Physical dynamics and biological implications of a mesoscale eddy in the lee of Hawai'i: Cyclone Opal observations during E-Flux III

Francesco Nencioli\textsuperscript{a}, Victor S. Kuwahara\textsuperscript{ab}, Tommy D. Dickey\textsuperscript{a}, Yoshimi M. Rii\textsuperscript{c} and Robert R. Bidigare\textsuperscript{c}

\textsuperscript{a}Ocean Physics Laboratory, Department of Geography, University of California Santa Barbara, Goleta, CA, USA
\textsuperscript{b}Currently at Faculty of Education, Soka University, Tokyo, Japan
\textsuperscript{c}SOEST, Department of Oceanography, University of Hawai'i, Manoa, HI, USA

Corresponding author: Francesco Nencioli, Ocean Physics Laboratory, University of California Santa Barbara, 6487 Calle Real, Suite A, Santa Barbara, CA 93117.
E-mail address: francesco.nencioli@opl.ucsb.edu

Keywords: Hawaii, Mesoscale processes, Cyclonic eddies, E-FLUX project, Physical-biological coupling

Abstract
E-Flux III (March 10-28, 2005) was the third and last field experiment of the E-Flux project. The main goal of the project was to investigate the physical, biological and chemical characteristics of mesoscale eddies that form in the lee of Maui and the Big Island of Hawai'i, focusing on the physical-biogeochemical interactions. This region presents favorable conditions for the formation of mesoscale eddies because of the interaction between strong and persistent trade winds and the Hawaiian Islands. The primary focus of E-Flux III was the cyclonic cold-core eddy Opal, which first appeared in the NOAA GOES sea surface temperature (SST) imagery during the second half of February 2005. During the entire period of the experiment cyclone Opal moved over 160 km, generally southward, so that the sampling design had to be constantly adjusted in order to obtain quasi-synoptic observations of the eddy. Analysis of ship transect-depth profiles of CTD, optical and Acoustic Doppler Current Profiler (ADCP) data revealed a well-developed feature characterized by a fairly symmetric circular shape with a radius of about 80 km. Depth profiles of temperature, salinity and density were characterized by an
intense doming of isothermal, isohaline and isopycnal surfaces and in some cases outcropping of several isopleths, typical features of a mature eddy. Isopleths of nutrient concentrations were roughly parallel to isopycnals, indicating that the doming of isopycnals and other physical properties reflected the upwelling of deep nutrient-rich water. The deep chlorophyll maximum layer (DCML) was generally confined within the $\sigma$-t$_{24.2}$ ($\sigma_t = 24.2$ kg m$^{-3}$) and the $\sigma$-t$_{24.4}$ ($\sigma_t = 24.4$ kg m$^{-3}$) isopycnals, and shoaled with them from a depth of about 150 m in the outer regions of the eddy to about 50 m in the center. Chlorophyll concentrations reached their maximum values in Opal's core region (about 30 km in diameter), where nutrients were upwelled into the euphotic layer. ADCP velocity data clearly showed the cyclonic circulation associated with Opal. Vertical sections of tangential velocities were characterized by values that increased linearly with radial distance from near zero close to the center to a maximum of about 60 cm sec$^{-1}$ at roughly 25 km from the center, and then slowly decay. The vertical extent of the cyclonic circulation was primarily limited to the upper mixed layer, as tangential velocities decayed quite rapidly within a depth range of 90 – 130 m. Analysis of the potential vorticity of cyclone Opal suggests that only a relatively small (about 50 km in diameter) and shallow (up to a depth of approximately 70 m) portion of the eddy is isolated from the surrounding waters. Radial movements of water can occur between the center of the eddy and the outer regions along density surfaces within an isopycnal range of $\sigma$-t$_{23.6}$ ($\sigma_t = 23.6$ kg m$^{-3}$) and $\sigma$-t$_{24.4}$ ($\sigma_t = 24.4$ kg m$^{-3}$). The biogeochemistry of the system might have been deeply influenced by these lateral exchanges of water at depth, especially during Opal's southward migration. While the eddy was translating, relatively deep water in front of the eddy might have been upwelled into the core region; this could have led to an additional injection of nutrients into the euphotic zone. At the same time, part of the chlorophyll-rich waters in the core region might have remained behind the translating eddy and, thus contributed to the formation of an eddy wake characterized by relatively high chlorophyll concentrations.

1. Introduction

The interaction between strong persistent northeasterly trade winds and the Hawaiian Islands produces favorable conditions for the formation of mesoscale eddies in the lee of Maui and the Big Island according to studies including those by Patzert (1969), Lumpkin (1998), Chavanne et al. (2002), Calil et al. (2007), and Dickey et al. (2007). These studies indicate that the Ekman transports associated with wind curl fields of trade winds in the leeward side of the Islands produce divergent and convergent flows in the upper water column that most likely induce localized upwelling and
downwelling and ultimately the formation of both cold-core, cyclonic and warm-core, anticyclonic mesoscale features. Mesoscale eddies spin-up quite regularly (roughly every few months or less) to the south-west of the Alenuihaha Channel almost year-round since trade winds are generally quite persistent in this particular region. The oligotrophic region to the west of Maui and the Big Island of Hawaii is therefore characterized and deeply influenced by the almost ubiquitous presence of these mesoscale features. Interestingly, Calil (2007) has described satellite altimeter data that indicate that the region of focus during E-Flux I and III field experiments (to the west of Hawaii) is very nearly coincident with the location of maximum oceanic eddy kinetic energy (centered at approximately 19°N, 157°W).

The first detailed characterization of the physical structure of a cyclonic Hawaiian eddy was performed by Patzert (1969). Subsequently, several other observations of mesoscale lee eddies have been reported, with most investigating the fundamental physical-biogeochemical-biological interactions occurring within those features (e.g., Lobel and Robinson, 1986; Falkowski et al., 1991; Allen et al., 1996; Lumpkin, 1998; Seki et al., 2001, 2002; Bidigare et al., 2003; Vaillancourt et al., 2003). These previous studies have generally characterized the basic characteristics of Hawaiian lee eddies. These eddies have typically been found to be between 40 – 150 km in radius and to exhibit velocities up to 100 cm sec⁻¹. The cold-core cyclonic eddies of most relevance to the present study are baroclinic. Their centers exhibit depressed (negative) sea surface height anomalies (SSHA) due to divergent near surface flow, and low sea surface temperatures (SST) due to the upward movement of deeper cooler water. The surface cold-core expression usually associated with those features make it possible to sometimes use satellite SST imagery to track and investigate Hawaiian eddies; however, cloud contamination and very near surface masking effects impose serious constraints. Satellite altimetry data, while somewhat useful for coarse views and seeing rough SSHA patterns, are marginally useful for more detailed studies of Hawaiian lee eddies because of inadequate spatial and temporal resolution, the O(100 km) horizontal scale of the eddies, and island/land effects on the measurements. Previously, it has been reported that cyclonic eddies have typical life spans ranging from one to several months and that they usually tend to propagate northwestward (e.g., Lumpkin, 1998; Calil, 2007); however, our present studies (i.e., summarized in Dickey et al., 2007), as well as some other reports (e.g., Patzert, 1969), indicate that unusual nearly stationary or southward translating lee cyclones can occur, as well. The upwardly displaced deep waters are relatively nutrient rich, so that mesoscale eddies establish an upwelling of nutrients into the oligotrophic euphotic
zone (with depths of ~100 - 120 m based on depths of the 1% light level). With the availability of sufficient nutrients and light, major modifications and increases in concentrations of phytoplankton communities result. More specifically, an overall increase of rates of primary productivity occurs, and the enhanced availability of nutrients trigger the succession of larger phytoplankton species, with subsequent increases in higher trophic level production. Concomitant increases in carbon remineralization, particle fluxes, and possibly carbon export are the focii of other papers in this volume (i.e. Brown et al., 2007; Maiti et al., 2007; Rii et al., 2007).

