Restoring number of suspended particles in ocean using satellite optical images and forecasting particle fields

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ABSTRACT

A method to retrieve concentrations of suspended large and small particles in seawater from satellite images is proposed. The method uses as input images of scattering and backscattering coefficients in several satellite channels as well as an image of concentration of chlorophyll. All these three properties are derived using an atmospheric correction algorithm and algorithms to derive inherent optical properties from remote sensing reflectance. The proposed method is based on several approaches developed previously by Twardowski *et al.*, van de Hulst, and Evans and Fournier and is based on Mie theory. The proposed method was applied to restore a number of suspended particles and their dynamics in ocean using SeaWIFs satellite optical images.

Keywords: Suspended particles, optical satellite images, optical remote sensing, SeaWIFs.

1. INTRODUCTION

This paper is a continuation of our previous work [1] presented at the II International Conference "Current Problems in Optics of Natural Waters," ONW'2003. We do present here the same particle algorithm, but illustrate it with different and more advanced application. Below we describe an approach to estimate concentrations of suspended scattering particles in seawater using spectral information obtained in optical channels from a satellite. Modeling results by various authors (Forand and Fournier [2], Twardowski and others [3]) show that spectral dependence of particular scattering and extinction (attenuation) coefficients are closely related to the shape of particle size distribution in seawater. In the first approximation the shape of size distribution may be represented in the form of Junge distribution. The spectral shape of scattering or particular extinction (or scattering) coefficient allows us to obtain a Junge parameter which is a key to compute an effective refractive index of seawater with suspended scattering particles. The value of effective refractive index allows us to estimate shares of organic and terrigenic fractions of scatterers. The total concentration of scattering matter is estimated through the total scattering coefficient and a scattering efficiency by arbitrary size particle averaged over restored size distribution (Evans and Fournier [4], van de Hulst [5]). The actual realization of the approach is implemented as a C code and tested with an optical SeaWIFs satellite data of sea water reflection in the Gulf of Mexico (Mississippi Bight area).

The inputs to the proposed algorithm are images of particle extinction c_p, scattering b_p and backscattering b_{Bp} coefficients,[6] and outputs are images of concentrations of organic C_p^{org} and terrigenic C_p^{ter} fractions of suspended matter.

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The input images are obtained from the images of remote sensing reflectance r_{rs} in several bands of a satellite optical sensor. We used algorithms of K. L. Carder [7] and R. A. Arnone [8] to obtain values of extinction, scattering and backscattering coefficients from the values of remote sensing reflectance. The spectral remote sensing reflectance [9] was obtained from the spectral values of radiances of the ocean-atmosphere system using an atmospheric correction algorithm developed by Howard R. Gordon.[10]

2. THE PARTICLE ALGORITHM

2.1. Derivation of effective refractive index of water with scatterers

The first step in the algorithm is to obtain the slope γ in the spectral dependency of particular extinction coefficient $c_p \sim \lambda^{-\gamma}$ using a linear interpolation method in a log-log scale. The next step is to restore main properties of size distribution of particles suspended in seawater. While realistic particle size distributions $N(r)$ (where r is a particle radius) are quite unique and only in very rare cases may be described by some theoretical kind of size distribution, they are in general, if plotted on a log-log scale: *i. e.* $\log N(r)$ versus $\log(r)$, exhibit a linear behavior. It means, that in the first approximation they can be described as a Junge (or hyperbolic) distribution, $N(r) \sim r^{-\nu}$, with positive value of parameter ν.

The extensive study of inherent optical properties of seawater with scatterers distributed according to Junge law was accomplished by Twardowski *et al.*[3] Among other results these authors obtain empirical relationship between slope of particular extinction coefficient and Junge parameter, as well as relationship that connects effective refractive index of seawater n_w with Junge parameter ν and particular backscattering b_{bp} coefficient. According to Twardowski *et al.*[3] the relationship between particular extinction slope γ and Junge parameter ν is linear:

$$c_p(\lambda) = A_c \lambda^{-\gamma}, \; \nu = \gamma + 3, \; r_{\min} = 0.006\,\mu\text{m}, \quad r_{\max} = 76\,\mu\text{m}, \tag{1}$$

here $r_{\min}$ and $r_{\max}$ are minimum and maximum radii in particles size distribution.

