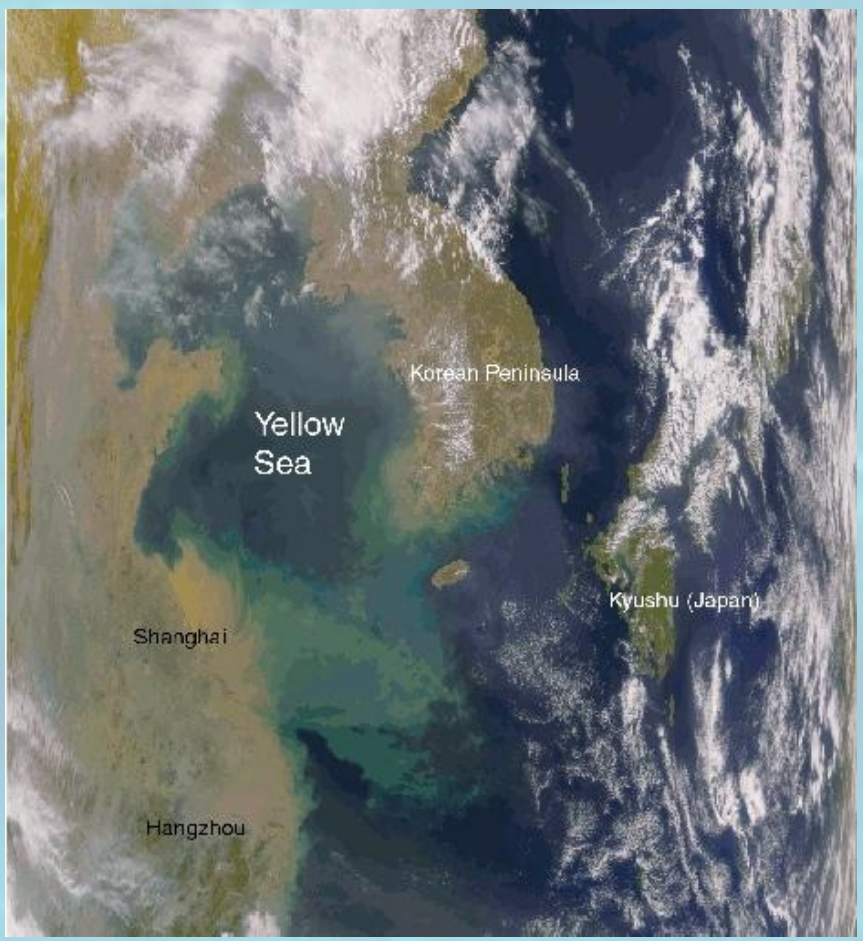
Through a Water Column Darkly, Part 1

There are only two types of ocean water "out there", if you listen to an optical oceanographer. Optical oceanographers refer to these two types of water as *cases*, so the two cases are Case 1 and Case 2, as you might expect. Case 1 water is the kind of water that is found in the open ocean, far from land, nearly as transparent as glass, a deep azure when viewed over the side of a ship. In Case 1 waters, all of the optical properties are determined by the concentration of phytoplankton and its associated chlorophyll. In Case 1 water, the concentration of phytoplankton and chlorophyll is usually low. This combination of properties means that the optical properties of Case 1 water are relatively easy to analyze, and thus relatively easy to model.

And then there's Case 2 water, which is everything else.

Case 2 water might be the muddy-brown water found at the mouth of the Amazon, Mississippi, or Yangtze rivers, or the coffee-black waters of the Suwanee and Apalachicola rivers in Florida. Case 2 water could be found where hurricane winds have pushed the sediments found in a coral lagoon offshore into the adjacent deep ocean. Or Case 2 waters could be teeming verdant green waters loaded with chlorophyll and mixed with a little mud from the sea bottom, found in a coastal upwelling zone.

