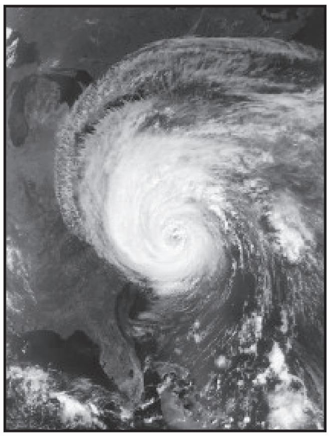

Isabel's Impact on Water Quality and Living Resources

IMPACT OF HURRICANE ISABEL ON THE WATER PROPERTIES OF THE CHESAPEAKE BAY AREA

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ABSTRACT

On 18 September 2003, the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard the NASA satellite Aqua (EOS PM) and Terra (EOS AM) took stunning pictures of Hurricane Isabel's landfall over the U.S. East Coast. Satellite images of the Chesapeake Bay region before and after landfall show important qualitative changes in the water properties due to the huge amount of sediment delivered to the Bay, extending far beyond the coastal region (more than 100 km). The impact on the ecosystem of this rare phenomenon deserves additional analysis.

Remote sensing data from the Terra and Aqua system can be inverted to estimate key water properties (chlorophyll, transparency, sediment loading), which can be validated using the network of measurements taken in the Chesapeake Bay area. Once validated, the remote sensing products can be used to estimate the change in water properties up to twice a day and over the entire area. In particular, comparison of the water properties before and after the landfall of Isabel provides a quantitative estimate of this hurricane's impact on selected water properties.

Using the co-analysis of precipitation measurements from the Tropical Rainfall Measuring Mission (TRMM) sensors, the basic factors responsible for changes in the water properties in the Chesapeake are isolated.

INTRODUCTION

Suspended matter plays an important role in water quality management since it is related to total primary production (e.g., nutrient release) and fluxes of heavy metals and micropollutants. Synoptic information on suspended matter at regular frequencies is difficult to obtain from the routine *in situ* monitoring network, since suspended matter, such as chlorophyll, is a spatially inhomogeneous parameter. Earth-observing satellite systems provide powerful high-technology tools that can monitor these phenomena. NASA's MODIS system (on the Terra and Aqua satellites) yields daily coverage of the study area. It has a visible and near-infrared channel with pixels of 250 x 250 m. These higher-resolution images can provide time-series regional synoptic views of suspended sediments. This information, integrated with "groundtruth" data, may prove useful in understanding and managing the impact of rare phenomena (such as a hurricane) on an ecosystem.

It is well known that water reflectance increases with increasing concentration of suspended matter in the visible spectrum and even some of the near-infrared portion of the spectrum [2] (Figure 1). Several studies have been performed based on this property. Most research with a large range (i.e., 0–200 mg·L^{-1}) of suspended sediment concentration found a curvilinear relationship between suspended sediment and radiance or reflectance [1, 3, 6, 8] because the amount of reflected light tends to saturate as suspended sediment concentration increases. If the suspended sediment values range between 0 and 50 mg·L^{-1}, reflectance from almost any wavelength will be significantly related to suspended sediment concentrations [7].

Gaseous and aerosol scattering and absorption, adjacency effects caused by the presence of land pixels and the inhomogeneous distribution of total suspended sediment, the bidirectional reflectance distribution function (BRDF) and atmospheric coupling effect, and contamination by thin cirrus clouds, all affect the reflectance signal.

An accurate atmospheric correction is the first step in performing further analysis. The MODIS instrument contains several features, which make the atmospheric correction algorithm more accurate than in the past. Most important is the availability of seven channels in the spectral interval 0.41–2.1 μm that enables the derivation of aerosol loading and aerosol optical thickness [4]. Likewise, reducing pixel size from 1 km in the previous satellite generation to 250 m in MODIS increases the ability to detect cloudy pixels and reduces contamination by subpixel clouds.

