Satellite and in situ observations of the bio-optical signatures of two mesoscale eddies in the Sargasso Sea

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ARTICLE INFO

Article history:
Accepted 24 January 2008
Available online 5 May 2008

Keywords:
Mesoscale eddies
Sargasso Sea
Satellite ocean color
Remote sensing
Bio-optics

ABSTRACT

Satellite ocean-color imagery and field spectroradiometer observations are used to assess the bio-optical signatures of two mesoscale features, a cyclone C1 and an 18°-water anticyclone A4, in the Sargasso Sea. Field determinations of upper layer bio-optical properties, such as the diffuse attenuation coefficient and remote-sensing reflectance spectra, show little statistically significant variations with distance to the eddy center. These contrasts field observations showing many-fold higher phytoplankton pigment biomass at depth (and for A4 higher primary production rates at depth) than is typical for this region. The cyclone C1 does show a significant decrease in the depth of the 1% photosynthetically available radiation (PAR) isolume with increasing distance from eddy center while the anticyclone A4 shows no coherent signal vs. distance. Vertical profiles of bio-optical properties show consistent patterns where subsurface maxima are displaced higher inside the core of the cyclone C1 than in the surrounding waters while the highest values of the diffuse attenuation coefficient at 443 nm are observed within the core of anticyclone A4. Satellite observations of near-surface bio-optical properties show signals consistent with eddy physical characteristics, although the magnitude of these variations is very small, barely detectable by typical field measurement protocols. Mean values of bio-optical properties are higher within the cyclone compared with its periphery but not for the anticyclone. For both eddies, significant inverse correlations are observed between time series of bio-optical properties and eddy center sea-level anomaly. Consistent response to wind speed is also noted: following strong wind events, bio-optical parameters are elevated inside the anticyclone and are reduced inside the cyclone. These observations demonstrate that a combination of physical processes, including vertical eddy uplift, eddy horizontal advection, and eddy-scale Ekman pumping, contribute to the bio-optical imprint of mesoscale eddies. The contributions of these forcing mechanisms change over the period of observation, illustrating the limitations of inferring eddy bio-optical dynamics from short-term, field observations. The present analyses provide insights into the potential as well as the drawbacks of bio-optical techniques for probing the biological and biogeochemical impacts of open-ocean eddies.

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1. Introduction

Mesoscale physical oceanographic features have long been recognized to be a major source of variability in biological and biogeochemical processes in the open ocean (e.g., Angel and Fasham, 1983; Falkowski et al., 1991; McGillicuddy, 2001). Mesoscale eddies alter isopycnal topology, influencing both nutrient and light availability while advecting and dispersing water parcels horizontally. It has been hypothesized that through their vertical motions eddies can lift nutrient replete waters into the euphotic zone, providing a previously unaccounted source of new nutrients for upper ocean ecosystems (McGillicuddy et al., 1998). Eddies also obfuscate the interpretation of temporal trends from fixed point observations (Dickey et al., 1993) and confuse the interpretation of sinking particle fluxes measured by fixed sediment traps (Siegel and Deuser, 1997). In all, mesoscale eddies are a source of disturbance to open-ocean ecosystems and often complicate the sampling of ocean processes.

Much of our understanding of how mesoscale physical features affect ocean biological and biogeochemical processes has come from the synoptic views afforded by satellite imagery (Gordon et al., 1980; Brown et al., 1985; Smith et al., 1987). Satellite ocean-color imagers provide large (>1000 km) swaths of imagery with a spatial resolution of ~1 km as they orbit the Earth providing synoptic views of the ocean biological and biogeochemical processes. In the absence of clouds, the Sea Viewing Wide Field
of view Sensor (SeaWiFS) has the ability to complete coverage of the Earth in 2 days (McClain et al., 2004a). By merging imagery from multiple satellite data sets, we can improve this coverage dramatically especially on daily time scales (Gregg et al., 1998; Maritorena and Siegel, 2005).

However, ocean-color signals only reflect what occurs in just the upper layers of the sea. This is typically thought of as the upper attenuation depth (1/4Kd) of the water column (Gordon and McCluney, 1975; Smith, 1981). For the clear waters of the Sargasso Sea (Siegel et al., 1995a, 2001; Siegel and Michaels, 1996), these depths correspond to the upper 10–30 m of the water column depending on the wavelength of light. This means that satellite ocean-color imagery will likely skim the surface of a mesoscale eddy and may not sample much of the biological and biogeochemical dynamics occurring within its interior. For example, McGillicuddy et al. (2001) found strong correspondence between satellite chlorophyll (Chl) and sea-surface temperature imagery during the spring in the Sargasso Sea but relatively little correspondence during the summer. This was due likely to strong vertical physical oceanographic gradients associated with seasonal heating effectively masking the biological activity that may be occurring below the mixed layer. This suggests that ocean-color imagery may be an imperfect tool for assessing the biological and biogeochemical impacts of mesoscale features.