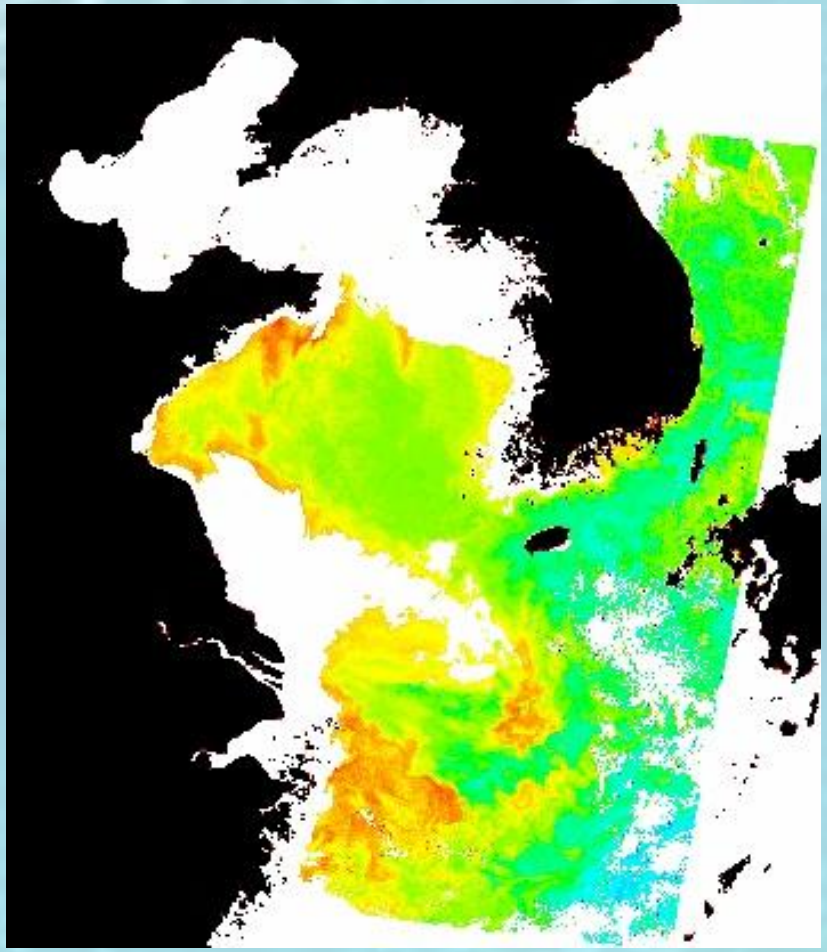
The image on the next page shows a SeaWiFS view of the Yellow Sea (Huang Hai) on April 1, 2001, when Case 2 waters extended considerably offshore the coast of China. The cause of the turbidity here is primarily sediments carried by the Yangtze (Changjiang) River (which enters the Yellow Sea at Shanghai) and other rivers during heavy river flow caused by spring rains. Phytoplankton growth offshore also appears to be enhanced due to nutrients carried by the rivers. This SeaWiFS data was acquired by the HRPT station at the Second Institute of Oceanography in Hangzhou, People's Republic of China.



In short, Case 2 waters consist of water that is generally termed *turbid*. And that means that Case 2 waters are an optical oceanographer's headache, compared to the serene clarity of Case 1 waters. But scientists love a challenge. So now we will look into the problem of turbidity, even though it might be difficult to see our way clear to a solution.

First of all, why are Case 2 waters important? There are two primary reasons. The first reason is that in many of the situations where Case 2 waters are encountered, these waters are significantly more productive than Case 1 waters. River mouths and coastal upwelling zones are two classic examples of this situation, where primary productivity (the production of carbon by photosynthesis, in this case by phytoplankton) is enhanced by the nutrients delivered by the river water or contained in the upwelling deep water. The increased productivity in these coastal regions makes them important to the global carbon cycle, and it is therefore vital to accurately quantify the productivity in these regions. Turbidity makes accurate quantification of the amount of chlorophyll in these waters difficult.