The objectives of this study were to determine the potential of remote sensing data to estimate sediment concentrations in the Chesapeake Bay and to study temporal variability in the sediment during 2003, particularly after Hurricane Isabel made landfall and affected the region.

MATERIALS AND METHODS

The Bay proper is approximately 320 km long, but contains over 7,100 km of shoreline. It ranges in width from about 6.5 km near Annapolis, Maryland to more than 50 km at its widest point, near the mouth of the Potomac.

Tributaries continuously discharge water into the Chesapeake Bay. Almost 85–90 percent of the fresh water entering the Bay comes from the northern and western areas. The Eastern Shore contributes the remaining 10 to 15 percent. Nearly an equal volume of salt water enters the Bay from the ocean. The tributaries supply waters with a broad geochemistry due to the influence of the three different geological provinces of the Chesapeake region. Each tributary contributes a unique mix of minerals, nutrients, and sediments.

Data have been collected from the Chesapeake Bay Program website *www.chesapeakebay.net/data* for the year 2003. The Chesapeake Bay Program, a cooperative effort of federal, state, and local governments, funds the states of Maryland and Virginia for routine monitoring of 19 directly measured water quality parameters at 49 stations in the mainstem Bay. The Water Quality Monitoring Program began in June 1984 with stations sampled once each month during the late fall and winter months and twice each month during the warmer months. Over the years, the number of sampling events has been reduced to 16 per year in Maryland and 14 per year in Virginia.

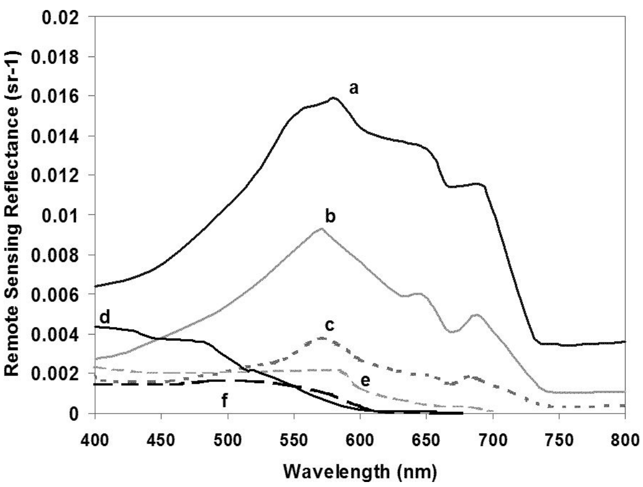


Figure 1. Reflectance from: a) waters with very high sediment; b) high sediment concentrations; c) moderate sediment with some phytoplankton; d) clear water; e) waters with moderate chlorophyll and sediment concentrations; and f) waters with moderate chlorophyll concentration [5].

The collecting organizations coordinate the sampling times at their respective stations, so that data for each sampling event, or "cruise," represent a synoptic picture of the Bay at a particular time. At each station, a hydrographic profile is made (including water temperature, salinity, and dissolved oxygen) at approximately 1- to 2-m intervals. Water samples for chemical analysis (e.g., nutrients and chlorophyll) are collected at the surface and bottom, as well as at two additional depths that depend on the existence and location of the pycnocline (the region or regions of density discontinuity in the water column). Correlative data on sea state and climate are also collected. Maryland, Virginia, and District of Columbia tributary data are included in this database.

