Characterization of CDOM in the South Atlantic Bight (United States) Based Upon Meteorological Forcing Events

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Introduction to work:

While a student in the Goddard Earth Science and Technology Graduate Student Summer Program (GEST GSSP), I completed work towards my master's thesis at Creighton University. The work includes characterizing colored dissolved organic matter (CDOM) in the South Atlantic Bight off of the Southeast coast of the United States. While at Goddard my main activities included gaining access to datasets, better learning computer programming skills, including IDL, to work with the Goddard SeaDas dataset, and characterizing hydrological and meteorological data. In addition, a large amount of my work was focused on literature review and understanding the atmospheric corrections that are being applied to models to help find the best products and algorithms to use for my study site. The following is a review of the work that I have completed over the past summer.

Introduction to Ocean Color:

Ocean color can be measured in the visible spectrum from 400-700 nm through the absorption and reflection of waves. Globally water can be broken into two categories, case 1 and 2 water. Case 1 water is noted as open ocean water which has had much success in using remotely sensed data to characterize bio-optical properties. Case 2 is noted as coastal water, often considered black water. The study of case 2 water while more difficult is increasing and algorithms are being better produced for this data. In case 1 water bio-optical properties can be remotely sensed to depths of 50 meters, while in case 2 water only the first few meters are recognizable.

The basic tenant of measuring ocean color is that subsurface reflectance is dependent

upon backscattering and absorption. Different bio-optical properties are best seen at varying wave lengths, CDOM is best noted at 410 nm and chlorophyll at 443 nm. However, both CDOM and chlorophyll have found exceptions the peak recorded wavelengths. In addition, at values over 500 nm chlorophyll absorption is found to be near zero and other bio-optical properties can be observed and thus removed, such as caratenoids.

The focus of my study is on CDOM, however it may also be noted as colored dissolved organic matter, chromomorphic dissolved organic matter; chromomorphic dissolved organic matter, yellow matter, gilvin, or gelbstoff. CDOM is a bio-optical property of all water that absorbs UV and shortwave light. Characteristically, CDOM is noted to dye waters yellow to brown in color. CDOM is usually associated with increases in turbidity in addition to run-off. Production originates by decaying detrital terrestrial matter that is then carried into estuarine and oceanic environments by run-off. CDOM has the ability to alter primary production of phytoplankton and other algal products. CDOM products are noted to decrease based on both mixing and photo-bleaching.

Study Site:

The South Atlantic Bight contains a variety of environmental conditions, that vary from coastal to Continental shelf. These contain injections from the Gulf Stream, as well as, the Sargasso Sea. Optical considerations of the Bight are affected by the range of phytoplankton composition, primary productivity, and the concentrations of colored dissolved organic matter (CDOM), and suspended matter (Brown et al. 2000)

Meteorological forcing is an important process in the transport of terrigenous CDOM in the South Atlantic Bight (SAB = Southeast Atlantic Continental Shelf; Seim et al., 2000). The SAB is a bounded continental shelf, located from Cape Hatteras, North Carolina to South Palm Beach, Florida. The shelf extends from 30-150 km off shore, and is divided into three regions, the inner, mid, and outer shelves. The inner shelf extends from the coast to the 20 m isobath and its circulation is controlled by winds, tides and freshwater inputs, and is characterized by low salinity. (Aretxabaleta et al., 2006)

In addition, to the SAB being influenced by meteorological forcing, the SAB is a large contributor to the building and development of storms. Many tropical storms pass through the SAB in the late summer and early fall, and systems derive their energy from the air-sea gradients. The middle and outer shelf regions are warmer due to their relative closeness to the Gulf Stream. Increased importance has been placed on predicting tropical storms near coastal regions. The South Atlantic Bight Synoptic Offshore Observation Network, SABSOON, provides for near constant mesoscale atmospheric observations and oceanographic measurements. This rare instance of monitoring is major reason to perform work in the SAB area.