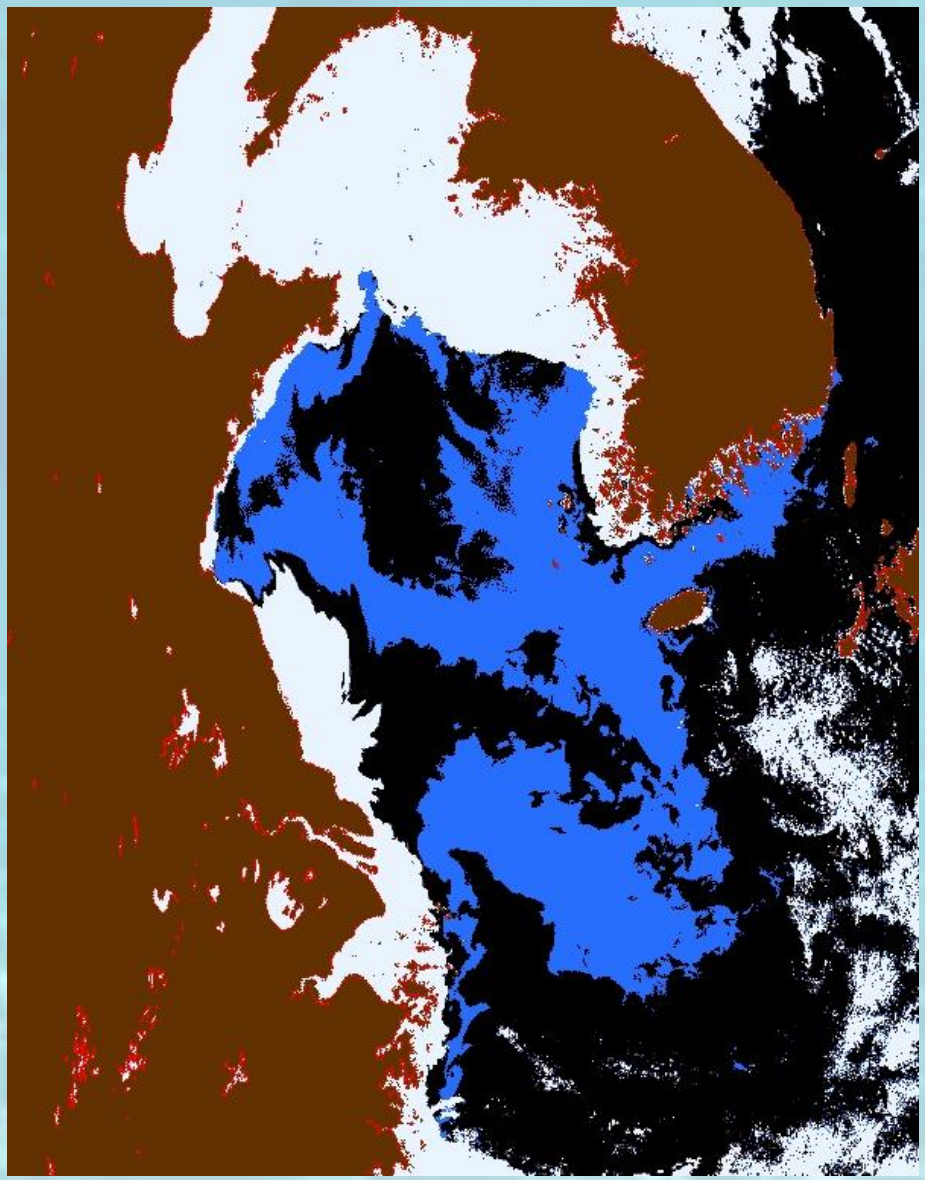
As an example, let's take a look at the processed (Level 2) chlorophyll concentration image of the scene on the previous page.



The large areas of white near the coast of China and extending offshore are areas where the reflection of light from the sediments is so bright that it is interpreted as clouds or land. The same problem affects the southern coast of Korea. It is obvious that the chlorophyll concentration over a large part of this region can't be analyzed at all.

A second reason that Case 2 waters are important is that the coastal waters where the human influence on the marine environment is most significant are very often classified Case 2. Furthermore, scientists consider Case 2 waters important because they can mislead the algorithms that are used to calculate optical properties and chlorophyll concentration. Case 2 waters usually reflect more light than Case 1 waters, and this increased radiance can exceed the limits where the algorithms are most accurate. Thus, unless Case 2 waters and the conditions that cause them are recognized, the algorithms may return erroneous overestimates of the chlorophyll concentration and primary productivity in these regions.

SeaWiFS data processing recognizes that the chlorophyll concentration algorithms might be incorrect in areas where turbid water is present. For that reason, such areas are assigned the "turbid water" flag. The main condition that is used to assign this flag is high reflectance at 555 nm. Below is the distribution of the turbid water flag for the Yellow Sea scene shown in the previous two images (shown in blue).



Because the large, curved area of black area east of Shanghai (corresponding to the curved white area east of Shanghai in the previous image) was covered by the cloud mask, this image demonstrates that there isn't much data in this image that is "above suspicion" in terms of returning reliable chlorophyll concentrations!

Now that we've both established the potential importance of Case 2 waters and seen an example of where they occur, let's look at the main reasons that analysis of Case 2 waters is difficult. Remember that for the optical properties of Case 1 waters, the two contributing factors are the optical properties of clear water and the concentration of phytoplankton. Case 2 waters may have several other factors mixed together to create their optical characteristics. In addition to phytoplankton, these factors might include:

- suspended sediments (sand, clay, or mud particles);
- colored dissolved organic matter (CDOM);
- *Gelbstoff* (which means yellow substance in German, referring to a polymeric organic material that's slightly too large to be considered dissolved);
- and even the presence of the sea floor, which can reflect some light, a situation called "bottom reflectance".