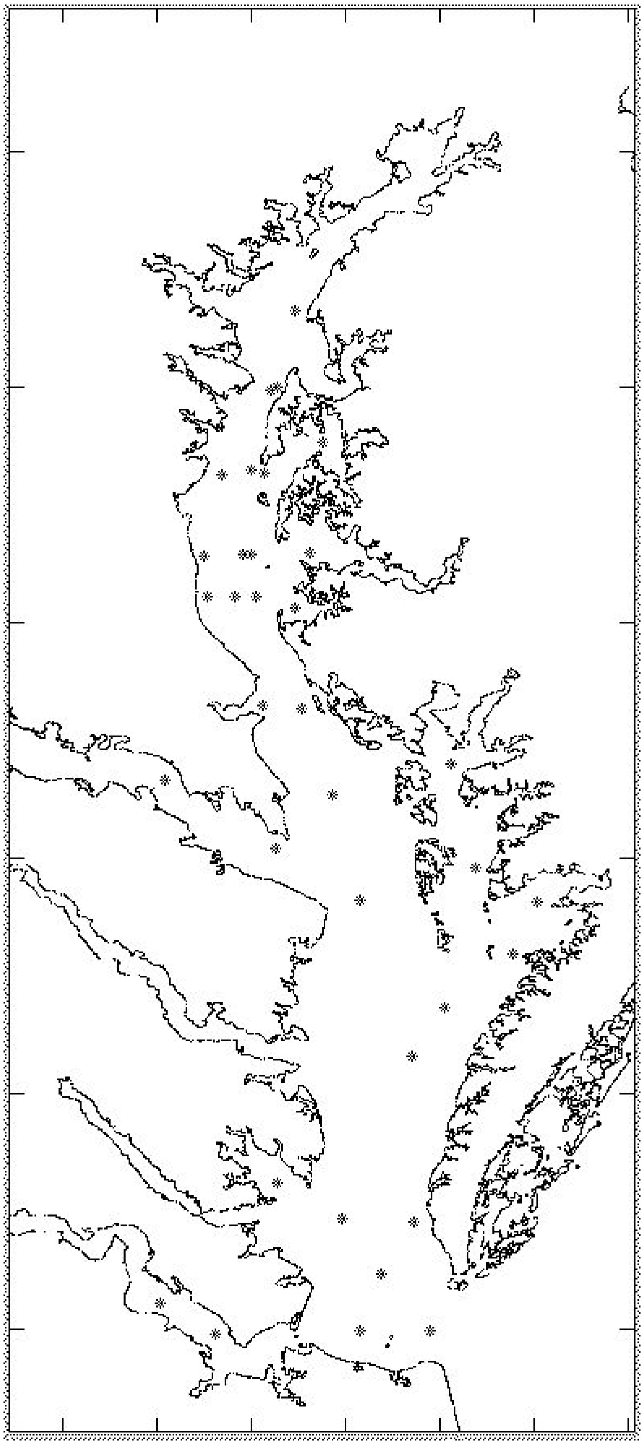


Figure 2. Field stations used for the calibration of the suspended sediment algorithm.

Sediment concentration can be measured using two different quantities: total suspended solids (gravimetric, dried at 103–105º C) and total suspended sediments (gravimetric, filtration, dried at 104º C), Although the total suspended sediments measurement is preferred, it was not available at the field stations chosen to calibrate the remote sensing algorithm (Figure 2). Stations chosen were sufficiently distant from the shore to avoid contamination of the satellite pixel by a land signal.

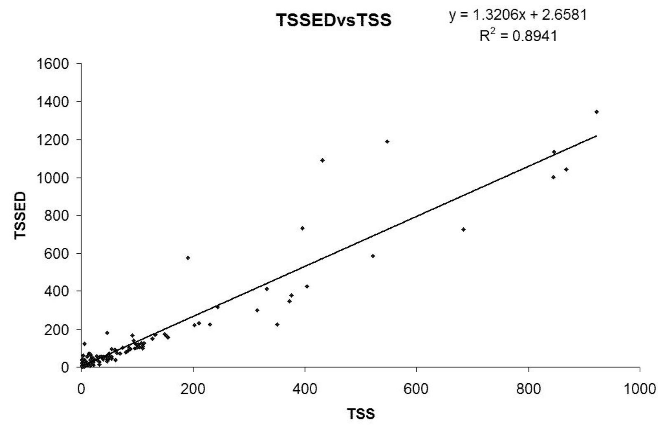


Figure 3. Relationship between TSSED and TSS.(F-statistic: 2189 on 1 and 139 degrees of freedom; p-value is 0)