A similar result was obtained previously by Forand and Fournier.[2] These authors implied a Junge distribution of scatterers with $r_{\max} = \infty$. They obtained the similar to Twardowski *et al.*[3] result for the case of particular scattering coefficient:

$$b_p(\lambda) = A_b \lambda^{-\tilde{\gamma}}, \quad \nu = \tilde{\gamma} + 3, \quad r_{\min} = 0, \quad r_{\max} = \infty. \tag{2}$$

We tested both regressions (1) and (2) and found that regression (1) produces more reliable results.

The effective refractive index of suspended particles is connected with backscattering probability by particulate matter $B_p = b_{Bp} / b_p$ (here b_p is a particular scattering coefficient) by the following regression [3] obtained from results of modeling using Mie theory:

$$n_p(B_p, \gamma) = 1 + B_p^{0.5377 + 0.4867\gamma^2}\left[1.4676 + 2.2950\gamma^2 + 2.3113\gamma^4\right]. \tag{3}$$

So, the equations (1) and (3) allow us to restore the parameter of the size distribution ν and effective refractive index of scatterers.

2.2. Estimation of number and concentration of organic and terrigenic fractions of scatterers

The total concentration of particular matter C_p could be found from the following relationships:

$$C_p = C_v \rho , \quad C_v = N_{tot} \bar{V}_p , \tag{4}$$

here C_v is a volume concentration of particular matter, ρ is a mass density of particles, N_{tot} is a total number of particles per unit volume, $\bar{V}_p$ is an average volume of one scattering particle which can be obtained using the following equation:

$$\bar{V}_p = \frac{4}{3}\pi \int_{r_{\min}}^{r_{\max}} r^3 f(r)\, dr , \qquad \int_{r_{\min}}^{r_{\max}} f(r)\, dr = 1 , \tag{5}$$

here $f(r)$ is a normalized size distribution of particles.

Taking into account that total number of scattering particles can be expressed through the particular scattering coefficient [5],

$$N_{tot} = \frac{b_p}{\pi \int_{r_{\min}}^{r_{\max}} Q_{sc}(n_w, x) r^2 f(r)\, dr} , \tag{6}$$

where Q_{sc} is a scattering efficiency. We can rewrite Eqs. (4)-(6) as follows:

$$C_v = \frac{4}{3} b_p \frac{S_v}{S_q} , \quad S_v = \int_{r_{\min}}^{r_{\max}} r^3 f(r)\, dr , \quad S_q = \int_{r_{\min}}^{r_{\max}} r^2 f(r) Q_{sc}(r)\, dr . \tag{7}$$

Integrals S_v and S_q also may be used to obtain a specific scattering coefficient of particular matter:

$$b_p^0 = \frac{b_p}{C_p} = \frac{3}{4\rho} \frac{S_q}{S_v} . \tag{8}$$

The scattering efficiency Q_{sc} of particles suspended in seawater depends on effective refractive index n_w of seawater and size parameter, $x = 2\pi r / \lambda$, where λ is a wavelength of light in vacuum. The value Q_{sc} can be computed numerically using Mie theory.[4] This approach while having superior accuracy is not good for our purposes due to its slowness. For that reason we have chosen to use an analytic expression for Q_{sc} proposed by Evans and Fournier: [4]

$$Q_{sc}(n_w, x) = \frac{Q_R}{\left[1 + \left(Q_R / Q_v T\right)^{\mu}\right]^{1/\mu}} , \tag{9}$$

here

$$Q_R(n_w, x) = \frac{8}{3} x^4 \left(\frac{n_w^2 - 1}{n_w^2 + 2} \right)^2 , \tag{10}$$

$$Q_v(n_w, x) = 2\left[1 - \frac{2}{\bar{\rho}}\left(\sin\bar{\rho} - \frac{1-\cos\bar{\rho}}{\bar{\rho}}\right)\right], \ \bar{\rho} = 2x(n_w - 1) , \tag{11}$$

$$T(x) = 2 - \exp(-x^{-2/3}) , \tag{12}$$

$$\mu(n_w, x) = \frac{1}{2} + (n_w - 1) + (n_w - 1)^2 + \frac{1}{x}\left[\frac{3}{5} - \frac{3}{4}(n_w - 1)^{1/2} + 3(n_w - 1)^4\right]. \tag{13}$$

Equations (9)-(13) give us a very good approximation to scattering efficiency, especially when used later for monodispersed scatterers. The testing of the algorithm to restore concentrations of scatterers based on Eqs. (4)-(13) confirms that the algorithm is stable and reliable.