Despite the numerous studies conducted in the lee region of the Hawaiian Island chain, very few detailed observations of the physical, chemical and biological structures of individual mesoscale Hawaiian eddies have been reported. A fundamental goal of the E-Flux experiment was to intensively investigate the physical, chemical, and biological structures, dynamics, and interactions of specific mesoscale cyclonic eddies, in order to improve our understanding of the physical-biogeochemical-biological coupling that occurs within these features. Overviews of E-Flux's interdisciplinary approach, sampling methods, and overall results are provided in Dickey et al. (2007). In this paper we present an extensive analysis of the physical and dynamical characteristics of cyclonic eddy Opal. Distributions of fundamental biogeochemical properties are related to the physical structure of the eddy to investigate possible physical-biogeochemical-biological interactions. More detailed analyses of biogeochemical and biological aspects of cyclone Opal can be found in other papers in this volume. Several details concerning the E-Flux I study of cyclone Noah and its similarities and differences with respect to cyclone Noah are given in Kuwahara et al. (2007).

2. Material and Methods

The data collected during the E-flux experiments came from drifters and satellite- and ship-based observations. The following section is limited to only the most relevant methodologies utilized during the E-Flux III field experiment. A more detailed overview of E-Flux observational methods can be found in Dickey et al. (2007).

2.1. Satellite observations

Satellite data were used during the E-Flux project to obtain synoptic near-surface views of the Hawaiian Island region before, during and after each field experiment. (see Dickey et al., 2007, for more details) Analyses of wind and SST fields enabled the retrieval of fundamental, though imperfect, information concerning E-Flux eddies including their wind forcings, positions, and life histories. Wind
data were obtained from NASA's QuikScat scatterometer satellite sensor, while the SST imagery was obtained from NOAA's Geostationary Operational Environmental Satellite (GOES) and NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. Again, satellite SSHA data were found to be of limited value for most of our purposes.

Based on satellite SST data, it is inferred that cyclone Opal formed to the southwest of the Alenuihaha Channel between February 18 and 25, 2005 after the return of intense northeasterly trade wind conditions over the Hawai'i region (see wind time series and satellite images in Dickey et al., 2007). Opal remained evident in the SST imagery until April, after which it was never again observed. Shipboard measurements commenced approximately three weeks after Opal was first detected.

2.2. Field observations

The E-flux III field experiment was conducted from March 10 to 28, 2005 aboard the R/V Wecoma. During the first week of the experiment (March 10 to 15), a series of five shipboard transects averaging roughly 150 km in length were conducted across the eddy. A sixth shipboard transect was also performed at the beginning of the third week (March 22 to 23). A total of 51 hydrographic casts with a survey station spacing of about 18 km were executed along the transects to determine Opal's general characteristics. Had cyclone Opal been a stationary (non-translating) eddy, the transects would have been spatially arranged in a star-like pattern, with each transect crossing the eddy through the initial center estimated from satellite imagery prior to the beginning of the experiment (this was in fact the case for cyclone Noah described in Dickey et al., 2007, and Kuwahara et al., 2007). Unfortunately from a sampling standpoint, cyclone Opal moved at a rather high velocity southward from its location of initial identification by about 160 km during the E-Flux III field experiment period. The average translation speed of the center of the eddy was about 0.33 km h⁻¹ (0.17 knots). Translation velocity showed high variability: maximum values greater than 1.5 km h⁻¹ occurred at the very beginning of the experiment, whereas minimum values less than 0.25 km h⁻¹ occurred at the end of the second week. Figure 1b shows the movement in time of cyclone Opal. This movement posed a serious tracking and sampling problem for the E-Flux III cruise. Several methods were utilized to track the translation of the eddy and to locate the position of its center, the best of which turned out to be the use of near real-time ADCP velocity data (Dickey et al., 2007). The sampling scheme was constantly adjusted so that each transect would pass through the best estimated coordinates of the center of the eddy. The method used for tracking the center of the eddy is discussed in Dickey et al. (2007), whereas the method to provide the very best post-cruise estimate of the eddy's center used in the analyses for this paper is discussed in
detail in the ADCP data section. As shown in Figure 1a, the resulting sampling pattern only partially resembled the planned star-like structure as each new track was adjusted to pass through the best estimated coordinates of the center of the eddy.

Stations determined to be very near the eddy center (IN-stations) and those well outside the influence of the eddy (OUT-stations or far-field stations) were sampled during the second and third weeks of the experiment (March 16-22 and March 24 to 27). IN-stations comprised 51 hydrographic casts (Cast 45–95) and were used to observe the temporal evolution of the physical, biogeochemical, and biological variables in the core of the eddy. OUT-stations comprised 26 hydrographic casts (Cast 105–130) and provided background values for physical and biological conditions. The locations of IN- and OUT-stations are shown in Figure 1b.

E-Flux III hydrographic casts were performed using a SeaBird 9/11+ CTD/rosette package equipped with 12, 10-liter sampling bottles. Continuous vertical profiles were usually conducted to depths of approximately 500 m, and temperature, conductivity, dissolved oxygen, chlorophyll \(a\) (chlorophyll fluorescence), conductivity and beam transmission were measured. Downcast CTD data were processed and binned into 1-m depth bins (see Dickey et al., 2007 concerning instrumentation and data processing and calibration). Sampling bottles were used at selected stations to collect \textit{in situ} water samples at discrete depths. The depths at which the bottles were tripped were determined from the vertical structure of physical and biological variables (i.e. depths of the mixed layer, specific isopycnal surfaces, and DCML). Water samples were collected for various analyses including concentrations of inorganic macronutrients and HPLC pigments (see Rii et al., 2007, for detailed explanations about methods and techniques used for these analyses).