Since total suspended sediment (TSSED) differs because of filtration, compared to the measurement of total suspended solids (TSS), the relationship between TSS and TSSED was investigated over another set of stations measuring

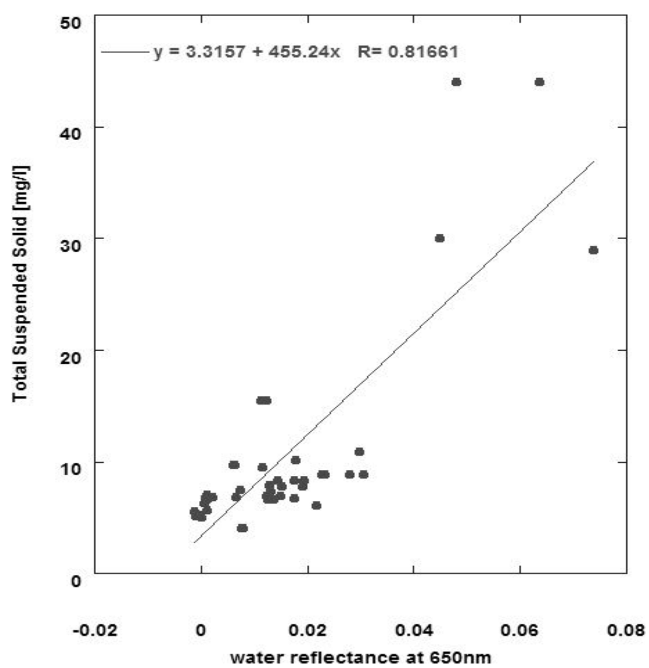


Figure 4a. Total suspended solids versus surface reflectance at 650 nm (F-statistic: 80.06 on 1 and 40 degrees of freedom; p-value is 4.306e-011).

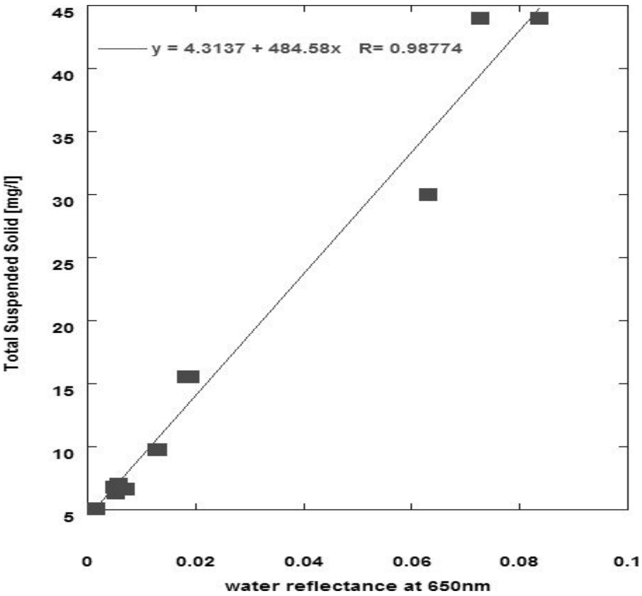


Figure 4b. Total suspended solids versus surface reflectance at 650 nm (for days 105 and 232 of 2003).