Satellite altimetry estimates of sea level have the advantage that they sense primarily displacements in thermocline depth as the effects of seasonal heating can be accounted for (Cazenave and Fu, 2000). Observations of sea-level anomalies (SLA) from the Sargasso Sea show mesoscale features with scales of 150–250 km propagating westward at speeds of 3–6 km day\(^{-1}\) similar to Rossby waves (Chelton and Schlax, 1996; Siegel et al., 1999). Correlation analyses of satellite estimates of Chl and SLA show correspondence coherent with the westward propagation of mesoscale features (Cipollini et al., 2001; Uz et al., 2001). However, digitally filtered Chl and SLA signals are often out of phase with each other (Glover et al., 2002; Killworth et al., 2004; Charria et al., 2006). These differences suggest that a variety of processes can affect the upper-ocean bio-optical response to mesoscale features.

Here, we highlight the importance of three basic mechanisms for how mesoscale eddies influence upper ocean bio-optical properties. We will denote these as the eddy uplift, eddy–Ekman pumping and eddy advection hypotheses (Fig. 1). The eddy uplift hypothesis assumes that the uplift of nutrient-replete isopycnal surfaces into the euphotic zone during the formation phase of an eddy (or during any adjustment of the eddy) results in an increase in rates of phytoplankton production (McGillicuddy et al., 1998; Siegel et al., 1999). One would expect the spatial distribution of bio-optical properties to be elevated in the center of a cyclone and a reduced in an anticyclone (see the left two panels of Fig. 1). Eighteen degree water eddies, also known as mode water eddies, are an exception to this, as elevated biological and biogeochemical properties are often found in the core of these features created by the uplift over the upper ∼400 m of the seasonal thermocline (McGillicuddy et al., 1999, 2007; Sweeney et al., 2003).

The second mechanism is the eddy–Ekman pumping hypothesis where the eddy’s orbital circulation interacts with a spatially uniform wind field to create a differential stress distribution across the eddy (Fig. 1 center panels). This results in an upwelling in an anticyclone and downwelling in a cyclone irrespective of the wind direction (McGillicuddy et al., 2007; Ledwell et al., 2008). This should lead to enhanced bio-optical properties within an anticyclone and reduced levels in a cyclone (see the center panels of Fig. 1) in opposition to expectations of the eddy uplift hypothesis. The upwelling velocity and therefore the vertical nutrient flux created by eddy–Ekman pumping will be proportional to the wind stress curl created by the eddy’s orbital velocity and the wind (Martin and Richards, 2001).

Last, the eddy’s orbital circulation can act to strain a meridional gradient in bio-optical properties resulting in elevated values to the west (east) of a cyclone (anticyclone) and reduced values on the other side (Fig. 1, right panels). This mechanism is a variant of the Rossby wave straining suggested by Uz et al. (2001) and Killworth et al. (2004). All three mechanisms have unique

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**Fig. 1.** Illustration of three hypothesized processes through which mesoscale eddies regulate upper-ocean bio-optical properties; eddy uplift (left panels), eddy–Ekman pumping (center panels), and eddy advection (right panels). The upper row of panels shows what is postulated for a cyclone (low sea-level anomaly) while the bottom row illustrates what should happen for an anticyclone (high sea-level anomaly). The shading provides a depiction of the relative change in bio-optical properties hypothesized for each mechanism. The case for an 18° water eddy is anomalous as upper-ocean isopycnal surfaces trend towards the sea surface within these features while the overall thermocline structure results in a high sea-level anomaly. See the text for further details.
spatial signatures local to a given eddy (Fig. 1). The distinction among these mechanisms is important as the eddy uplift and eddy–Ekman pumping hypotheses result in altered rates of new production whereas the eddy advection mechanism to first order will only stir existing gradients and should not have a significant biogeochemical impact.

To gain an understanding of these mechanisms and how they impact upper ocean bio-optical properties, we assess two well sampled mesoscale features in the Sargasso Sea during the EDDIES experiment using satellite ocean-color and field radiometric determinations of bio-optical properties. The two eddies are a cyclone (C1) sampled in the summer of 2004 and an 18° water anticyclone (A4) sampled in the summer of 2005 (McGillicuddy et al., 2007; other papers in this volume). These two eddies showed greatly elevated phytoplankton pigment concentrations at depth and for the anticyclone A4 elevated primary production rates at depth, though many other factors (particle export, bacterial abundance and rates, and zooplankton biomass) were roughly similar to typical conditions for this region of the Sargasso Sea (McGillicuddy et al., 2007). In particular, both eddies had subsurface dissolved oxygen minima that implied a remineralization of export of 1–3 times the annual new production for this region (McGillicuddy et al., 2007). Our goals are to understand how mesoscale features affect bio-optical properties in the Sargasso Sea and to provide insights into how bio-optical data could be used to assess coupled biological–physical processes in pelagic ecosystems.