The next final step in our algorithm is to separate organic and inorganic components of suspended matter.

The final step in this algorithm is to separate organic and terrigenic fractions of suspended matter. The simplest approach is to assume that scattering particles consist of two fractions, organic and terrigenic, with different refractive indices and the same size distributions. In this case an effective refractive index of suspended particles is determined by

$$n_p = \alpha^{org} n^{org} + (1 - \alpha^{org}) n^{ter} . \tag{14}$$

where α^{org} is a share of organic matter in suspended scattering fraction. Consequently,

$$\alpha^{org} = \frac{n^{ter} - n_p}{n^{ter} - n^{org}} . \tag{15}$$

And, correspondingly, the concentrations of organic and inorganic fractions of suspended matter are:

$$C_p^{org} = \alpha^{org} \rho^{org} C_v , \qquad C_p^{ter} = (1 - \alpha^{org}) \rho^{ter} C_v . \tag{16}$$

According to Refs. [3, 11, 12] relative refractive index of organic fraction can be accepted as $n^{org} = 1.04$ (phytoplankton cells), and for terrigenic fraction as $n^{ter} = 1.157$ (quartz-like inorganic matter). The mass densities are accepted as: $\rho^{ter} = 2 \cdot 10^3 \ \mathrm{g/dm^3} \ (\mathrm{or\ g/l})$, $\rho^{org} = 10^3 \ \mathrm{g/dm^3} \ (\mathrm{or\ g/l})$.

This size distribution algorithms has been integrated into the Navy Automatic Processing System (APS) [13] reference where SeaWiFS imagery is used to determine the ocean optical properties that are used as inputs to this particle size algorithms. Figures 1, 3 show results of sample computation using proposed algorithm. Figures 1 represent SeaWIFS images for March 1, 2006 for the Mississippi Gulf Coast for backscattering coefficient of particles b_{Bp} at the same spectral band obtained using the quasi-analytical algorithm.[14] Figures 2 and 3 display output images of the number of particles for the large organic matter α^{org} and number of particles for the small terrigenic part of the scatterers C_p^{ter} generated using proposed algorithm.

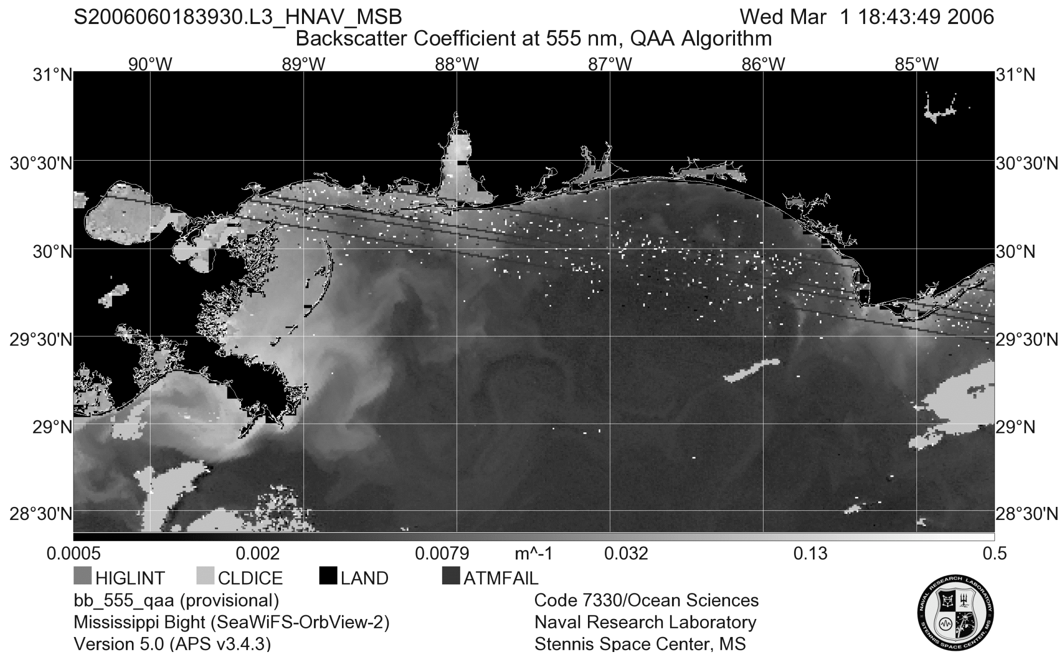

Figure 1: Backscattering coefficient at 550 computed from SeaWIFS data of the Mississippi Gulf Coast (March 1).