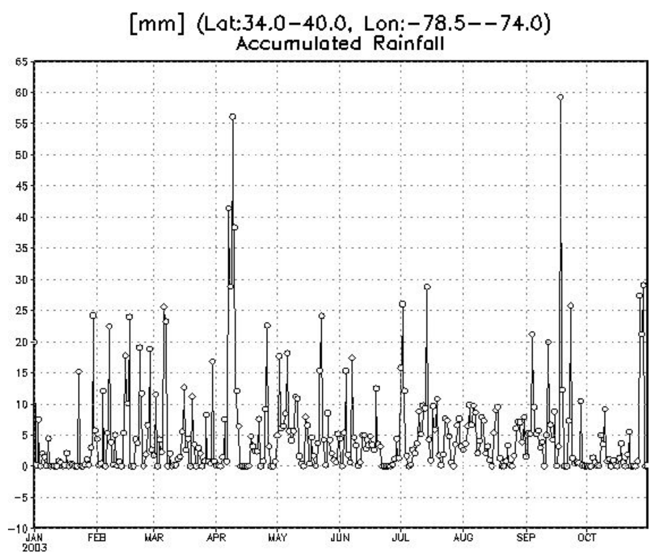


Figure 5. Rainfall (mm) over the Chesapeake Bay in 2003.

both parameters. The agreement between the two parameters is good (Figure 3) and justifies the hypothesis of using TSS values to calibrate the remote sensing algorithm.

The preliminary atmospheric correction performed was the same one used on the MOD09 MODIS product, with an urban model. The correction is obtained using a table that provides transmittance and path radiances for a variety of sun-sensor geometries and aerosol loadings [9]. Aerosol optical thickness has been derived from MODIS using a method similar to that of the atmosphere group [4], but adapted for coastal water (not discussed in this paper).

Once corrected, reflectance values in band one (650 nm) showed a correlation with TSS (Figure 4a). The derived algorithm is:

$$TSS = a*R(b1) + b \qquad (1)$$

where a = 455.24 and b = 3.315.

The relationship can be greatly improved if only part of the dataset is considered—for example, the relationship obtained by considering only days 105 and 232, which have similar geometrical conditions (Figure 4b).

RESULTS AND DISCUSSIONS

The Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI) is a passive microwave sensor that provides quantitative rainfall information over a wide swath under the TRMM satellite. By carefully measuring the minute amount of microwave energy emitted by the earth and its

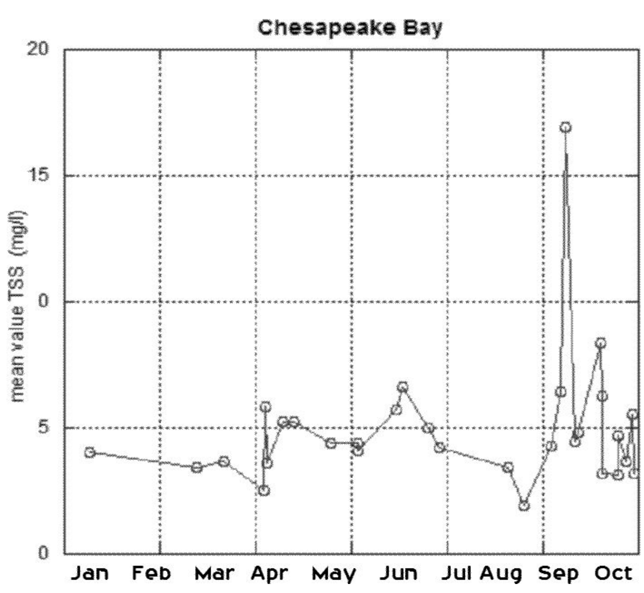
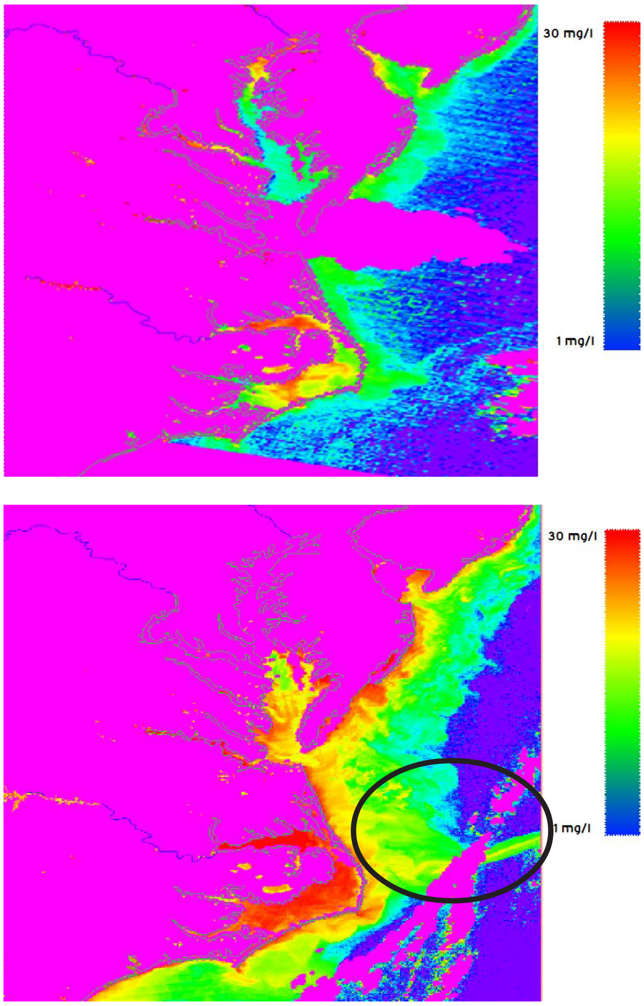


