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New tools for the study of oceanic eddies: Satellite derived inherent optical properties

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Abstract

Satellite study of oceanic eddy formation, propagation, interactions, and fate was first conducted by sea surface temperature derived at infrared wavelengths. For visible wavelength ocean color reflectances, it is shown that recent radiative transfer model inversions provide additional characteristics of eddies: their constituent absorption and backscattering inherent optical properties. The chromophoric dissolved organic matter absorption coefficient has the highest contrast and is therefore the most visually evident inherent optical property (while the phytoplankton absorption coefficient and backscattering coefficients are respectively less discernible). For use as an analytical tool, comparisons suggests that the chromophoric dissolved organic matter absorption coefficient has a ~10× higher contrast (i.e., ~5% vs. 50%) in the Middle Atlantic Bight making eddy events detectable over longer time periods than with SST imagery. Example imagery illustrates the application of chromophoric dissolved organic matter and phytoplankton absorption coefficient inherent optical properties to the visual injection of dissolved and particulate organic carbon into the deep ocean by a Gulf Stream ring.
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1. Introduction

To date, mesoscale studies of the oceanic eddies have largely used satellite sea surface temperature derived from thermal infrared wavelengths (Anonymous, 1981; Cornillion et al., 1994; Olsen, 1991). To a lesser degree other methods have been applied: (a) microwave satellite altimetry (Cheney et al., 1983; Hansen & Maul, 1991) and (b) visible wavelength empirically derived phytoplankton pigment concentrations (Garciamoliner & Yoder, 1994; Smith et al., 1987). The inherent optical property applications in this paper are discussed and compared only to the more abundant SST methodology.

To address the application of an inherent optical property (IOP) to eddy studies the work described herein uses, for example, Gulf Stream eddies that form rings. Long-lived eddies are frequently called rings and can be loosely defined as vortices that represent a wrapped-up piece of a major ocean current (Olsen, 1991). Simplistically, a ring forms when a linear ocean current becomes unstable and begins to meander. When the meander forms a "loop" that is almost closed upon itself, the current may again choose the shorter less restrictive linear path in such a way that the loop is pinched off and left to stand alone as a high velocity outer portion enclosing the water from which the meander originally departed. To date rings have been frequently described using a physical property of the *water* itself: temperature. Thus, for a current such as the Gulf Stream, poleward meanders give rise to warm core rings (WCRs) and equatorward meanders give rise to cold core rings (CCRs). In the northern hemisphere WCRs and

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Table 1
Eddy classification according to observables of the (a) ring water and (b) its optically active constituents

Water	Constituent IOPs		
Temp.	CDOM	Phytoplankton	Backscattering
WCR	DCCR	DPCR	DBCR
CCR	ECCR	EPCR	EBCR

WCR: warm core ring; CCR: cold core ring; DCCR: depressed CDOM core ring; ECCR: elevated CDOM core ring; DPCR: depressed phytoplankton core ring; EPCR: elevated phytoplankton core ring; DBCR: depressed backscattering core ring; EBCR: elevated backscattering core ring.

CCRs rotate clockwise (anticyclonic) and counterclockwise (cyclonic), respectively.

But the *constituents* carried within these poleward and equatorward water masses have observable signatures too (Hoge et al., 2001). These signatures are their absorption and backscattering IOPs. These IOPs serve as tracers of the ring and convey additional important information about its *physical* evolution, movement, and fate. More importantly, the IOPs convey important *geochemical* and *biological* information since, as will be shown, the chromophoric dissolved organic matter (CDOM) absorption coefficient, phytoplankton absorption coefficient, and backscattering coefficient IOPs of the rings can be concurrently mapped. From these latter IOPs it is hoped that the production, movement, and sequestration of carbon by rings can be obtained resulting in improved understanding of the carbon cycle and climate change. Estimates of carbon injected into the Middle Atlantic Bight will not likely change but the estimated amount transported to the deep ocean may change due to the robust CDOM absorption coefficient imagery available using the methods described herein.

It is the objective of this paper to (1) suggest additional tools for the study of oceanic eddies: IOPs, and (2) use IOP tools to demonstrate the visual injection of dissolved and particulate organic carbon into the deep ocean by a Gulf Stream ring.