2. Methods

2.1. Field observations of apparent optical properties

Spectroradiometry observations were made from both the R/V Oceanus and the R/V Weatherbird II during the 2004 and 2005 EDDIES project field seasons (McGillicuddy et al., 2007). A total of 146 spectroradiometry casts were made averaging 36 for the four surveying periods for the two ships combined. We will focus here on the sampling of eddies of the cyclone C1 in the summer of 2004 and the anticyclone A4 in the summer of 2005 and not the other features sampled on these cruises (see supplementary section of McGillicuddy et al., 2007 for more details). This resulted in 62 and 45 casts within 100 km of the two eddies (Table 1; note that the numbers of casts in the statistical summaries below may differ because some casts are short or were unusable due to ship shadowing). Spectroradiometer casts are only made during daylight condition; hence, the resulting data cannot be used to produce synoptic maps of bio-optical properties. However, these data can be used to assess bio-optical property patterns as a function of distance from the center for the two eddies.

Spectroradiometer profiles were made with profiling instrumentation that are “kited” away from the ship to avoid the ship’s shadow (Waters et al., 1990; Weir et al., 1994). On the R/V Oceanus, a Satlantic (Halifax, NS, Canada) Micro-Profiler II with 11 spectral channels of upwelling radiance and downwelling irradiance was deployed. On the R/V Weatherbird II, a Satlantic SeaWiFS Profiling Multispectral Radiometer was deployed again with 11 channels of upwelling radiance and downwelling irradiance spectra. Both instruments monitored incident downwelling irradiance spectra from a mast on the ships and the spectral channels ranged from 325 to 683 nm. These profiles are used to determine the diffuse attenuation spectrum, $K_d(\lambda)$, the remote-sensing reflectance spectrum, $R_s(\lambda)$, and the depth of the 1% photosynthetic available radiation isolume, $Z_{1\%}$, following standard methods (Siegel et al., 1995b, 2001; Mueller et al., 2003). Values of $K_d(\lambda)$ are averaged over the upper 25 m of the water column. Estimates of $K_d(\lambda)$ were determined via least-squares regression of the log-transformed upwelled radiance spectrum over the upper 25 m of the water column to provide an assessment of the upwelled radiance spectrum just beneath the sea surface ($L_u(0,\lambda)$). These values of $L_u(0,\lambda)$ are propagated through the sea surface using a constant factor that accounts for differences in the indices of refraction for air and seawater and the reflectivity of the surface (0.524; Gordon et al., 1988) and then divided by the incident irradiance spectrum to calculate $R_s(\lambda)$. The averaging interval of the upper 25 m was chosen to best represent the bio-optical properties that might be sensed using ocean-color satellite sensors. Values of photosynthetically available radiation (PAR) and depth of the 1% incident PAR isolume are calculated from the spectral irradiance observations following standard procedures (Siegel et al., 2001).

2.2. Satellite ocean-color observations of optical properties

We search for eddy signatures in satellite ocean-color data using retrievals of Chl concentration and the absorption coefficient for colored detrital and dissolved materials at 443 nm (CDM) using the Garver–Siegel–Maritorena algorithm (GSM01; Maritorena et al., 2002; Maritorena and Siegel, 2005; Siegel et al., 2005). Data from both the SeaWiFS and the Moderate resolution Imaging

Table 1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Eddy</th>
<th>N</th>
<th>Mean</th>
<th>Std. dev.</th>
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<th>Slope as $f(R_{s(443)})$ (units km$^{-1}$)</th>
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<td>0.0017</td>
<td>0.012</td>
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Significant linear regression slopes are shown in boldface where the optical property and radial distance to the eddy center are significantly from zero at the 95% confidence level.
Spectrometer of the Aqua platform are merged together to produce daily mapped images of Chl and CDM (Maritorena and Siegel, 2005). The use of multi-mission merged imagery provides ocean-color observations with the greatest coverage. In addition, the merging methodology produces estimates of CDM that are likely to be more responsive to vertical advection induced by the mesoscale features than Chl due to its far shallower summertime subsurface maximum (Nelson et al., 1998; Siegel et al., 2002; Hoge and Lyon, 2005).

The merged daily Chl and CDM data fields are aggregated onto a 1/4° regular grid over the entire Sargasso Sea (20°–42°N and 75°–10°W) and weekly averages are constructed after log-transforming the data fields (Campbell, 1995; Doney et al., 2003). Spatial anomalies are determined by first calculating a moving 15 × 15 pixel (375 km × 318 km) spatial average of the ln(Chl) and ln(CDM) fields and subtracting these low-passed fields from the original ln(Chl) and ln(CDM) fields.

Eddy center locations are taken from the analysis of merged satellite altimeter sea-level anomaly imagery and shipboard acoustic Doppler current profilers (McGillicuddy et al., 2007; Ledwell et al., 2008). These locations are used to assess the satellite ocean-color distribution following each eddy and to assess changes in field observed bio-optical properties as a distance from eddy center. SLA of the eddy center (SLA$_{eddy}$) are calculated from the SSALTO/DUACS merged altimetry data set (www.aviso.oceanobs.com/html/donnees/duacs/welcome_uk.html). These data are objectively analyzed dynamic topography fields on a 1/3° resolution grid with a temporal resolution of 3.5 days where observations from as many as six satellites are merged. A large-scale (>1500 km) spatial mean is removed from each scene to remove the effects of seasonal heating on sea level (Siegel et al., 1999). The resulting sea-level anomaly field is sampled following determinations of eddy center. QuikSCAT wind speeds are also projected onto the eddy trajectories from 1/4° gridded, twice daily vector wind images (McGillicuddy et al., 2007).