A ship mounted VM-150 kHz ADCP was used to measure current velocity. Vertical profiles of horizontal currents were provided near-real time during the entire cruise. The profiles depths ranged form 40 to 450 m with a vertical resolution of 10 m, and were recorded as 15-min averages.

3. Observational Results

Even with extensive satellite measurements and dedicated ship-based and drifter observations, dynamic and rapidly evolving mesoscale eddies cannot presently be sampled synoptically (i.e., Dickey and Bidigare, 2005). Again, the fast movement of \textit{Opal} represented a major challenge for synoptic sampling. However, the continuous modifications of the original sampling pattern allowed the sampled data to be treated as quasi-synoptic when plotted and interpreted with respect to the moving center of
the eddy in a quasi-Lagrangian reference frame.

In the next sections, the temperature, salinity, density, biogeochemical, and velocity measurements from Transect 3 and 4 are shown and their analyses are discussed in detail. Transect 3 encompassed Cast 13 to 25 (March 13 to 14). Bottle measurements from Cast 19 were discarded from the dataset because of sampling problems. Transect 3 was selected because it was the most intensely sampled of all transects and several biogeochemical variables were measured and analyzed from the collected water samples. Transect 4 included Cast 26 to 36 (March 14 to 15). It was selected for detailed analyses not only because it was oriented perpendicular to Transect 3, but also because the translation speed of Opal's center was relatively low when the two transects were performed. Since the center positions of these two transects were relatively close to each other, the errors introduced in the analysis by considering their measurements to be quasi-synoptic are much smaller than for any other pair of transects. The two transects were also selected because they both appeared to have passed very close to Opal's center, and are good representations of the results from all E-Flux III transects.

3.1. Hydrographic Data

Vertical sections of temperature, salinity, and density for Transects 3 and 4 and their anomalies are shown in Figure 2 and 3, respectively. Vertical dotted lines in the plots indicate the positions where CTD data were collected. As can be noticed from Figure 2, during Transect 3 an extra CTD cast (Cast 20) was performed to sample at the estimated center of cyclone Opal. The anomalies shown in these figures were computed for a specific variable at a given depth as the difference between its value within the eddy and its value in the surrounding oligotrophic waters. Differential property anomalies or DPAs (i.e., Simpson et al., 1984) are defined as

\[ DPA(r, z) = STAR_{cast}(r, z) - OUT_{avg}(z) \]

where \( STAR_{cast}(r, z) \) is the value of the specific variable measured at a depth \( z \) at a given station at a specified distance \( r \) along the transect, and \( OUT_{avg}(z) \) is the value of the same variable at the same depth measured in the OUT-station or far-field waters outside the influence of the eddy. Water properties in the far-field were determined using the data collected at the OUT-stations and the \( OUT_{avg} \) vertical profile for a specific variable was computed as the arithmetic average of the 26 OUT-station profiles.

Vertical contours of temperature and density from Transects 3 and 4 are characterized by almost identical features, indicating that temperature is clearly the main controlling factor for density in the region (Figures 2 and 3). The sections reveal an intense doming of both isothermal and isopycnal surfaces with the outcropping of some of the isotherms and isopycnals at the surface. Both of these
features strongly suggest that cold-core cyclone Opal was still in the physically mature phase of its lifetime when the E-Flux III experiment was conducted.

Temperature and density contours have been used to estimate Opal's dimensions by assuming the radial extent of the eddy to be located where the slopes of isotherms and isopycnals reach near zero values. The $\sigma_{t_{24}}$ ($\sigma_t = 24$ kg m$^{-3}$) isopycnal surface proved to be an important reference level in determining Opal's general characteristics, since it was found to be nearly coincident with the base of the surface mixed layer. The depth of the mixed layer was computed for each profile sampled during the experiment as the depth at which the temperature difference with respect to the 10 m depth was 1°C. From the density contours in Figures 2 and 3 Opal's diameter can be conservatively estimated to be roughly 160 to 180 km. The maximum vertical displacements of the $\sigma_{t_{24}}$ isopycnal indicate the approximate positions of the center of the eddy at about 105 km along Transect 3, and at about 80 km along Transect 4. In both cases, the maximum eddy-induced uplift is roughly 80 – 100 m, with the $\sigma_{t_{24}}$ surface shoaling from a depth of between 130 and 150 m at the edges of the eddy to between 40 and 50 m at its center. More precise positions of Opal's center for the two transects were determined using ADCP velocity data. The fact that the doming of isothermal and isopycnal surfaces from these both transects, as well as from the others not discussed in this paper, is generally symmetric indicates that Opal was a nearly circular feature.

Further information concerning Opal's characteristics can be inferred from the analyses of the distributions of the differential anomalies of temperature and density. The vertical structures of these quantities are dominated in both transects by large regions of relatively high anomalies, up to -3°C for temperature, and up to 1 kg m$^{-3}$ for density; these anomalies clearly indicate the areas where the vertical uplift was most intense. Contour plots of differential density anomaly in Figures 2 and 3 deserve particular attention. For both transects, the area of high anomaly can be roughly characterized by the 0.5 kg m$^{-3}$ contour line. In Transect 3, this area is 60 km wide and is confined within depths of 40 and 160 m. In Transect 4, on the other hand, this area is much narrower, roughly 40 km, and relatively shallower and deeper, extending from 50 m to 180 m depth. These differences between the two sections suggest that Transect 4 might not have crossed cyclone Opal as close to its center as Transect 3. This aspect will be discussed further when we describe the ADCP data section. Values of differential density anomaly decrease with depth below the area of high values for both transects, indicating that the eddy-induced uplift decreases with depth. The edges of Opal are characterized by absolute values of temperature and density anomalies larger than zero, especially within the sub-mixed layer region.
These differences between the vertical profiles at the eddy's boundary and the mean profiles computed from the OUT-stations most likely result from spatial variations of the background conditions that unavoidably exist between the Alenuihaha Channel region, where the transects were sampled, and the area where the OUT-stations were collected, which was further North and closer to land (see Figure 1).

Despite evidence that the doming of isohaline surfaces is similar to the doming observed for isotherms and isopycnals, the differential salinity anomaly contours in Figures 2 and 3 show slightly different features. There is evidence of a region of high negative differentials (about -0.4) below a shallower region of high positive differentials (about 0.2). The presence of these two regions is a direct consequence of the deep salinity maximum (>35) that characterizes the vertical contours of salinity. The eddy-induced uplift brings more saline waters to the surface, establishing the shallow region of positive anomaly, but at the same time the uplift brings less saline waters to depths usually occupied by the deep salinity maximum, which produces the deeper region of negative anomalies.