And there's another problem. Because Case 2 waters are generally brighter (more reflective) than Case 1 waters, the atmospheric correction algorithms that rely on the fact that most ocean water is optically dark at certain wavelengths become less reliable. Furthermore (as if that wasn't enough already), as Case 2 waters are frequently found in coastal areas, the overlying atmosphere is also a bit more muddled by terrestrial input, including smoke, the haze of pollution, and dust. This makes atmospheric correction more difficult as well.

What are we to do?

One thing that can be done is to conduct intensive analyses of how the optical properties of Case 2 water vary, to determine if patterns in their optical properties can be used to help analyze their content. Researchers at the City University of New York have found a unique way to observe changes in water turbidity in the Shinnecock Canal, located on Long Island.

Turn to "Through a Water Column Darkly, Page 2

SCIENCE FOCUS: Turbidity

Through a Water Column Darkly, Part 2

The Shinnecock Canal Study

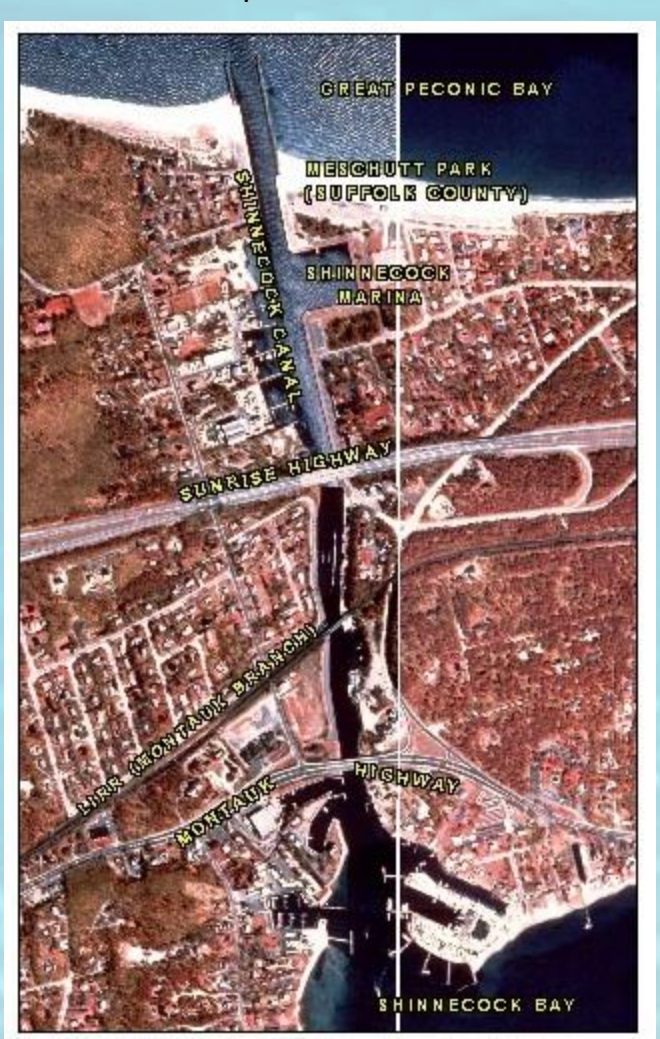
Aerial photograph of the Shinnecock Canal, Long Island, NY

The Shinnecock Canal Study was conducted by Karl-Heinz Szekielda, Samir Ahmed, Fred Moshary, Barry Gross, Jorge Peche and Yiping Zhang. Dr. Szekielda is in the The Graduate Center, Earth and Environmental Sciences, of the City of University of New York (CUNY). His colleagues are with CUNY's Optical Remote Sensing Laboratory in the Center for Water Resources and Environmental Research. Dr. Szekielda contributed the following description of this study.

Background: In near-coastal waters with high chlorophyll concentrations and where there is a significant presence of inorganic particulate matter, the algorithms used to calculate chlorophyll concentration and other properties may no longer be valid. The data must be interpreted in qualitative terms, e.g., for patch recognition and processes related to tidal and current changes. The failure of existing algorithms over turbid water can be further attributed to invalid assumptions, such as the assumption that there is no radiation from the water surface in the near-infrared bands at 765-865 nm (Ruddick et al., 2000). Although spectral analysis of reflected light from the open ocean is well understood, the problem and need of interpreting optical properties of near-shore water have been addressed, amongst others, by Bagheri, Zetlin, and Dios (1990).