We diagnose the time-averaged impacts of these two eddies on the ocean-color fields by conditionally sampling ln(Chl) and ln(CDM) (and their anomalies) over a 552 km × 527 km domain (hereafter referred to as the “500 km box”) centered on the location of the two eddies on a weekly basis. The time period for these analyses spanned June through the end of August for both sampling years (14 weeks). A canonical eddy with a nominal diameter scale of 170 km is used in a masking procedure to determining ocean-color property values inside and outside, as well as east and west, of the two eddies. To assess east vs. west differences, the canonical mask is moved one eddy radius west and east of the eddy center location and statistics within the mask are determined. A 170 km eddy diameter is typical for mesoscale features observed with the same data set (Chelton et al., 2007).

3. Results

The trajectories of the two eddies C1 and A4, the near-field sampling of radiometric profiles and their respective summer mean Chl distribution (June 1–September 1) are shown in Fig. 2. For both field seasons, remote-sensing estimates of Chl concentrations are low, typically less than 0.06 mg m$^{-3}$ for the region surrounding the two eddies (the black tracks in Fig. 2). Seasonal mean values of Chl increase to the north and around the Bermuda plateau following typical patterns for the Sargasso Sea (Nelson et al., 2004; McClain et al., 2004b). Though the meridional changes in Chl are small in absolute magnitude (∼0.02 mg m$^{-3}$),
they are large relative to the low values observed (Figs. 2A and B). If anything, regional summer mean values of Chl are higher in 2004 (during the sampling of C1) than they are during the summer of 2005 (when A4 was sampled). Further, zonal structures in the Chl field with spatial scales of several 100 km are observed (see also Nelson et al., 2004). The black tracks in Fig. 2 note the trajectories for eddies C1 and A4 for the period June through end of August of each year. During this time, both eddies occupied a narrow meridional window—roughly 30–31°N, traversing from east to west.

The spectroradiometer data show mean values for the depth of the 1% incident PAR isolume, $Z_{1\%}$, of 97.3 m for the cyclone C1 and 96.5 m for the anticyclone A4 (Table 1, Fig. 3), which are similar to annual mean values found at the BATS site (mean 97 m, s.d. 12 m; Siegel et al., 2001). There are no significant differences in the mean values of $Z_{1\%}$ either between the two eddies or for the two occupation periods of each of the two eddies (data not shown). For the anticyclone A4, no statistically significant relationship was found between observations of the $Z_{1\%}$ depth and distance from the eddy center (Fig. 3, Table 1). However, for the cyclone C1, a statistically significant (at the 95% c.i.) relationship was observed between the $Z_{1\%}$ depth and distance from the eddy center (Fig. 3, Table 1) where the depth of the 1% incident PAR isolume decreases with increasing distance from the eddy center. This indicates that water-column PAR attenuation is lower inside the cyclone than outside, which is contrary to expectations based upon the eddy uplift hypothesis.

The mixed-layer average determinations of the diffuse attenuation spectrum, $K_d(\lambda)$, and the remote-sensing reflectance spectrum, $R_{rs}(\lambda)$, exhibit similar patterns as seen for $Z_{1\%}$ (Table 1, Fig. 3). As before, the mean apparent optical properties are similar to the long-term averages observed for BATS (Siegel et al., 1995a, 2001). For the anticyclone A4, no significant relationships are found between any apparent optical property determination and radial distance to the eddy center (Table 1). However, for cyclone C1, small yet significant relationships are observed between
determinations of $K_d(412)$, $R_{rs}(412)$, and $R_{rs}(443)$ vs. the distance to the eddy center (Table 1). The sign of the regression slopes indicates that these bio-optical properties are clearer inside the cyclone rather than outside (Table 1). This relationship is significant more often for the 412-nm waveband, which supports the notion of using colored dissolved organic matter as a tracer of mesoscale eddy activity (Hoge and Lyon, 2005).

Contrasting the findings with the surface and vertically integrated optical properties, vertical profiles of the diffuse attenuation coefficient at 443 nm, $K_d(443)$ show some changes in the vertical profile of $K_d(443)$ as a function of distance from eddy center for both of the eddies (Fig. 4). Profiles were smoothed using a 10-m median filter and are limited to measurements made within 100 km of the eddy centers. The profiles within 10 km of