Figure 4 shows mean vertical profiles to 1000 m of (a) temperature, (b) salinity, and (c) density from both Opal's core region ($IN_{avg}$) and the far-field away from the influence of the eddy ($OUT_{avg}$). Again, the $OUT_{avg}$ profiles were computed using the 26 OUT-stations (Casts 105–130), while the $IN_{avg}$ profiles were computed using the casts made at the center along each transect (Casts 8, 20, 30, 43 and 96) along with the 51 IN-stations. Opal's movement and the ship's drift made it particularly challenging to remain close to the eddy's center during the week of the IN-stations. As a result, some of the IN-station data were collected too far from the center to be useful for the analysis of Opal's core characteristics. Evaluation of whether each hydrographic station was positioned close enough to the center to be used for IN-station analyses was based upon ADCP current data, since velocity values decrease toward zero approaching the center of the eddy (as it will be discussed in the ADCP Data section). A threshold criterion was adopted, and casts collected with a 40 to 100 m averaged current value higher than a certain threshold were removed for the analysis. The threshold value was determined from the ADCP current data obtained during Transects 2, 3, 4 and 5. Analyses of velocity values measured close to Opal's center during those transects suggested 25 cm sec$^{-1}$ as a reasonable threshold value. According to this criterion 9 casts had to be removed, so that only 42 IN-stations were finally used along with the stations collected at the transect centers to compute the $IN_{avg}$ profiles. The dotted lines at the sides of each profile in Figure 4 indicate the 1 standard deviation interval associated with the averaged property at each depth. Clearly standard deviations for all the properties from both $IN_{avg}$ and $OUT_{avg}$ are minimal.
Comparisons of the mean profiles of temperature, density and salinity shown in Figure 4 are consistent with the presentation of data in Figures 2 and 3. Specifically, the eddy-induced uplift is reflected in an upward displacement of the seasonal thermocline, deep salinity maximum and base of the surface mixed layer by about 80 – 100 m at the center of the eddy; and the magnitude of upward displacement decreases with depth. Despite the decreasing uplift with depth, vertical profiles in Figure 4 clearly reveal that the influence of Opal extended to depths of about 600 – 700 m.

Important information concerning the water masses characterizing cyclone Opal can be inferred from classic T-S relations as shown in Figure 5. Figure 5 shows T-S diagrams for the (a) 26 OUT-stations, (b) for the 42 selected IN-stations, and (c) for all of the transect stations, including center casts. The S-shaped T-S curve shown in Figure 5a is typical for the Hawaiian oceanic region and is established by the presence of five distinct water masses. These are in order from greatest depth to the surface: the North Pacific Bottom Waters (NPBW), characterized by moderate salinity (>34.5) and low temperature (<4ºC); the North Pacific Deep Waters (NPDW), characterized by moderate-to-low salinity (34.5 to 34.2) but still relatively cold waters (4 to 6ºC); the North Pacific Intermediate Waters (NPIW), characterized by low salinity (<34.2) and relatively higher temperature (6 to 12ºC); the Subtropical Subsurface Waters (SSW) characterized by high salinity (>34.5) and much warmer temperatures (~20ºC); and the shallowest near surface waters characterized by high temperatures (~25ºC) and lower salinity being deeply influenced by rainfall fresh water inputs (i.e., Wyrtki, 1984). Salinity, rather than temperature, is clearly the variable that can be used most successfully to identify the different water masses of the region. For this reason the depths at which these masses occur can be easily determined from the OUTavg vertical plot of salinity in Figure 4b. The NPDW water masses extend from below 1000 m up to depths between 700 and 800 m, and above the NPIW water masses are confined between 300 and 600 m of depth. The SSW water masses are found between 100 and 200 m depth, and the near surface waters are only limited to the upper 20 m of the water column. The NPBW water masses are much deeper than 1000 m depth and therefore they are not shown in the plot.

The T-S diagram data shown for the IN-stations in Figure 5b is practically identical to the T-S diagram data for the OUT-stations. This indicates that only moderate entrainment occurred at the center of the eddy, and therefore the observed shoaling of isotherms, isohalines and isopycnals toward the center is likely almost entirely determined by an eddy-induced vertical movement of water. It is because of this upwelling that at Opal's center the SSW water masses that usually occur only at depths deeper than 100 m are brought to the surface, and thus establish the saline, cold core typical of the
Hawaiian cyclonic eddies. Figure 5c shows slightly different features compared to the previous two diagrams. The T-S curves in the diagram that are still identical to the ones evident in Figure 5a and b are from the transect casts sampled at Opal's center, and confirm the conclusions from the analysis of the previous T-S diagrams. However, there are also many curves characterized by much lower salinity SWWs even though NPIWs and near surface waters show quite typical temperature and salinity values. Data making up these curves are from the peripheral transect casts. The much less pronounced deep salinity maximum found outside the core region of the eddy most likely indicates an enhancement of lateral or vertical mixing, or a possible entrainment of different water masses within the depth levels occupied by the SSWs. The absence of a pronounced deep salinity maximum is particularly evident at the beginning of Transect 3 (Figure 2), and it results in the large area of low differential salinity anomaly (<-0.2) that extends between 20 and 60 km along the transect, and from 120 to 170 m in depth.

3.2. Biogeochemical Data

Color shaded vertical sections of nitrate + nitrite, total chlorophyll $a$ and dissolved oxygen concentrations for Transect 3 are shown in Figure 6. Isopycnal contour lines are superimposed on these sections and DPAs are shown to the right of each of these plots. Nitrate + nitrite and total chlorophyll $a$ concentrations were measured directly from collected water samples (for further details see Rii et al., 2007). Since samples were collected only during Transect 3, this is the only transect for which it was possible to reconstruct a vertical section of nitrate + nitrite. Figure 7 shows the same data types for Transect 4 except for nitrate + nitrite. The black dots in the vertical section of nitrate + nitrite in Figure 6 indicate station locations and depths at which the water samples were collected. The values of total chlorophyll $a$ displayed in both of the sections of Transects 3 and 4 were derived from CTD fluorometer voltage using a regression curve determined using the total chlorophyll $a$ concentrations measured from the water samples (described in methods section of Benitez-Nelson et al., 2007). The yellow curves in the chlorophyll $a$ figures represent the depths of the 1% light level. These depths were computed from vertically integrated total chlorophyll $a$ concentrations after a relationship between those values and the measured 1% light level depths was derived (following Morel, 1988; see methods section of Benitez-Nelson et al., 2007). It was not possible to post-calibrate the dissolved oxygen sensor and no bottle sample data were available for dissolved oxygen concentrations. Thus, absolute values of oxygen may well be in error. Nonetheless, individual profiles obtained during E-Flux III may be compared. Unfortunately, it is not possible to compare E-Flux III oxygen concentrations with
concentrations from the other field experiments of the project (for further details see Dickey et al., 2007).

As indicated by the data displayed in Figure 6, the vertical section of nitrate + nitrite concentration closely tracks Opal's density structure. Nitrate + nitrite isopleths shoal toward the center of the eddy roughly parallel to the isopycnals indicating that the nutrient distribution is influenced at depth by the physical forcing induced by the eddy. The presence of a region of high positive differential nitrate + nitrite anomalies (>2 μM) between 80 and 130 km and 90 and 220 m depth, slightly below the region of positive differential density anomalies, clearly demonstrates an effective eddy-induced pumping of nutrient-rich waters from depth up into the euphotic zone in the vicinity of Opal's center.