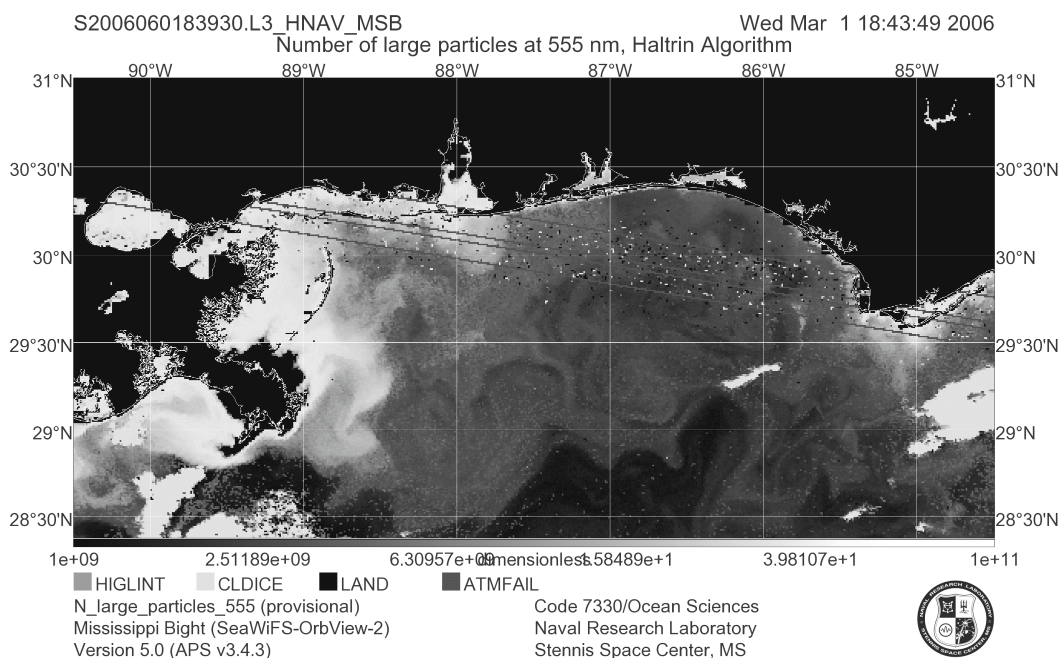

Figure 2, a: Large particles. The backscattering image was partitioned into the large and small particles based on the proposed algorithm. Small particles are assumed to be terrigeneous and large particles are assumed to be biologic.