![Fig. 4. Vertical profiles of $K_d(443)$ (in m$^{-1}$) taken within 100 km of eddy center for the sampling of (A) the cyclone C1 and (B) the anticyclone A4. Profile values within 10 km of the eddy center are shown in the red lines. All profile values shown have been smoothed using a 10-m moving median filter.](image-url)
the eddy center ("at the center") are shown in Fig. 4 with the red lines. As expected, vertical profiles of $K_d(443)$ show a subsurface maximum reflecting an increase in solar radiation attenuation at the subsurface Chl maximum (Siegel and Dickey, 1987). The depth of the $K_d(443)$ subsurface maximum lies between 75 and 120 m overall (Fig. 4). For the most part, $K_d(443)$ subsurface maxima lie deeper in the core of cyclone C1 (solid lines in the upper panel of Fig. 4) than in the waters surrounding it. This downward displacement of the $K_d(443)$ subsurface maximum is not found for all profiles in C1. The patchy nature of Chl distributions within cyclone C1 has been noted previously (McGillicuddy et al., 2007; Bibby et al., 2008). No other consistent changes in the $K_d(443)$ profiles are observed for C1 either in or out of the cyclone or in time of sampling. Within the anticyclone A4, values of $K_d(443)$ within its subsurface maximum are often substantially greater than in the waters surrounding it (lower panel of Fig. 4), although there is less of a sense of vertical displacement of the depth of the $K_d(443)$ maximum. Observations of the high $K_d(443)$ values at the eddy center of A4 occurred on July 8, August 18 and 24, 2005 and correspond to the highest values of bottle Chl a concentrations observed from the cruises (McGillicuddy et al., 2007). As shown before (Fig. 3), values of $K_d(443)$ within the upper 25 m of the water column are similar inside vs. outside for both eddies (Fig. 4).

Satellite ocean-color data provide another view of the bio-optical impacts of the two mesoscale features. Knowing eddy center location in time (Fig. 2), the time-averaged distribution of bio-optical properties in a 500 km × 500 km domain following each eddy can be created. These distributions for Chl and CDM (in standard units) and their spatial anomalies (in log-transformed units) are averaged for the 3-month sampling period (June–August) are shown in Fig. 5A for the cyclone C1 and in Fig. 5B for the anticyclone A4. These eddy centric maps of bio-optical properties make several important points. First, values of consistent spatial variations in the retrieved Chl and CDM values on the scale of the two eddies are very small; roughly 0.01 mg m$^{-3}$ for Chl and 0.001 m$^{-1}$ for CDM. Second, the averaged bio-optical properties show only a semblance of coherence with their physical eddy footprint (the solid black ~170 km diameter circle in each of the figures). Last, the time-averaged depictions of bio-optical properties do show patterns consistent with the eddy advection hypothesis (the right panels of Fig. 1). In the cyclone (counter-clockwise circulation), the Chl and CDM distributions are
lower in the east and higher in the west (Fig. 5A). That is, the cyclone appears to be distorting the mean meridional gradient in optical properties increasing in its lead edge (west) and decreasing in its trailing edge (east). The opposite case is found for the anticyclonic (Fig. 5B). Hence, eddy advection straining the meridional gradient of bio-optical properties is clearly one element of how eddies affect satellite ocean-color signals.

The question of whether the eddy’s bio-optical signals are coherent with their physical structure can be tested statistically providing a test for the eddy uplift hypothesis (left panels of Fig. 1). Although difficult to visualize using Fig. 5A, mean values of \( \ln(\text{Chl}) \) and \( \ln(\text{CDM}) \), \( \Delta \ln(\text{Chl}) \), and \( \Delta \ln(\text{CDM}) \), are significantly higher (better than the 95% c.i.) within the cyclone C1 than in the rest of the 500 km box surrounding it (Table 2). For the anticyclone A4, no significant differences for either of the remote-sensed bio-optical properties are found comparing mean values in vs. out of the anticyclone. This suggests that significant mean spatial patterns are observed for the cyclone C1 that are consistent with the eddy uplift hypothesis, but not for the anticyclone A4.

Table 2
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<tr>
<th>Eddy</th>
<th>Property</th>
<th>Units</th>
<th>Mean in</th>
<th>Mean out</th>
<th>Mean in-out</th>
<th>t-Value</th>
<th>% c.i. of significant difference</th>
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<tbody>
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<td>C1</td>
<td>Chl anomaly</td>
<td>( \ln (\text{mg m}^{-3}) )</td>
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<td>-0.004</td>
<td>0.042</td>
<td>0.002</td>
<td>99.8</td>
</tr>
<tr>
<td>C1</td>
<td>CDM anomaly</td>
<td>( \ln (\text{m}^{-1}) )</td>
<td>0.019</td>
<td>-0.004</td>
<td>0.023</td>
<td>0.039</td>
<td>96.1</td>
</tr>
<tr>
<td>A4</td>
<td>Chl anomaly</td>
<td>( \ln (\text{mg m}^{-3}) )</td>
<td>-0.016</td>
<td>0.003</td>
<td>-0.019</td>
<td>0.205</td>
<td>79.5</td>
</tr>
<tr>
<td>A4</td>
<td>CDM anomaly</td>
<td>( \ln (\text{m}^{-1}) )</td>
<td>0.010</td>
<td>0.002</td>
<td>0.008</td>
<td>0.636</td>
<td>46.4</td>
</tr>
</tbody>
</table>

Means are calculated over the 14-week record and t-values are testing if the inside and outside mean spatial anomaly estimates are significantly different from each other. Significant relationships are in boldface font (significance level is 1 minus the t-value).
A strong inverse correspondence is observed between time variations in SLA_{eddy} and the differences between Δln(Chl) and Δln(CDM) sampled in and out of the target eddies (Figs. 6A and B). In both cases, the absolute magnitude of SLA_{eddy} is decreasing indicating a decrease in eddy intensity. Correlation coefficients between SLA_{eddy} and Δln(CDM) are negative and statistically significant at the 95% confidence interval (Table 3). Strong correlation coefficients also are found for Δln(Chl) though not at the same confidence interval. This indicates that the observed decrease in eddy intensity for the two eddies correspond to decreases in bio-optical properties, consistent with expectations for the eddy uplift hypothesis (the left panels of Fig. 1).