A common characteristic of vertical profiles of total chlorophyll a was the presence of sharp and narrow peaks of maximum concentrations associated with the DCML, which was confined between the σ-t24.2 and the σ-t24.42 density surfaces (Rii et al., 2007). The transect sections shown in Figures 6 and 7 were generated by interpolating chlorophyll a concentrations with respect to density before plotting versus depth. This procedure was necessary because of the pronounced vertical variations in the DCML depth along the transect caused by the isopycnal doming. Application of this procedure allows for more realistic representations of the extent of the DCML, especially near the center of the eddy, where the isopycnal shoaling was more intense. The two vertical sections of total chlorophyll a are characterized by almost identical features. In both transects the DCML shoals from depths of about 110 m in the peripheral regions to depths of about 60 - 70 m at the center of the eddy; the DCML concentrations increase where the DCML shoals, reaching maximum values near Opal's center. A relatively thin layer of enhanced chlorophyll a concentrations (proxy for phytoplankton concentrations) extends quite symmetrically around the center of the eddy. The horizontal extent of this area as well as the maximum values of the DCML are slightly different between the two transects. Specifically, the area of enhanced chlorophyll a concentrations in Transect 3 is roughly 40 km in diameter and shows maximum values well above 1 mg m$^{-3}$ (~1.5 mg m$^{-3}$); in Transect 4, on the other hand, this area is only 30 km in diameter and shows maximum values below 1 mg m$^{-3}$. Again, as was for the case for analogous data displayed in Figure 2 and 3, these differences likely result because Transect 3 crossed cyclone Opal much closer to its center than Transect 4. The vertical sections of positive differential chlorophyll a anomaly reflect the shoaling of the DCML toward the center of the eddy, showing an area of high positive anomaly where the DCML was shallower and more intense and an area of low negative anomaly that extends immediately below it down to depths of 150 m. Absolute values of positive anomaly are much larger.
than absolute values of negative anomalies, and positive anomalies in Figure 6 are found above the region of high differential nitrate + nitrite anomaly. These observations clearly indicate that cyclone Opal actively influenced the phytoplankton community not only by forcing the shoaling of the DCML, but also by increasing nutrient concentrations and availability in the euphotic zone (i.e., enhanced primary production, see Brown et al., 2007; Landry et al., 2007; Rii et al., 2007).

Vertical sections of dissolved oxygen concentrations exhibit a pronounced doming of oxygen isopleths closely related to the doming of isopycnal surfaces; this is consistent with the other variables discussed above. Contour plots of differential oxygen anomaly show a region of negative values in the vicinity of Opal's center. This region extends from depths of 150 m to the depth of the DCML. Relatively sharp gradients of oxygen anomaly are evident at the top of this region as indicated in Figures 6 and 7. Our analyses of the mean vertical plots suggest that the oxygen anomaly results not only from a forced uplift of deep and less oxygenated waters, but also through increased processes of remineralization. It is worth noting that the initial portion of Transect 3 between 20 and 60 km, and 120 and 170 m in depth appears anomalous also with respect to its biogeochemical components, supporting the hypothesis that entrainment of different water masses might have occurred.

Vertical profiles of nitrate + nitrite, total chlorophyll a and dissolved oxygen concentrations, along with profiles of these quantities versus density, are shown in Figure 8a-ef. IN$_{avg}$ and OUT$_{avg}$ profiles of chlorophyll a and dissolved oxygen were computed using the same method utilized for the CTD data. Since nutrient concentrations were measured only for casts where water samples were collected, IN$_{avg}$ and OUT$_{avg}$ profiles of nitrate + nitrite were computed by averaging a limited number of IN- and OUT-stations (Cast 20, 63, 67 and 73 for IN$_{avg}$ and Cast 111, 119 and 127 for OUT$_{avg}$). Nutrient concentrations were measured only at discrete depths, so that the resulting nitrate + nitrite profile is not continuous, unlike the profiles of other variables displayed in Figures 4 and 8. Also, this profile is limited to the upper 300 m of the water column. Mean vertical profiles of chlorophyll a were plotted for the upper 300 m depth in order to be more comparable with the nutrient profiles and to have a better resolution of the DCML region. As evidenced by the error bar intervals in the figures, standard deviations are generally small for all the variables except for the IN$_{avg}$ chlorophyll a concentrations. These relatively larger standard deviations result from the higher variability that characterizes the depth and magnitude of the DCML at the IN-stations, along with the ship positioning issues discussed in the Field Observations section.

The mean vertical profiles of nitrate + nitrite in Figure 8a reflect an eddy-induced uplift of the
nutricline associated with upwelling of nutrients into the euphotic layer as evident in the vertical sections shown in Figure 6. Particularly interesting are the differences in shape between IN avg and OUT avg profiles when they are plotted against density (Figure 8d): nutrient concentrations start to increase below the σ-t23.7 density level, whereas the IN avg profile shows low nitrate + nitrite concentrations extending below the σ-t24 level. These limiting nutrient concentrations above the σ-t24 surface most likely explain the IN avg DCML occurring at higher density levels than the OUT avg DCML (Figure 8e). Nitrate + nitrite concentrations at the σ-t24.5 level are similar for both IN avg and OUT avg profiles. However the gradient from these concentrations toward the minimum nutrient concentrations occurring in the near surface waters is much steeper for the IN avg profile, especially between 50 and 100 m of depth. As shown in Figure 8eb, the density interval within which this gradient occurs is characterized by the presence of the DCML occurs, suggesting that the rapid decrease in nutrient concentrations measured at the IN-stations might be a direct result of an increased nutrient uptake associated with the higher concentrations of phytoplankton that characterize Opal's core region (see Rii et al., 2007 for more details). The OUT avg profile of chlorophyll a concentration indicates quite typical values for the region with a DCML chlorophyll a concentration on the order of 0.4 mg m⁻³, and the DCML depth located at about 120 m (e.g., Falkowski et al., 1991). As already noted, the IN avg profile reveals that the DCML shoals upward to depths between 60 and 70 m at the center of the eddy, and average chlorophyll a concentrations almost double, reaching values above 0.7 mg m⁻³.