Figure 6. TSS averaged over the Chesapeake Bay (for water pixels between 37.00 N to 39.50 N and -77.0 W to -75.50 W) from maps produced by applying the algorithm for the year 2003.



Figures 7 and 8. Distribution of TSS on 14 April and 19 September 2003. The circled region highlights a narrow plume of sediment moving toward the ocean.

atmosphere, TMI can quantify the water vapor, cloud water, and rainfall intensity in the atmosphere. Daily data of accumulated rainfall are available at *http://lake.nascom.nasa.gov/tovas/*.

The time series of rainfall over the Chesapeake Bay in 2003 shows two main events with more than 55 mm of rain in one day (Figure 5). The first one corresponds to four days of rain (7–10 April); the second corresponds to the passage of Hurricane Isabel (18 September).

By applying the empirical relationship determined in the previous section (Equation 1) on the cloud-free MODIS band 1 (650 nm) surface reflectance data, several maps of TSS during 2003 have been produced and used to extract a time series of TSS averaged over the Chesapeake Bay (Figure 6). The sediment concentration averaged around 5 mg·L^{-1} during the entire year except for a single peak on 19 September (262 Julian Day)—the day after Isabel's landfall when the concentration reached 17 mg·L^{-1}.

The distributions of TSS for 14 April and 19 September are very different (Figure 7 and Figure 8, where the same color map has been used and the land and clouds are masked in magenta). Even though the rainfall of the two events was similar (Figure 5), the quantity of suspended solids in the Bay after Isabel considerably increased in value and area, spreading over the ocean, compared to the aftermath of the April storm.

The different sediment distribution can be explained by the distribution of accumulated rainfall from TRMM data (Figure 9). In the April storm, moderate precipitation resulted in runoff and sediment transport in the upper Potomac and northern Bay. In Isabel, however, short duration