Field Experiments: The field experiments were designed to determine time frames for the settling of suspended particles under a variety of current velocity and turbulence conditions, to distinguish between settleable and non-settleable fractions in the water column, and observe the effect of settling on reflected spectra.

To conduct these experiments, the Shinnecock Canal of eastern Long Island (New York) was selected as a natural tank in which to observe optical parameters and to estimate the residence time of suspended matter in the water column under the different current speeds and turbulence arising from tidal changes. Inlets with tidal ranges demonstrate large ranges of particulate and dissolved organic and inorganic constituents. They are therefore excellent test areas to relate spectral properties with the varying concentrations of material in suspension and in solution that occur over a tidal cycle.



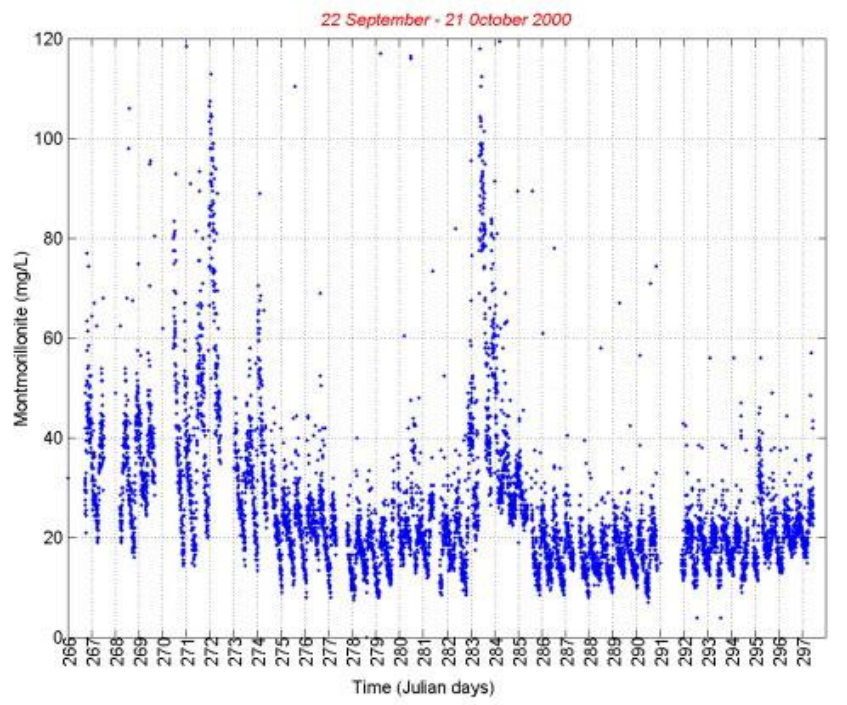
Landsat image of the Shinnecock Canal

The principal function of the Shinnecock Canal and its operating lock system is to control the flow of water in one direction, from the Peconic Bay to the Atlantic Ocean through Shinnecock Inlet. This prevents the flow of water with low salinity from Shinnecock Bay to Peconic Bay. As a result, the flow of saline water from Peconic Bay to Shinnecock Bay flushes through the Shinnecock gate with a particle load originating primarily from one major source area.

In the field experiments, spectral reflectance measurements were carried out using a spectroradiometer (GER 1500) covering the UV, visible, and near IR at wavelengths from 0.35 to 1.05 µm. For final analysis, however, only the 400-850 nm spectral region was selected for further processing. The spectroradiometer uses a diffraction grating with a silicon diode array with 512 discrete detectors. It includes a memory for stand-alone operation as well as capability for computer-assisted operation. A total of 483 spectral readings can be stored for subsequent downloading and analysis using a personal computer with a standard serial port and GER operating software.