Consistent with the vertical profiles shown in Figure 4, 1000-m vertical profiles of dissolved oxygen (Figure 8c) indicate that the eddy-induced uplift of isopleths extends down to depths between 600 and 700 m. The oxygen profiles are characterized by a homogeneous and relatively well oxygenated surface layer through the upper 200 m. Below, there is a region where oxygen concentrations decrease quite sharply to values of roughly 6 mg L⁻¹. Comparison of Figure 8c with Figure 4c clearly indicates that the oxygenated surface layer corresponds to the upper mixed layer, and that this layer is much shallower at the IN-stations because of the eddy-induced uplift. Most importantly, the IN avg profile shows that a much steeper gradient toward low oxygen values occurs at depths just below the DCML, as also indicated by the sharp decrease in oxygen concentrations between the σ-t24 and σ-t24.5 levels in Figure 8f. As mentioned above in the discussion of the dissolved oxygen sections shown in Figures 6 and 7 this observation suggests increased oxygen consumption, which is most likely caused by enhanced remineralization processes at the center of the eddy below the DCML.
3.3. ADCP Data

ADCP velocity vectors at 40 m depth for Transects 3 and 4 are shown in Figure 9, clearly revealing a velocity field dominated by the presence of the strong cyclonic flow associated with cyclone Opal. The positions of the center of the eddy are approximately indicated in both transects by the areas of minimum velocity. Velocities gradually increase with radial distance from those areas before peaking and then slowly decaying. The fact that during Transect 3 the velocity vectors were almost perpendicular to the transit track, changing direction after having fallen to near zero values, indicates that this section passed very near to Opal's center. By comparison, Transect 4 didn't pass as close to the center; this transect likely crossed the eddy a few km to the east of its center according to the ADCP data as well as CTD and biogeochemical data discussed above. The presence of multiple velocity values sampled at each hydrographic station results from the relatively long time interval required to perform a CTD cast (usually 45 to 60 min) compared to the ADCP sampling interval (15 min, see Dickey et al., 2007). The several velocity measurements collected at each CTD cast location were replaced with their mean value before ADCP data were analyzed. The resulting velocity records were characterized by a more regular spatial distribution of the data along each transect. This characteristic revealed to be particularly important to prevent the occurrence of anomalously large values when horizontal gradients of velocity were computed.

Due to the cyclonic nature of the velocity field, the analysis of Opal dynamics is conducted using cylindrical coordinates, and the recorded zonal and meridional velocities are decomposed into radial and tangential components. The origin of the reference system is centered at the eddy's center, so that in order to convert the velocity field into cylindrical coordinates, the first step was to accurately locate the position of the center of the eddy at every depth for the two transects. An area of about 30 by 30 km around the minimum velocity zone of each transect was divided into a grid of 30 by 30 points. ADCP velocities were decomposed into tangential and radial components relative to each point of the grid, so that every point of the grid was tested as a possible location for the center of the eddy. At every depth the center of the eddy was best estimated as the grid point for which the mean tangential velocity computed from the 25 nearest ADCP records was maximal. The decision of using only the 25 nearest velocities was made so that the location of the center was not affected by the peripheral regions where the cyclonic flow associated with Opal becomes more perturbed due to the growing influence of the outer velocity field.

Figure 10 shows the 40 m depth positions of the center of Opal as computed for Transect 3 (a) and...
Transect 4 (b). In each figure the contour plot defines the area where the 30 by 30 points grid was defined, and isopleths indicate equal values of the mean tangential velocity associated with each grid point. The ADCP velocities used to determine the eddy center position are shown as blue vectors. Clearly the two figures confirm what was already described in previous sections: Transect 3 crossed cyclone *Opal* almost exactly at its center, whereas during Transect 4 the center of the eddy was a few km to the west of the transit track. Variations of the position of the center with depth are much less pronounced for *Opal* than for E-Flux I cyclone *Noah* (see Kuwahara et al., 2007). For this reason the center position determined at 40 m depth can be taken as a good approximation of the center position throughout the whole water column.

The center of the eddy could also have been best estimated as the grid point at which radial velocities are minimized. More precisely, the center of the eddy could have been located at the grid point for which the root mean square of the radial velocities is minimal. However, since radial velocities within the eddy are usually much smaller than tangential velocities, and therefore more sensitive to the variations associated with background noise, the center positions found using this method was considered to be less accurate. It is important to emphasize that differences between the two methods are usually relatively small and that the center positions determined by maximizing the mean tangential velocity are always located within the same areas where the RMS values of the radial components are minimum, indicating that the analytical method we developed to locate *Opal*'s center is quite accurate.

Since the center of the eddy is the origin of the cylindrical coordinate system relative to which we have derived the radial and tangential components of velocity, the analysis of the radial distribution of these components can further confirm that the best estimates of the position of *Opal*'s center are relatively precise. In Figure 11a and b the 40 m depth radial and tangential velocity components computed for Transect 3 are plotted against distance from the center of the eddy. Data from the transect were grouped into two radial sections, blue dots corresponding to data collected before crossing the center of the eddy (from Cast 13 to 20), while red crosses referring to data collected after the center was crossed (from Cast 20 to 25). Radial velocities are relatively small, less than 20 cm s\(^{-1}\), throughout the whole transect. Values of tangential velocities are close to 0 cm s\(^{-1}\) up to a few km from the center, and, as already indicated for Figure 9, they increase linearly with radial distance to reach their maximum value of about 60 cm s\(^{-1}\) at roughly 25 km from the center. After peaking they slowly decay as the radial distance further increases. The most striking feature evidenced by the plot is the great
symmetry that characterized the two sections of this transect. At any given radial distance up to 25 km from the center, the magnitude of tangential velocities of both radial sections is roughly the same, indicating that the cyclonic circulation associated with Opal was fairly symmetrical. All these features (i.e. small radial velocities; near zero tangential velocities at small radial distances from Opal's center; high symmetry in the cyclonic velocity field) indicate that the position of Opal's center was estimated with very high accuracy for Transect 3. The small uniformly negative (inward) radial velocities found for Transect 3 seems to suggest a gradual relaxation of the pressure gradient associated with the eddy, as Opal was spinning down. However, this conclusion cannot be generalized for the whole duration of the experiment, as radial velocities from other transects, such as Transect 4 (see Figure 12), 2, and 6 (not shown here), don't show similar characteristics.

Important information concerning the dynamics of the eddy can be inferred by plotting tangential velocities as normalized by the maximum tangential velocity of each section ($V_{\text{max}}$) against radial distances normalized by the radius at which the maximum tangential velocity was found ($R_{\text{max}}$) (i.e. Olson, 1980). Normalized tangential velocities and radial distances for Transect 3 are plotted in Figure 11c. The solid line in the figure represents values of constant angular velocity $V_{\text{max}}/R_{\text{max}}$. The figure shows that since tangential velocities increase almost linearly from the center up to a radial distance $R_{\text{max}}$, the angular velocity (defined as the tangential velocity divided by the radial distance from the center of the eddy; $C/\theta/\tau$) of cyclone Opal is roughly constant up to a radial distance of about 25 km from the cyclone's center. Since $V_{\text{max}}$ is ~60 cm s$^{-1}$ and $R_{\text{max}}$ is ~25 km, the angular velocity is ~2.4 $10^{-5}$ rad s$^{-1}$, and the corresponding angular period ~3 days. The portion of Opal characterized by a constant angular velocity roughly corresponds to the portion of the eddy that rotates as a solid body. This is an important aspect of the system since the portion of the eddy that is in near solid body rotation is likely relatively isolated from the surrounding waters. For this reason its extent is expected to significantly affect the distribution of biogeochemical properties and processes of the system.