SABSOON, located off the coast of South East United States, monitors atmospheric and oceanographic conditions, temperature, wind, pressure, salinity, chlorophyll fluorescence, and currents, among others. (Seim et al., 2000) Mesoscale weather events such as tropical storm, coastal nor'easter winter storm events, and severe flooding events could all impact the transport of CDOM. By affecting ocean currents and salinity gradients, mixing would be impacted and transport of carbon altered. It was recently noted that the area of meteorological forcing in the SAB has not been completely characterized or understood. (Nelson, 2007)

The characterization and analysis of the fates and roles of CDOM in the SAB is an active research area, particularly within the larger context of carbon cycling (Wang et al., 2005). Remote sensing technologies for CDOM estimation of are of interest for studies of sources and distribution patterns; interference by CDOM in ocean color chlorophyll assessments; air-sea gas exchanges including carbon products of CDOM photochemical reactions; formation of reactive oxygen and its relation to biological principles and geochemical cycling; a method to trace influence of contributories to estuarine and marine environments; carbon cycling in coastal waters; and attenuation of UV light in surface waters. (Kowalczuk et al., 2003).

Motivation to Study CDOM in Coastal Environments:

The importance of understanding the hydrodynamic regimes of an estuarine body has begun to be characterized in a variety of sites, including the focus area of this project the South Atlantic Bight. Varying freshwater inputs can have great impacts upon current regimes, biomass production, and other coastal processes. Using colored dissolved organic matter as a trace dye, the impacts of various meteorological forcing events will be studied coupled with discharge ratios to investigate the changing environment of estuarine ecology.

Monitoring the health of United States Coastal waters is of particular concern to both the National Aeronautical and Space Agency (NASA) and to the National Oceanic and Atmospheric Administration (NOAA). Numerous satellite sensors (SeaWiFS, MODIS, OMI, etc.) are in use to provide synoptic satellite data of the U.S. coast. Ocean color sensors are of great importance in measuring the water quality of coastal regions. (Brown et al. 2000)

Dissolved Organic Matter (DOM) represents one of the largest pools of reduced carbon on the earth. (Hedges and Farrington 1993) It has been noted that there is as much carbon in the DOM in the oceans, as there is carbon in carbon dioxide in the atmosphere. (Hansell and Carlson, 1998) In addition, it was previously thought that the SAB is a net atmospheric sink of CO2. However, recently Wang et al., (2005) published an alternate hypothesis that the SAB is a new carbon source to the atmosphere. These authors discussed the significance of coastal sources of dissolved organic carbon leading to net heterotrophy in the SAB system. Shelf waters of the SAB have higher concentrations of DOC (hence, CDOM) than the surrounding open water (Moran et al, 1991; Moran et al. 1999).

When dissolved organic matter (DOM) is exposed to natural sunlight, the chemical structure is modified. It creates a series of photoproducts, both organic and inorganic, that can affect *in situ* biological productivity, as well as global system effects, such as, atmospheric fluxes of carbon monoxide, carbon dioxide, and ocean carbon cycling.

(Kieber et. al, 1989) In spite of the global-scale implications, little research has been performed, and there are limited quantitative assessments of DOM photoproduct formation at global or even ecosystem levels. (Moran and Zepp, 1997)

Characterizing Data:

It is likely that freshwater delivery to coastal shelf areas will decrease in the near future, associated with human and agricultural demands. Changes in this salinity regime will affect species of plants and animals especially in riparian ecosystems. This has been noted in Georgia and can be applied to all other states impacted in the South Atlantic Bight. (Alber, 2002)

Estuarine composition greatly depends upon freshwater flow. This can be viewed in quantity, timing, and quality of flow. (Alber, 2002) Estuarine conditions vary as a result of freshwater input, this is evident in salinity gradients, as well as other physical attributes of the estuary including the distribution of dissolved and particulates materials. (Alber, 2002)

In some rare cases, a large quantity of evaporation paired with low rainfall and decreased freshwater input can result in hypersaline conditions. In the South Atlantic Bight, two major rivers are the Satilla and the Altamaha River Estuaries. The two rivers are located in close proximity to each other, roughly 37 km apart. However, discharge regimes in the two rivers vary by a factor of ten. With this freshwater is encountered 20km upstream in the Altamaha, whereas in the Satilla it is found 50km upstream. (Smith et al. 2001) This variance in output greatly impacts the amounts of CDOM observed within the Bight.