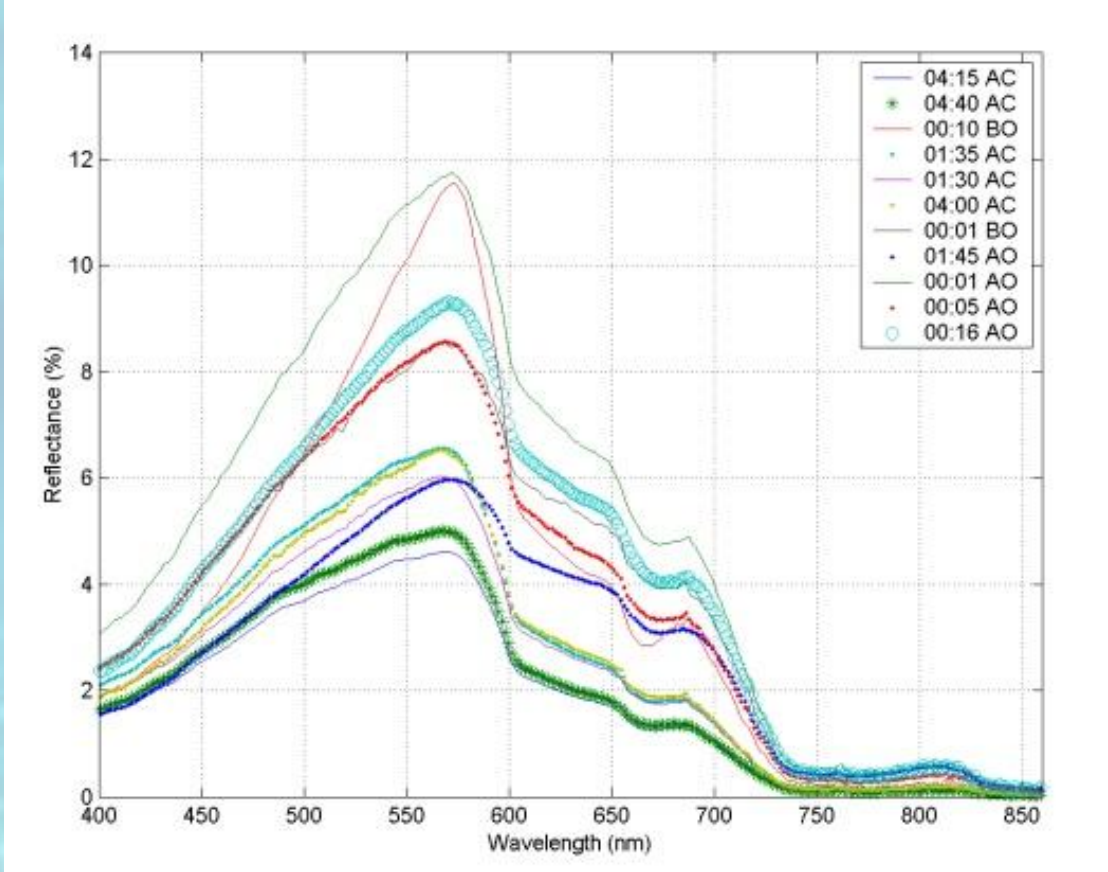
Computer-based operation allows for real-time display and data analysis. In the experiments, upwelling radiance was monitored through a calibrated fiber cable positioned in a down-looking micro-buoy. Results are presented as a percent of the incident solar irradiance. Salinity, temperature, pH and turbidity were collected using a Hydrolab H_20 multi-sensor simultaneously with the spectroradiometer readings. Instead of using an organic dye (formazine) for calibrating the turbidity measurements, however, calibration was carried out with a montmorillonite suspension, since the optical properties of clays are closer to the spectral behavior of Total Suspended Sediments (TSS) in coastal regions. Correlation of varying concentrations of suspended matter with turbidity (in NTU) and spectral reflectance data, showed good reproducibility and are in excellent agreement with data published more recently.

Turbidity Measurements: The figure below shows the turbidity variations measured over a lunar month in the tidal gates of Shinnecock Canal. These measurements cover the period 22 September—21 October, 2000. Time is given in Julian days, and the vertical axis represents the concentration of suspended sediment in milligrams measured against a standard montmorillonite suspensions. These field experiments demonstrate the occurrence of rapid turbidity changes, and also indicate that the settling of TSS is highly dependent on the tidal stage and the residence time (reduced turbulence) of entrapped water after the tidal gate is closed.