Evidence for the eddy–Ekman pumping hypothesis is also found in the time series of wind speed for both eddies (Figs. 6A and B). For the cyclone C1, values of Δln(Chl) and Δln(CDM) inside the eddy are generally greater than those outside of it until the wind speed at the eddy center increases to more than 10 m s\(^{-1}\).

![Fig. 6](A) Upper panel: time series of spatial anomalies of ln(Chl) (X's) and ln(CDM) (square's) for the region inside (solid) and outside (dashed) of the eddy mask for the cyclone C1 during the summer of 2005. Middle panel: Quikscat wind speed (solid, left axis) and squared wind speed (dashed, right axis) time series averaged over the 500 km box following the cyclone C1. The Quikscat data are smoothed using a 3-day running mean. The timing of the in situ sampling is plotted in the middle panel as the O's for R/V Oceanus and the W's for the R/V Weatherbird II. Lower panel: values of SLA_{eddy} (cm) sampled following C1.

![Fig. 6](B) Upper panel: time series of spatial anomalies of ln(Chl) (X's) and ln(CDM) (square's) for the region inside (solid) and outside (dashed) of the eddy mask for the anticyclone A4 during the summer of 2005. Middle panel: Quikscat wind speed (solid, left axis) and squared wind speed (dashed, right axis) time series averaged over the 500-km box following the anticyclone A4. Lower panel: values of SLA_{eddy} (cm) sampled following A4. The Quikscat data are smoothed using a 3-day running mean. The timing of the in situ sampling is plotted in the middle panel as the O's for R/V Oceanus and the W's for the R/V Weatherbird II.
Then the values of $D \ln(\text{Chl})$ and $D \ln(\text{CDM})$ decrease dramatically. The opposite pattern is seen for the anticyclone where values of $D \ln(\text{Chl})$ and $D \ln(\text{CDM})$ inside the feature are greater than those outside only after the wind speeds exceed roughly 10 m s$^{-1}$ (Fig. 6B). The correspondence between the $D \ln(\text{Chl})$ and $D \ln(\text{CDM})$ and the wind forcing is most apparent when viewed as the wind speed squared which is proportional to the wind stress (Figs. 6). Statistical correlations observed between the time variations in weekly mean wind speed and squared wind speed and the differences between $D \ln(\text{Chl})$ and $D \ln(\text{CDM})$ sampled in and out of the target eddies are insignificant for all cases (Table 3).

Table 3

<table>
<thead>
<tr>
<th>Eddy</th>
<th>Property</th>
<th>$R$ (wind vs. XX)</th>
<th>$r$ (wind$^2$ vs. XX)</th>
<th>$r$ (SLA vs. XX)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Chl anomaly</td>
<td>-0.202 (0.487)</td>
<td>-0.225 (0.439)</td>
<td>-0.528 (0.052)</td>
</tr>
<tr>
<td>C1</td>
<td>CDM anomaly</td>
<td>-0.149 (0.612)</td>
<td>-0.191 (0.512)</td>
<td>-0.638 (0.014)</td>
</tr>
<tr>
<td>A4</td>
<td>Chl anomaly</td>
<td>0.204 (0.484)</td>
<td>0.252 (0.385)</td>
<td>-0.427 (0.128)</td>
</tr>
<tr>
<td>A4</td>
<td>CDM anomaly</td>
<td>-0.081 (0.784)</td>
<td>0.144 (0.624)</td>
<td>-0.813 (0.000)</td>
</tr>
</tbody>
</table>

Linear correlation coefficients are calculated over the 14-week observation record. Corresponding $p$-values are given in the parentheses and correlations that are significantly different from zero (at the 95% c.i.) are shown in boldface font.
increases in winds correspond to decreases in bio-optical properties in the cyclone C1 and increases in Δln(Chl)in–out for the anticyclone A4 (Table 3). This evidence suggests a role of wind in the bio-optical imprints of a mesoscale eddy (the middle panels of Fig. 1).