In addition, changes in freshwater input can alter the hydrodynamic regime of the estuary. Decreases in discharge will serve to increase the influence of the tide on circulation patterns. With high freshwater flows, bays stratify which leads to a decrease in turbidity and nutrient concentrations, and an increase in biomass production and acceleration of residual currents. (Alber, 2002) Freshwater run-off is typically confined during winter seasons. This prevents CDOM from entering open ocean and confining to

near coastal waters (Blanton et al. 1985; Lee et al. 1985).CDOM concentrations are likely to be greater in coastal areas due to the creation of fulvic acids by decomposition of seaweed.

The variations in inflow have the ability to change the size and shape of the estuary, the geomorphology of the estuary. Freshwater tends to carry sediment into the estuarine system, and with lowered discharge there can be a loss in tidal deltas, benthic communities, and habitat. (Alber 2002; Boesh et al. 1994)

Most important to this project is that freshwater discharge in a source of dissolved and particulate matter to an estuary. Changes in freshwater input have important consequences for the intrusion of organic matter, suspended particles, nutrients and pollutants. With decreased freshwater input, there is reduced transit time. (Alber and Sheldon 1999) The transit time is a measurement of the time it takes for river water to move through a system, and consequently flush out materials. As the time increases, the concentrations of various materials including pollutions and pathogens increase. (Alber 2002)Rivers that impact the South Atlantic Bight drain from both coastal and piedmont areas of North Carolina, South Carolina, Georgia, and northeast Florida.

Coastal ocean waters house a variety of dissolved and particulate materials of both terrestrial and marine sources. The concentration of these materials can be determine through algorithms by both chlorophyll a (chl a) and water-leaving radiance estimates from sea-viewing wide field-of-view sensor (SeaWiFS).

Variability in phytoplankton biomass and productivity in the South Atlantic Bight is altered by many processes. Upwelling and the input of large concentrations of nutrients from the Gulf Stream front are associated with surface and subsurface phytoplankton blooms. (Bontempi and Yoder 2004; Verity et al. 1993) Processes with anomalously high or low concentrations of optical signals do not spread uniformly through coastal waters. (Bontempi 2004)

Imagery obtained with SeaWiFS provides ocean optical signals that are more frequent and cover larger spatial frames than in situ sampling. (Yoder 2000) The imagery's pixel size is to a kilometer. In the South Atlantic Bight large diversity in water conditions exist with boundaries separating the differentiating backscattering components. (Bontempi and Yoder 2004) Large amounts of backscattering occur in regions with large amounts of sediment and high levels of organic detritus. It is known that, high CDOM levels have absorptive effects upon the chl a algorithms (Roesler and Perry 1995), this will lead to greater characterization needed of other bio-optical properties of the Bight.

CDOM absorbs greater at L_{wn} (443nm) than at L_{wn}(490), there should be stronger and steeper gradients at 443 nm near shore, as river discharge is a contributing factor of CDOM into the Bight (Bontempti and Yoder 2004). Based on Bomtempi and Yoder (2004) imagery at 443nm and 490nm showed many cases of non-congruent chl a gradient fronts for a 1998 data set. This suggests an outside forcing mechanism in distribution of both phytoplankton biomass and CDOM, such as meteorological forcing events.

Algorithms in place for SeaWiFS include OC4v4 (O'Reilly et al. 2000), OC2v4 and OC2v2 (O'Reilly et al. 1998), OCse (Stumpf et al. 2000) and UCSB (Garver and Siefel 1997). Others include Johannsen and Fichot. A preference has been seen for the USCD, a semi-analyitcal algotithm due to defined estimates of both backscatter and CDOM absorbtion. This then has the possibility of greatly reducing error. Numerous networks of academic, state and federal agencies, non-profits, and economic interests have teamed to create observational networks for SAB. These include the South Atlantic Bight Synoptic Offshore Observation Network (SABSOON), the South Atlantic Bight Limited Area Modeling program (SABLAM), and SEACOOS. Blue chlorophyll-a has an absorption peak at that of 440nm. This peak is usually masked by CDOM and detritus absorption (Harding et al. 2005).