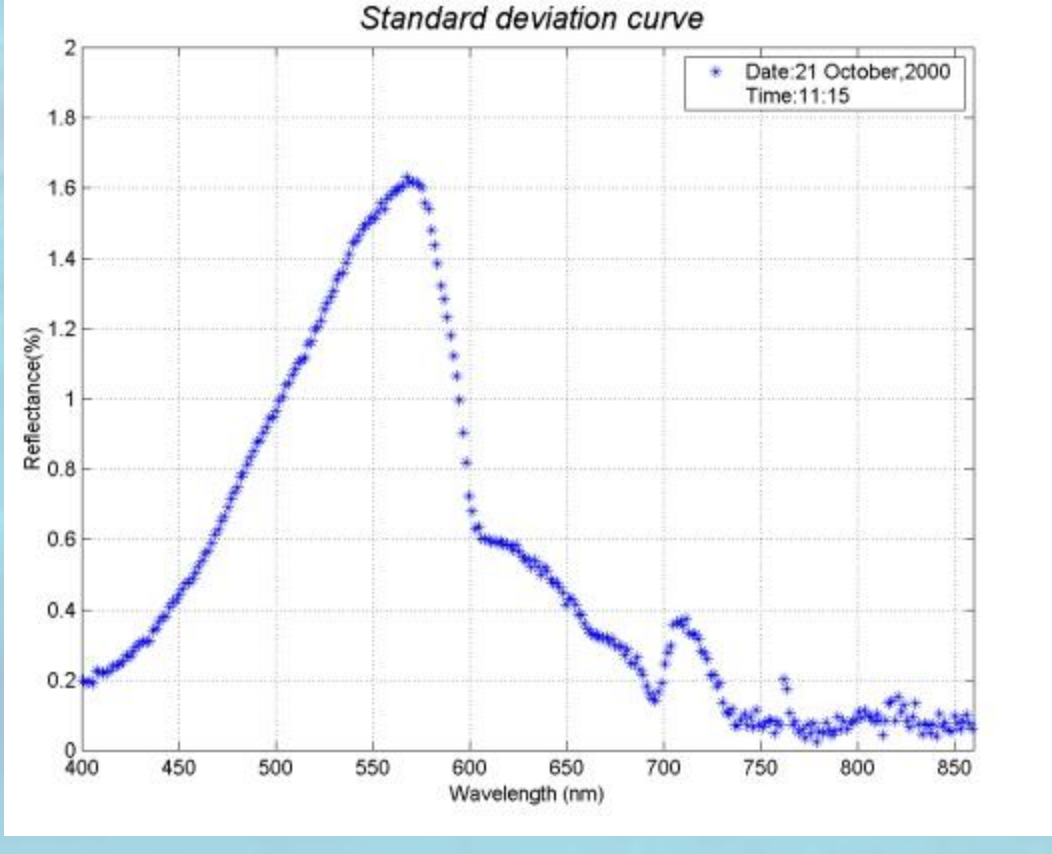
Suspended matter concentration expressed in terms of mg montmorillonite per liter

Spectral Measurements: Spectral measurements of upwelling radiance were taken at different time intervals (before, during and after closing of the tidal gate). These measurements confirm the fast settling of particles during reduced turbulence conditions which occur while the sampled water parcel is trapped during closed gates. The figure below shows reflected spectra measured for different settling times in the tidal lock. The data represent averaged spectra for different days with a standard deviation of less than 1% reflectance.



Reflectance spectra of suspended matter in the Shinnecock Canal. Times shown refer to canal lock events: AC=After Closing, BC=Before Closing, AO=After Opening.

For each spectral reflectance measurement corresponding to a specific water condition, 32 complete spectra were sampled and averaged. To check reproducibility of data, this step was repeated and the standard deviation calculated throughout the spectrum. The next figure shows the high degree of reproducibility attained.



Examination of the reflected spectra show that the visible reflectance is typically reduced by about 50% after particulate matter in an entrapped water parcel settles for 4 hours. This reduction is seen in the reflectance spectra for 550-600 nm wavelengths. In general, the data show that reflectance decreases with decreasing turbidity throughout the monitored spectral regions. In fact, reflectance, turbidity, and concentration of suspended material are correlated throughout the spectral range of 400 to about 850 nm. This is in good agreement with laboratory results reported by Bhargava and Mariam (1990), who showed that for the spectral region 700-900 nm, high correlation and low standard errors existed between these variables for the clay material used in suspension in their experiments. Our laboratory measurements over a continuous spectral range from 400-860 nm using a miniature fiber-optic spectrometer equipped with a high sensitivity CCD detector also confirm the correlation of reflectance over the entire wavelength range with changes in the water constituents and their concentration.

Conclusions: The results of the field experiments discussed above demonstrate the importance of taking into account the separation of settleable and non-settleable TSS for the interpretation of ocean color satellite imagery over coastal regions. This analysis is required in order to resolve the time-and-space relationships of the TSS distribution patterns. For future work, revisits by satellites spaced as closely as one hour may be required in order to better understand the coastal dynamics of suspended sediments.