In Figure 12, radial and tangential velocity components at 40 m depth for Transect 4 are plotted in the same way they were for Transect 3 in Figure 11. Clearly this figure does not display the remarkably clear results that were obtained for Transect 3. In particular, radial velocities for Transect 4 are much greater, and far from the center they sometimes reach values of the same magnitude of tangential velocities. Since Transect 4 did not pass directly through the center of the eddy tangential velocities were measured only up to 10 km. Thus it is not possible to ascertain whether they decreased to near zero values at the center. Furthermore, the symmetry between the two sections of this transect seems
much less pronounced. The fact that Transect 4 crossed Opal ~10 km clearly makes it far more difficult for the center of the eddy to be positioned with the same accuracy as for Transect 3. We expect that this problem may well account for some of the differences between the two transects. However, some of the anomalies that characterize the velocity field in Transect 4, especially in its first section (blue dots in Figure 12), cannot be simply explained on the basis of inaccurate velocity decomposition caused by inaccurate location of the eddy's center for Transect 4.

The first section of Transect 4 (from Cast 26 to Cast 30) is characterized by high radial velocities. They can reach values of about 50 cm s\(^{-1}\) at radial distances greater than 40 km. On the other hand, tangential velocities are relatively small. The very first portion of the transect is also characterized by negative tangential velocities. Maximum values of tangential velocity are found at about 20 km from the center, a distance that is similar to that found for Transect 3; however, they are much smaller, being only ~35 cm s\(^{-1}\). A possible explanation for these anomalies can be found in the location of the first portion Transect 4. First of all, the initial section of this transect is relatively close to the Big Island of Hawaii, and the cyclonic circulation associated with Opal tends to move the waters towards the island. Therefore, it is possible that the velocity field at the beginning of Transect 4 could have been perturbed by a coastal effect. Moreover, the region to the southwest of the Big Island is characterized by eddies that develop due to the shear between the southernmost tip of the Big Island itself and the westward North Equatorial Current that is partially blocked by the island (Qiu et al., 1997; Calil et al., 2007). It is possible that the perturbations in its cyclonic velocity field are due to interactions between cyclone Opal and one of those shear generated eddies.

Despite being somehow anomalous, Transect 4 still displays some of the characteristics that were observed for Transect 3. Along the second portion of the transect, far from the Big Island (from Cast 30 to Cast 36; red crosses in Figure 12), maximum tangential velocities are on the order of 60 cm s\(^{-1}\) and are found at roughly 20 km from the center. Moreover, as shown in Figure 12c, even for Transect 4, tangential velocities tend to decrease linearly with radial distance toward near zero values at the center of the eddy. These data seems to indicate that the position of Opal's center was determined with good accuracy even for Transect 4. Furthermore, it seems reasonable to conclude that the eddy dynamics derived from the analysis of the velocity field of Transect 3 can also be generalized to transects characterized by a more perturbed cyclonic circulation.

Tangential velocities from Transects 3 and 4 are plotted in , which is the analog to the plot shown in Figure 9. Except for minor differences, particularly evident in the southernmost region of Transect 4,
The vector fields of the two figures appear to be nearly identical on these scales. This is another indication that the estimated, adjusted positions of the eddy's center, and consequently the origin of the cylindrical coordinate systems used to decompose the ADCP velocities, are quite accurate for both transects.

Transects 3 and 4 were sampled within a time interval of about one day. As already discussed, during that period of time the center of the eddy moved only about 13 km to the southeast, as the translational speed noticeably decreased during this portion of the experiment compared to the first few days. For these reasons the two transects, more than any others sampled during E-Flux III, can be considered to be quasi-synoptic. Interpolating the data from Transects 3 and 4 after the two transects were realigned over a common center, it was thus possible to reconstruct an approximate 3-dimensional structure of cyclone Opal. A perspective view of this structure is presented in Figure 13. The top panel shows 40-m depth velocity vectors superimposed on the contour plot of temperature at the same depth. The bottom panel shows the depth of the $\sigma-t_{34}$ isopycnal surface, which was previously noted to be a good indicator for the depth of the upper mixed layer. Some of Opal's characteristics, such as the cyclonic circulation around the cold core and the large areal extent of the isopycnal doming, are clearly evident in this figure. The reconstructed eddy's structure in the figure is characterized by a highly symmetrical circular shape. Even though both CTD and ADCP data revealed Opal to be quite symmetric and circular in shape, it is possible that these characteristics are enhanced in Figure 13 by the data interpolation, since the 3-dimensional structure of the eddy was derived using only data collected along the two main diagonals.

ADCP velocities at 120 and 200 m are plotted in Figure 14 a and b as vector maps analogous to the one shown in Figure 9 for the 40-m depth. The vector maps reveal that velocities decrease quite rapidly with depth. At the 120-m depth, velocities never attain values greater than 50 cm s$^{-1}$. Nonetheless, the cyclonic eddy feature is still evident. At the 200-m depth, velocities have further decreased and their maximum values are roughly 25 cm s$^{-1}$. More important, the presence of the cyclonic flow is not as evident as it was at shallower depths, especially close to the two centers and along Transect 4. Since the cyclonic circulation does not extend to depths much deeper than 200 m, the decomposition of zonal and meridional velocities into radial and tangential components and the analysis of their vertical distributions along the two transects are limited to the upper 200 m of the water column.

Vertical sections of tangential and radial velocities for Transect 3 are shown in Figure 15a and b, respectively. In these sections, the center of the eddy is located at a distance of about 110 km from the
beginning of the transect. Since the analyses were performed using a cylindrical coordinate system, tangential velocities are defined positive when the circulation is cyclonic, that is the direction of positive tangential velocities is out of the paper to the left of the center of the eddy, and towards the paper to its right. On the other hand, radial velocities are defined positive when their direction is away from the center and negative when it is toward the center. The black crosses at 0 m depth in Figure 15 are locations along the transect where CTD casts were collected. The small dots in the vertical section indicate the positions where the ADCP data used to generate the contour map were sampled.

It is evident in Figure 15a that velocities are usually very small close to the center of the eddy, and even at a depth of 40 m they can drop to values that are roughly the same order of magnitude as the natural background noise, which can thus be a significant component of the velocity field at those points. For this reason, velocities sampled at small radial distances are characterized by directions that are often inconsistent with the cyclonic flow that characterizes the more radially distant portions of the transects. When decomposed into tangential and radial components, these velocities result in anomalous values that can mislead the interpretation of the vertical structure of the velocity field associated with Opal (i.e. at small radial distances vertical sections of tangential velocities were usually characterized by areas of negative values). In order to ensure that vertical sections are not influenced by these small values, the velocities sampled very near the center of the eddy were removed for the purposes of generating Figure 15 through 21, with the exception of Figures 17 and 18. Since velocity decreases with depth, the area around the center within which tangential velocities have to be removed slowly increases with depth. At 40 m depth, only the two closest records to the center were removed, while at 200 m depth six data were removed up to a distance of 10 km from the center.