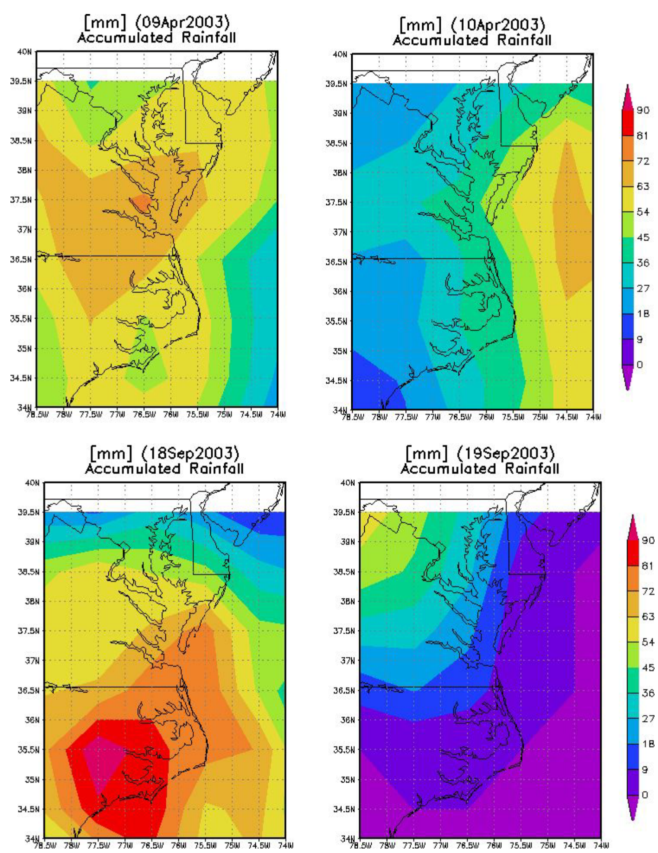


Figure 9. Accumulated rainfall on 9 and 10 April 2003 and on 18 and 19 September 2003.

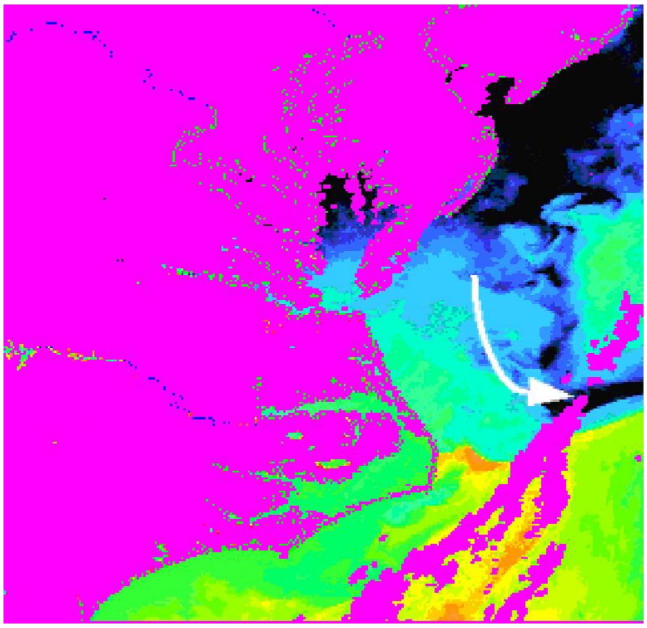


Figure 10. Temperature distribution on 19 September 2003.

precipitation was focused over the southern Bay, leading to modest sediment input in this region. The southern Bay sediments were, in turn, supplemented with surge- and wave-induced resuspended sediment for subsequent transport out of and south of the Chesapeake's mouth.

The distribution of TSS for 19 September also shows a narrow sediment plume (circled region in Figure 8). Measurements on that day (Figure 10) indicate two fronts separating water of different temperatures: one in the northeast region of the ocean and the other in the southern region, generating a cold current moving from the north portion of the image to the east (see arrow) associated with the sediment plume.

CONCLUSION

This paper shows that it is possible to recover sediment concentrations from the MODIS Aqua and Terra data, improving synoptic information of water quality in the Chesapeake Bay with higher temporal frequency. It also demonstrated that the sediment concentrations in the Chesapeake after the landfall of Isabel reached the highest level observed in 2003 and that the main factor responsible for the increase was not the amount of precipitation, but other parameters (wind, storm surge) associated with the storm.

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