References

Bagheri, S., C. Zetlin, and R. Dios (1999). Estimation of optical properties of near-shore water. *Int. J. Remote Sensing*, **20**, 3393-3397.

Bhargava, D.S., and D.W. Mariam (1990). Spectral reflectance relationship to turbidity generated by different clay materials. *Photogrammetric Engineering and Remote Sensing*, **56**, 225-229.

Ruddick, K.G., F. Ovido, and M. Rijkeboer (2000). Atmospheric correction of SeaWiFS imagery for turbid coastal and inland waters. *Applied Optics*, **39**, 897-912.

Through a Water Column Darkly, Part 3

What to Do Next [written in 2001]

The problem of turbidity won't "settle" down anytime soon, and in the near future it may get even worse, as nutrient inputs and erosion from agriculture increase from Third World countries. In addition, global warming could even exacerbate the problem with increased rainfall, causing more floods, and sea level rise, causing increased coastal erosion.

One way to address the problem is with better sensors. SeaWiFS was primarily designed to accomplish the goal of observing the entire global ocean and determining the chlorophyll concentration everywhere to an accuracy of 35%. The SeaWiFS Project currently uses a global algorithm (the OC4 algorithm, described in “More than Meets the Eye”) that switches the bands used to calculate chlorophyll concentration as radiance changes, which adapts the algorithm to a range of conditions.

But this algorithm only goes so far. Optical oceanographers know that knowledge of regional water characteristics can be used to tune analytical algorithms to produce better results than a single algorithm used to analyse the entire world. So one way to address the problem of turbidity and Case 2 waters is to create a set of regional algorithms that overlapto cover problematic areas.

The next way to improve the analyses is to add more bands to the instrument. The optical properties of the various materials and conditions that create Case 2 water conditions interact to produce what the sensors observe. By adding more bands, algorithms employing these bands can "unravel" the tangled knot of optical characteristics and isolate the contribution of each. An example of how this might be done is the use of the 412 nm band found on SeaWiFS and MODIS. *Gelbstoffe* absorbs light strongly at this wavelength, much more than chlorophyll, so light absorption in this band can be used to calculate the concentration of *Gelbstoffe*.

Beyond the addition of bands, improving the optical capabilities of the instrument also aids the discrimination of optical properties in Case 2 waters. In overly simple terms, the "signal"due to chlorophyll in Case 2 waters is obscured by the optical "noise"of the other factors that have been described. By improving the optical performance of the instrument, the instrument will be more sensitive to the signal compared to the noise.The signal-to-noise ratio of the optical bands in SeaWiFS was more than 10 times better than its predecessor, the Coastal Zone Color Scanner, and MODIS is significantly improved over SeaWiFS. Furthermore, the width of the bands in MODIS is smaller than for SeaWiFS, which also helps to isolate the signal that is being measured.

The final factor that can be added is increased creativity by scientists studying the complex optical mixture found in Case 2 waters.Some researchers have employed iterative algorithms that test a variety of possible conditions until they converge on a single, hopefully accurate, answer. These algorithms take much more computational effort than the band ratio algorithms employed by the SeaWiFS Project, but they offer one of the only current ways to separate the contributions of various factors. Other groups have successfully improved atmospheric correction over turbid coastal waters by changing the assumptions that go into the global analytical algorithms.(See "Atmospheric Correction of SeaWiFS data for turbid waters" below.)

Looking to the future, the next major advance in Case 2 water analysis may be a hyperspectral ocean color sensor.A hyperspectral sensor, such as the **Hyperion** instrument on the **Earth Observer-1 (EO-1)** mission, collects data in many more bands than SeaWiFS or MODIS. Hyperion has 220 bands in the 0.4 to 2.5 µm wavelength range. To be effective, a hyperspectral ocean sensor would have to possess the same optical capabilities of SeaWiFS or MODIS – and such an instrument has not been built yet.

ACKNOWLEDGMENT

Dr. Kevin Ruddick of the Ocean Colour Research Unit of the Management Unit of the North Sea Mathematical Models (MUMM) provided a review of this Science Focus! *article.*

LINKS

Remote Sensing and Ecosystem Modelling Team (REMSEM)

Management Unit of the North Sea Mathematical Models

Water Column Correction Techniques

See also: Classic CZCS Scenes, Chapter 10: River Plumes and Estuaries