Last, the mean impact of the eddy advection hypothesis (right panels of Fig. 1) can be tested by evaluating the patterns in the spatial anomalies of Chl and CDM to the west and the east of the two eddies. This is done by moving the eddy mask one radial distance west and east of the center and evaluating the differences in the mean spatial anomaly values for the two sampling regions (Table 4). Mean values of the spatial anomalies of ln(Chl) and ln(CDM) are significantly higher (at better than the 95% c.i.) to the west of the cyclone C1 than for the same eddy mask but now displaced to the east of it (Table 4). This follows the expected result for the eddy advection hypothesis where the counter-clockwise circulation induced by the eddy results in high values of bio-optical properties from the north to the western quadrant and low values from the south to the eastern side of the eddy. Consistency with the eddy advection hypothesis is also found for the anticyclone A4 where mean values of ln(CDM) are significantly lower (at better than the 99% c.i.) to the west of the anticyclone A4 than they are to the east of it (Table 4). Values of the spatial anomalies for ln(Chl) are lower west of the anticyclone compared with just east of it similar to what is observed for ln(CDM) (though the confidence level is at the 92% level; Table 4). These results provide further validation of the importance of the eddy advection on creating local patterns in bio-optical properties (the right panels of Fig. 1).

4. Discussion

The present results provide an insight into the bio-optical structure of mesoscale eddies in the Sargasso Sea and the processes regulating these signals. In the following discussion, we will address these points and provide an assessment of the sampling of transient bio-optical dynamics of open-ocean eddies using co-incident field and satellite-based observations.

4.1. Bio-optical structure of two mesoscale eddies in the Sargasso Sea

Coincident field and satellite observations of the two open-ocean eddies show the near-surface bio-optical manifestations of these mesoscale features are weak at best. Consistent relationships between field observations of bio-optical properties and radial distance from the eddy centers are found only for the cyclone C1 and only for a few optical properties (Z443, Kd(412), Rrs(412), and Rrs(443); Table 1). These relationships all suggest that the bio-optical properties are clearer (cf., deeper Z443, lower Kd(412) and higher Rrs(412) and Rrs(443) determinations) within the core of the cyclone than outside of it. However, the summertime mean satellite ocean-color observations surrounding the cyclone show elevated values of bio-optical parameters within it (Table 2). The anticyclone A4 shows no significant long-term differences from the field (Table 1) or satellite observations (Table 2). Both eddies show bio-optical signals consistent with the eddy uplift hypothesis in response to changes in their sea-level anomaly (Figs. 6A and B).

Both eddies show consistent signals associated with the depth and strength of the subsurface Kd(443) maximum (Fig. 4). Within the core of cyclone C1, the depth of the subsurface Kd(443) maximum is generally displaced downward by about 20 m (Fig. 4A). This downward displacement of the subsurface Kd(443) maximum will act to reduce water-column-integrated measures of water clarity, such as Z443. Observations of a vertical depression in the subsurface Kd(443) maximum is consistent with the relationship between the near-surface bio-optical properties and the distance from the eddy center (Fig. 3). The downward displacement of the subsurface Kd(443) maximum within the cyclone is also consistent with the eddy–Ekman pumping hypothesis, where winds create a downward displacement of material surfaces within the core of a cyclonic eddy (Fig. 1, upper right panel).

The deep signals with the anticyclone A4 show no consistent displacements in the depth of the subsurface Kd(443) maximum, although observed values of the maximum are often elevated near the core of the anticyclone compared with the surrounding waters (Fig. 4B). In the subsurface Chl maximum of A4, some of the highest Kd(443) values were observed when compared with the long-term BATS record (Siegel and Michaels, 1996; Siegel et al., 2001). Further, the bottle Chl determinations are the highest observed within the entire BATS record (McGillicuddy et al., 2007). McGillicuddy et al. (2007) showed that the elevated values of Chl in the core of the anticyclone A4 were generated by eddy–Ekman pumping that raised the nutrient replete isopycnal surfaces into the euphotic zone (whose depth is little affected by the eddy; Fig. 3). These elevated nutrient concentrations resulted in increases in diatom phytoplankton productivity at the base of the euphotic zone (Goldman and McGillicuddy, 2003; McGillicuddy et al., 2007; Bibby et al., 2008). These temporal changes in eddy dynamics likely have an important bearing on interpretations of eddy bio-optical structure based upon field observations (see below).

4.2. Linking satellite ocean-color eddy imprints to regulating mechanisms

A variety of mechanisms have been proposed to explain the expression of a mesoscale eddy physical signals on satellite ocean-color signals (McGillicuddy et al., 1998; Uz et al., 2001; Kawamiya and Oschlies, 2001; Killworth et al., 2004). These physical processes are illustrated in Fig. 1. The distinction among mechanisms is important. The eddy uplift and eddy–Ekman pumping mechanisms can perform biogeochemical work and lead to altered local rates of new production whereas the eddy advection
hypothesis will, to first order, only stir existing large-scale gradients with little influence on regional scale biogeochemical cycling.

In an attempt towards understanding these mechanisms, we evaluated ocean-color signals following the two eddies (Figs. 5 and 6). Although very small, the time mean bio-optical signals were significantly higher within the cyclone C1 than in its surrounding waters, consistent with the eddy uplift hypothesis; while the anticyclone A4 showed no significant difference in the time averaged bio-optical signals inside vs. outside the feature (Table 2). However, both eddies showed significant correlations in their bio-optical signals with temporal changes in local sea level consistent with the eddy uplift hypothesis (Table 3, Figs. 6). The eddy advection hypothesis was tested by assessing differences in bio-optical parameter signals between an eddy radial distance west and east of the features (Table 4). These west vs. east eddy differences are highly significant and of the correct sign indicating that eddy advection hypothesis is an important controlling mechanism for both eddies. Last, consistent signals in the time series of the spatial anomalies for Chl and CDM, Δln(Chl) and Δln(CDM), sampled within the eddies and in the surrounding 500-km box are found with variations in the wind speed over the eddy (Fig. 6) providing evidence supporting the role of the eddy Ekman pumping mechanism.