However, in the SAB near Sapelo Island, part of the Georgia Bight, Cedric Frichot has demonstrated an algorithm for CDOM that is used with both SeaWifs data and *in situ* measurements.(Fichot, 2005) By using this algorithm, I hope to determine the

transport of dissolved carbon in mixing events caused by meteorological forcing. The algorithm takes into account the natural variability of ocean color in different oceanic provinces. Using approaches similar to Traykovski and Sosik (1998) and Traykovski *et al.* (2002), the classification is based on remote sensing spectrums. Although ocean color varies over a continuum of values, it is possible to divide this continuum into domains of ocean color. The entire classification procedure looks at the main characteristics of the remote sensing reflectance spectrum of a particular mass. (Fichot, 2005) While, this algorithm seems to have promise for the area based upon ocean color data, a greater atmospheric correction factor will seem to increase its accuracy.

Understanding Corrections:

Two major steps in processing remotely sensed ocean color data are application of atmospheric correction and use of bio-optical algorithms to understand water leaving radiance to the physical properties of the water. Much success has been noted in case 1 waters (open oceans) however problems exist in case 2 waters. Mainly, atmospheric correction is inferred by case 2 water properties and the coupling effects of optical properties that exist in case 1 waters are not the same or noticed in case 2 water. (Hoge and Lyon, 2002)

The atmosphere contributes more than 80% of the signal that is measured for ocean color. Atmospheric correction procedure exists to illuminate the bias of the atmosphere combined with the bias of the satellite. Using satellite remote sensing technology, the absorption coefficient of CDOM is easily retrievable using ocean radiance modeling. However, problems exist in finding the "correct" absorption coefficient based upon the following problems. The first being that downwelling irradiance photo-oxidizes the CDOM. This causes a degradation of the CDOM in the upper layer of the ocean. Therefore using the SeaWiFS record, higher CDOM absorption should be found after storm events.

Secondly, vertical differences in CDOM absorption coefficients are significantly greater under stratified conditions of the ocean. (Hoge and Lyon, 2002) A strong thermocline creates a barrier from the upper water mass to the lower water mass, with respective high and low solar radiation. This is a noted problem since the period of maximum hurricane activity in the Atlantic is from July to September and the thermocline is at it's strongest. (Hoge and Lyon, 2002)

Hoge and Lyons (2002) have measured CDOM relative to three distinct categories pre-storm values, adjacent undisturbed storm values, and post-storm photodegraded surface waters. CDOM absorption coefficient increases of 100-200% have been commonplace.

Error for finding CDOM has been found in a variety of sources, while all models have a correction factory for these issues, finding the best fit for the area surrounding the coastal southeast has and is continuing to be a challenge. Topics of consideration for error are ozone, sun glint, foam and white caps, Rayleigh scattering, diffuse transmittance, and finally and most importantly aerosols.

Most algorithms use calibrated reflectances, then use the ozone total column to correct for ozone absorption, precipitable water to correct for water vapor absorption, surface atmospheric pressure to calculate Rayleigh optical depth, and surface wind velocity. Winds are accounted for by both speed and direction. Wind speed is used to correct for whitecap reflectance (Frouin et al., 1996) and to calculate Rayleigh reflectance, and the wind velocity is used to construct a sun glint mask.

Data such as the absorbing aerosol index from the Ozone Mapping Profiling Suite (OMPS) may also be used in a future version of the algorithm for handling pixels with strongly absorbing aerosols. However, it seems that the Total Ozone Mapping System (TOMS) may become favorable for this work.

Conclusion:

The work completed at Goddard Space Flight Center (GSFC) as a product of GEST GSSP program allowed me to focus on the atmospheric corrections and possible photo-degradation issues associated with using remote sensing data. In addition, it allowed me to gain full access to a set of data that will be increasingly helpful in my data collection as I begin to chose time frames to evaluate the movement of CDOM through the South Atlantic Bight during varying forcing conditions. This summer, the focus of my research was on finding tropical storm events along with evaluating river data from USGS gauge stations to serve as an indicator for weather events. In addition, a large amount of data was stored and found with the help of the GSFC Ocean Color Team and the University of Georgia's Skidaway Institute for Oceanography.

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