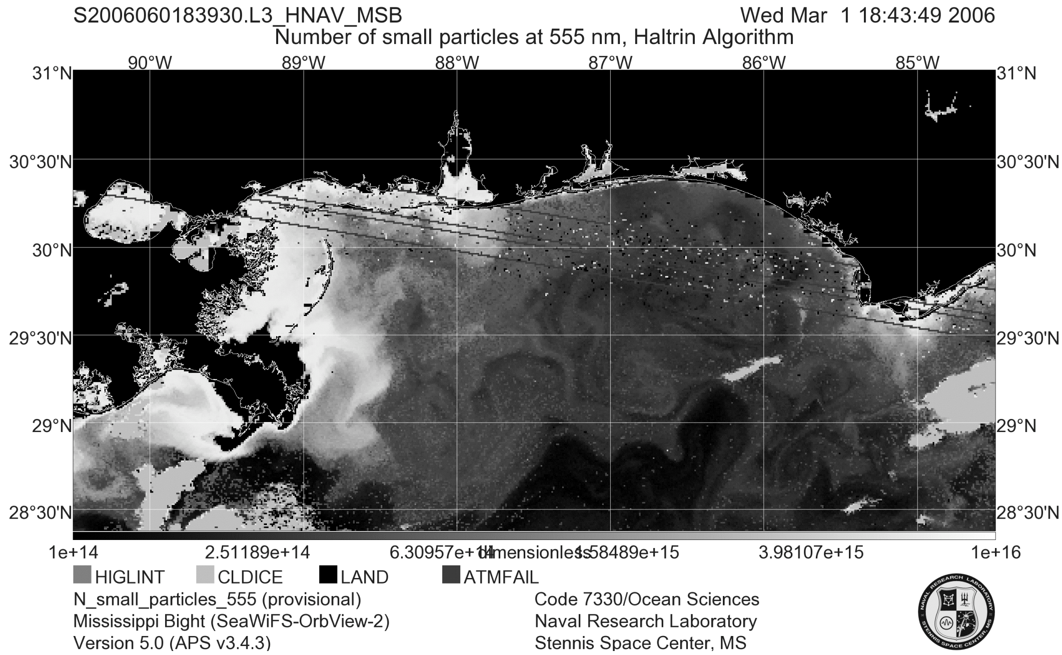

Figure 2, b: Small particles. The backscattering image was partitioned into the large and small particles based on the proposed algorithm. Small particles are assumed to be terrigeneous and large particles are assumed to be biologic.

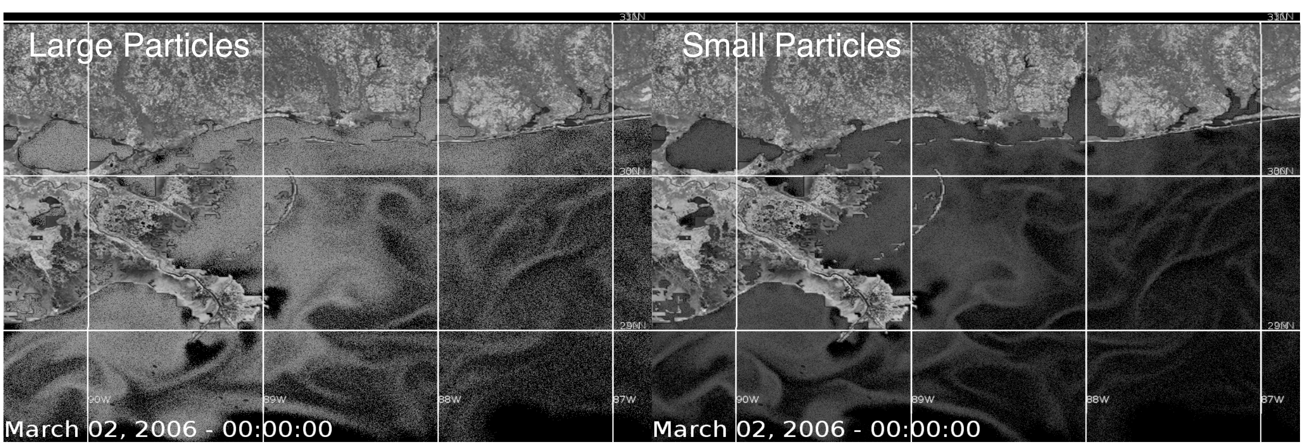

Figure 3. The particle trajectory field for the SeaWIFS on March 1 was used to determine the 24-hour forecast. The two size distributions of particles were used to initialize the seed field for the NCOM advection model. The small and the large particle field were propagated hourly for forecast.

3. INTEGRATING THE SATELLITE PARTICLE SIZE DISTRIBUTIONS INTO OCEAN MODELS

We used the number of particles obtained from the SeaWIFS image with numerical models forecast of the currents to advect the particles forward in time on an hourly bases to determine the 24- and 48-hour particle concentration forecast.[15] The distribution of the particles size was integrated into the Intra America Seas Nowcast Forecast system that runs the Navy Coastal Ocean Model (NCOM) for the northern Gulf of Mexico.[16, 17] NCOM output products of the 3rd current fields were initialized with a 'surface' seed of the number of particles from the SeaWIFS imagery. The initial seed field of particle number was further portioned into large and small particles and advected as a particle tracking using hourly updates from the model. The path and resulting distribution of the particle field were then used as a forecast of the particle concentration image, which was compared with the next day SeaWIFS backscattering image. The particle trajectory field represents a conservative tracer of how particles are controlled solely by physical processes. This simple particle tracking procedure does not account for the particle growth and decay from biological processes, resuspension, flocculation et al. Additionally, the procedure assumes that particles are initialized only at the "surface" and will not account for particles introduced from upwelling processed or downwelling processes.