Table 1 summarizes phenomena, abbreviations, nomenclature, and partitioning associated with eddy classification according to observables of the (a) ring water and (b) its optically active constituents. The description of the results will extensively utilize the abbreviations in Table 1.

2. Methods

2.1. Retrieval of oceanic inherent optical properties from SeaWiFS water-leaving reflectances

The inherent optical properties are retrieved from SeaWiFS water-leaving reflectances. Briefly, an oceanic radiance model (Gordon et al., 1988) is inverted by linear matrix inversion methods (Hoge & Lyon, 1996, 1999; Hoge et al., 1999a, 1999b, 2001) to retrieve the three principal inherent optical properties: phytoplankton absorption, $a_{\mathrm{ph}}(\lambda_i)$, CDOM/detritus absorption, $a_{\mathrm{d}}(\lambda_i)$, and non-water total constituent backscattering, $b_{\mathrm{bt}}(\lambda_i)$. See the Nomenclature section for definition of symbols and acronyms.

The IOPs are related to the satellite-derived water leaving radiances via (Gordon et al., 1988),

$$L_{\mathrm{w}}(\lambda) = F_0\cos(\theta_0)M\ R/Q \tag{1}$$

where $M=(1-\rho)\ (1-\bar{\rho})/m^2\ (1-rR)$ and where

$$R/Q = \left(l_1X + l_2X^2\right) \tag{2}$$

Here l_1=0.0949 and l_2=0.0794 and

$$X = b_{\mathrm{b}}/(b_{\mathrm{b}} + a) \tag{3}$$

Eq. (3) yields the fundamental linear form for the retrieval of the IOPs

$$a + b_{\mathrm{b}}\left(1 - \frac{1}{X}\right) = 0 \tag{4}$$

where X is obtained from the solution of the quadratic equation in Eq. (2). For convenience define $v=(1-(1/X))$. Then, it is easily seen that the desired constituent IOPs are related to the sea water IOPs by

$$a_{\mathrm{t}} + b_{\mathrm{bt}}v = -(a_{\mathrm{w}} + b_{\mathrm{bw}}v) \tag{5}$$

where the subscript t labels the non-water constituents IOPs, and subscript w labels the water IOPs. Then, invoking the wavelength dependancy and inserting the IOP models, the three principal IOPs can be retrieved from the following matrix equation (Hoge et al., 1999a, 1999b),

$$a_{\mathrm{ph}}(\lambda_{\mathrm{g}})\exp\left[-(\lambda_i-\lambda_{\mathrm{g}})^2/2g^2\right] + a_{\mathrm{d}}(\lambda_{\mathrm{d}})\exp[-S(\lambda_i-\lambda_{\mathrm{d}})] + b_{\mathrm{bt}}(\lambda_{\mathrm{b}})(\lambda_{\mathrm{b}}/\lambda_i)^n v(\lambda_i) = h(\lambda_i) \tag{6}$$

where $h(\lambda_i)=-[a_{\mathrm{w}}(\lambda_i)+b_{\mathrm{w}}(\lambda_i)\ v(\lambda_i)]$ is the column matrix, or vector, of hydrospheric constants (sea water absorption and backscattering) and the oceanic water-leaving radiances (Hoge & Lyon, 1996; Hoge et al., 1999a, 1999b). Each of the IOP models for phytoplankton absorption coefficient, CDOM/detritus absorption coefficient, and total constituent backscattering has already been described in detail (Hoge & Lyon, 1996). The IOP model reference wavelengths, λ_{g}, λ_{d}, and λ_{b} need not coincide with the sensor observational bands (Hoge & Lyon, 1996). The matrix formulation of the radiance model inversion exemplified by Eq. (6) is a powerful framework for IOP retrievals as well as analysis of errors in the retrievals (Hoge & Lyon, 1996). These error analyses have shown that the accuracy of the CDOM/detritus absorption retrieved by linear inversion is strongly dependent on the accuracy of the exponent n in the constituent backscattering spectral model, $b_{\mathrm{bt}}(\lambda)=b_{\mathrm{bt}}(\lambda_{\mathrm{b}})$