We must conclude that all three mechanisms have roles in the ocean-color imprint of the two eddies. The observed correspondence of the eddy’s bio-optical signals with the temporal changes in the eddy’s sea-level anomaly and wind forcing suggest important roles for both the eddy uplift and the eddy–Ekman pumping mechanisms. In effect, these processes lift and depress shallow isopycnal surfaces effectively pumping upper open ocean biogeochemical processes. Clearly, the relative contributions of these mechanisms change throughout an eddy’s lifetime. However, their distinction is important if one were to diagnose the biogeochemical impacts of these features from satellite ocean-color data. In particular, the eddy advection mechanism will not likely have an important biogeochemical impact as its net effect will be to displace upper-ocean water parcels on a spatial scale equivalent to an eddy’s diameter (~170 km).

This present study addressed the dynamics of two well-sampled mesoscale eddies. It seems likely that the answers to questions about the global implications and fluxes associated by physical oceanographic mechanism on eddy bio-optical signals will have come through the analysis of a larger and more comprehensive data set. However, this simple case study illustrates that eddies are forced by several, possibly interacting, physical oceanographic processes.

4.3. Lessons learned from the simultaneous analysis of field and satellite data

The present analysis of satellite and field determined bio-optical structure of two eddies from the Sargasso Sea also provides an assessment of the potential and limitations of sampling transient features in the open sea. First, mesoscale eddies are dynamic entities whose bio-optical characteristics change on synoptic time scales. Here, we show that eddy dynamic evolution and local wind forcing are two factors driving changes in the bio-optical fields within an open-ocean eddy.

Second, the bio-optical signals consistently associated with the eddies are very small. Mean spatial variations in the satellite retrieved Chl and CDM values are ~0.01 mg m⁻³ for Chl and ~0.001 m⁻¹ for CDM at 443 nm (Figs. 5A and B). These values are barely resolvable for Chl and unobtainable for CDM using standard field sampling and analytical protocols (Nelson et al., 1998, 2007; Mueller et al., 2003). Here, these signals are detectable in the satellite analysis because of the long sampling intervals, large spatial averaging windows used and the vertical averaging inherent in ocean-color signals.

The highly dynamic nature of these physical features and the small eddy associated bio-optical signals make these features hard to sample using conventional means such as a research vessel. This likely has a bearing on the conflicting results found between the satellite and field observations of the cyclone C1. The field spectroradiometer observations show that the waters in the center of the cyclone C1 were clearer than those surrounding it (Fig. 2, Table 1). This is inconsistent with the time-averaged evaluation of bio-optical properties following the feature (Fig. 5A), which show a significant increase in the spatial anomalies for Chl and CDM, Δln(Chl) and Δln(CDM), within the feature (Table 2). It is likely that the dynamic changes in the cyclone’s bio-optical properties (Fig. 6A) have aliased the detection of coherent signals as a function of distance from the eddy’s center. Examination of the times when spectroradiometer casts were made (the w and o symbols in Figs. 6A and B) show that these field observations were made during periods where the satellite determined Δln(Chl) and Δln(CDM) values were changing up time (Fig. 6A). Hence, the field observed trends in bio-optical properties for the cyclone C1, although statistically significant (Table 1), may not be truly reflecting the time averaged spatial patterns for this mesoscale feature.

These results point to the importance of multi-platform sampling of transient features in the open sea (Smith et al., 1987; Dickey et al., 2006). The problem is that satellite ocean-color observations only sample bio-optical properties within the surface layer. Here, we find changes in bio-optical properties are most apparent in the vertical profiles (Fig. 4). These results suggest that observations of the full three-dimensional structure of these features over time are needed to complete our understanding of the dynamics and impacts of mesoscale features. New observational platforms, such as gliders and floats, enable vertical profiling of bio-optical properties, which are one way of developing these data sets (Sherman et al., 2001; Davis et al., 2001; Dickey et al., 2006). These instrumentation systems can sample features for a long enough period of time to provide stable determinations of bio-optical parameters—which is necessary due to the extremely low bio-optical signals associated with open-ocean eddies. The integration of these observations with satellite observations and numerical models are the future for understanding the dynamics and impacts of these important dynamical features.

Acknowledgments

The authors thank Dennis McGillicuddy for his energy, persistence and patience (!) in leading the EDDIES project. Eddy trajectories and the QuikSCAT wind speed time series following the target eddies were created by Valery Kosnyrev. We thank the reviewers (and the editor) for their detailed comments on our manuscript. We would also like to acknowledge the support of the National Science Foundation (OCE-0241011) and NASA (NNG04GM15G and NNG04GE66G).

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