From the SeaWIFS imagery for March 1, 2006, we computed the number of large (>1.3 μm) particles which are assumed organic and the number of small particles (<1.3 μm) which are assumed terrigeneous (Figure 2 a, b). Based on the size and density of large and small size distributions, we estimated a settling velocity of the 20 and 100 cm per day respectively and were used in differential settling with the NCOM advection on hourly time scale.

The advection methods used to track the particles fields used the "xvison" software to adjust parameters such as dispersion, and settling velocities. Hourly modeled currents of x, v, w components were used to generate the 24- and 48-hour forecast. The particles field for 24-hour period as large particles (organic) and small particles (terrigeneous) and their dispersion after 24 hours are shown in Figure 3. This figure represents a total number of particles integrated over depth for large and small particle distributions. After 24 hours, we observe a separation of the smaller particles and the larger particles (which could be observed in a color plot better). The surface velocities advect the smaller, lower settling velocities faster than the larger higher settling velocity particles. We next accumulated the total number of small and large particles within a 1 km grid, which is similar to SeaWIFS grid (Figure 4a), and converted the particles back into the backscattering coefficient. This advection particle field represents the SeaWIFS forecast backscattering coefficient and can be compared with the March 2, 2006 SeaWIFS image (Figure 4b).

Note the distribution of the Mississippi plume and the distribution of large and small particles that occurs on March 1 and 2 how they have propagated within 24 hours.

4. CONCLUSION

We proposed here a new method to retrieve concentrations of suspended organic and inorganic particles in seawater from satellite images. The method uses as input values of extinction, scattering and backscattering coefficients in several satellite channels. The outputs to this method are concentrations of organic and terrigenic fractions of suspended matter in seawater.

This algorithm was applied to SeaWIFS satellite image and provides a method to characterize spatial distributions of particle size distributions. The particle size distribution was used with numerical models to provide an initial seed for particles trajectory. The different size particles were used for differential settling velocities which were used to advect and settle particles. By combining the particles and numerical circulation models, we demonstrated the capability to forecast the backscattering coefficients based on particle tracking and settling. The disperion of the Mississippi River Plume was used as a test example of how particles disperse with in a 24-hour period. The forecast backscatter image was compared with the SeaWIFS next day image and showed excellent agreement.

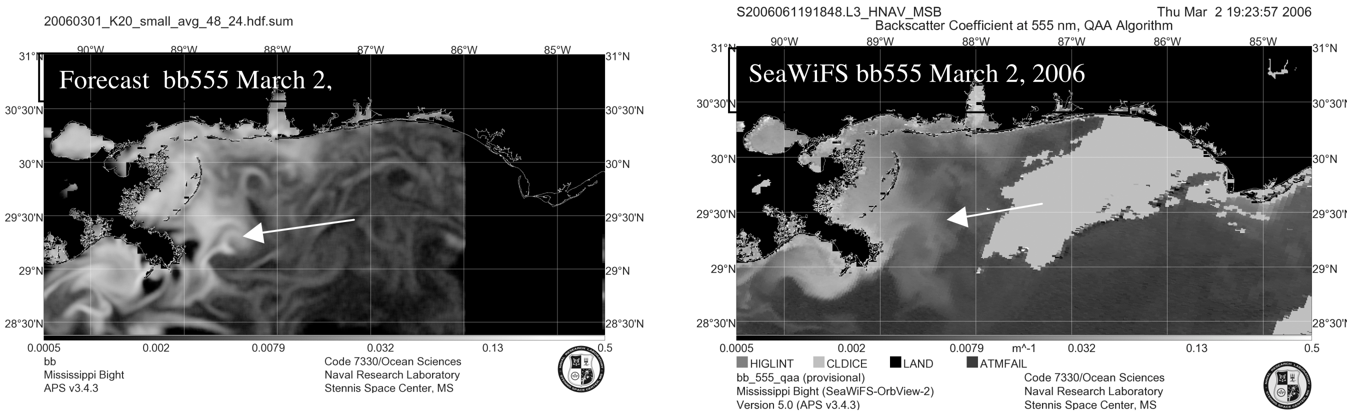

Figure 4. The forecast particles fields were accumulated to the same grid as the next March 2, SeaWIFS image. The forecast and the SeaWIFS image show similar dispersion of the Mississippi River Plume.

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References 1, 6, and 11 are available in a PDF format for downloading from **http://haltrin.freeshell.org**.