The vertical section of tangential velocity in Figure 15a shows a typical structure with two areas of relatively high positive tangential velocities that extend almost symmetrically on the two sides of the center. A common feature for tangential velocities at any depth is to increase quite rapidly from the center of the eddy up to a distance of 25 – 35 km where they reach their maximum values. Beyond those distances, they slowly decay with distance moving away from the center. As already noted, velocities decay relatively rapidly with depth, especially within a depth range of 90 – 130 m, so that the cyclonic circulation associated with the eddy is limited to the upper 150 meters. For this reason, cyclone Opal can be considered from a dynamical prospective to be a relatively shallow feature. Radial velocities in Figure 15 are relatively small and their vertical section does not show any relevant structure. The radial components do not decay with depth as fast as tangential velocities and therefore
the ratio between the two tends to increase with depth. This is a further indication that the cyclonic circulation becomes less and less pronounced with increasing depths and is insignificant at depths greater than 200 meters.

Figure 16a and b show vertical sections of tangential and radial velocities for Transect 4, respectively. Again, this transect did not pass directly through the center of the eddy, so that the smallest radial distance at which data were collected was 10 km. For this reason, none of the ADCP measurements were removed from the data to generate the contour maps, except for a few points at depths greater than 180 m. The lack of data points at the very end of the transect is due to instrument failure. Since the center of the eddy was far from the transit track in the case of Transect 4, the midpoint used to divide the transect into two radial sections is the position along the transect at which Opal's center was closest. This occurred at a distance of roughly 90 km from the beginning of the transect. As already indicated from Figure 16b, the two radial sections of Transect 4 are not as symmetric as the those of Transect 3. The first section is characterized by high radial velocities that extend throughout the whole water column, whereas the area of high tangential velocities is limited in both its vertical and horizontal extent. Maximum velocities found at 40 m in this area are about 40 cm sec\(^{-1}\), roughly 2/3 of the maximum velocities usually found at that depth. This limits the vertical extent of the area of high tangential velocities, since they have already decayed to values lower than 25 cm sec\(^{-1}\) at depths shallower than 90 m. On the other hand, limitations on the horizontal extent of the area are due to the presence of a deep area of negative tangential velocities at the very beginning of the transect. This seems to support the previously discussed hypothesis that there may have been eddy-eddy interactions in the region to the southwest of the Big Island. The second radial section is quite similar to the two sections described for Transect 3. Tangential velocities increase rapidly from the midpoint of the transect, and they reach their maximum values at distances comparable to the ones found for the previous transect. Even in this section, tangential velocities decrease quite fast with depth, mainly within depths between 80 and 110 m, giving further indication of the shallow nature of cyclone Opal. Tangential velocities in Transect 4 never reach near zero values as in Transect 3 since the transect did not pass through the center of the eddy.

Vertical and horizontal shears of velocity were computed by using finite differencing of the following partial differential equations:
\[
\frac{\partial \bar{U}}{\partial z} = \left( \left( \frac{\partial C_{\theta}}{\partial z} \right)^2 + \left( \frac{\partial C_r}{\partial z} \right)^2 \right)^{1/2};
\]

\[
\frac{\partial \bar{U}}{\partial d} = \left( \left( \frac{\partial C_{\theta}}{\partial d} \right)^2 + \left( \frac{\partial C_r}{\partial d} \right)^2 \right)^{1/2};
\]

where $C_{\theta}$ and $C_r$ are tangential and radial components of velocity respectively, and $d$ is the distance along the transect. None of the velocity data were discarded for computing the two quantities.

Vertical sections of vertical and horizontal shear from Transects 3 and 4 are shown in Figure 17a and b and Figure 18a and b. Contour maps of the two quantities were superimposed on density contours in order to determine to what extent the shear distribution is related to the density field. These vertical sections show features that are common to both transects. Figure 17a and 18a show that maximum values of vertical shear are found within 25 – 35 km of the center where velocities are usually higher and that they roughly follow the doming of the $\sigma$-t$_{34}$ isopycnal surface. Again, this surface generally coincides with the depth of the mixed layer. This indicates that the thermocline most likely acts to prevent a deep penetration of the cyclonic circulation, and confines the dynamical structure of Opal within the surface mixed layer. Vertical sections of horizontal shear in Figure 17b and 18b do not display any major structures. However, there are two narrow areas of high values limited to the upper 100 meters that occur close to the center of the eddy. These peaks occur in the areas where tangential velocities increase linearly with radial distance from the center of the eddy. Along Transect 4 two other shallow areas of high values of horizontal shear occur at distances of 60 and 120 km. From Figure 18b, it is apparent that these two peaks arise from sharp variations of the radial component of velocity rather than variations of the tangential component.

Vertical sections of angular velocity ($C_{\theta}/r$) from Transects 3 and 4 are shown in Figure 20a and b, respectively. Values of angular velocity are highly sensitive to radial distance, and even small tangential velocities divided by small radial distances result in very large values of angular velocity. For this reason, the tangential velocities from which angular velocities were computed are the same ones used in Figures 15a and 16a. Vertical sections of angular velocity show similar structure to that of the vertical sections of tangential velocity for both transects. As expected, Transect 3 displays a more symmetrical distribution of angular velocities than observed for Transect 4. Transect 3 angular velocity distribution is also characterized by a region minimum values that occur close to the center of the eddy where tangential velocities decay to very small values. An analogous minimum is not evident in the
angular velocity distribution of Transect 4; as expected, less symmetry is seen in the angular velocity of Transect 4. Less accurate estimated position of the center for Transect 4 resulting from the offset of the transect from the true center of the eddy likely explain part of the asymmetry as well. Both transect sections show areas of high values of angular velocity that are bounded by zones of sharp gradients. While these areas are relatively shallow in both transects, their horizontal extent is much broader in Transect 3 than in Transect 4. Again, this difference between the two transects likely arises from the fact that the two transects crossed Opal at different distances from its center. As already mentioned, the areas characterized by similar values of angular velocity can be used to roughly define where the eddy rotates as a solid body. According to angular velocity data for the two sections, the portion of cyclone Opal that was in near solid body rotation was roughly 50-60 km in diameter, and hardly reached depths greater than 100 – 130 m. Thus, from a dynamical perspective, cyclone Opal was a relatively shallow feature and was most likely limited to the mixed layer region.

3.4. Potential Vorticity

Important information concerning the dynamics of a vortex can be inferred from the analysis of the various terms that contribute to the equation for conservation of potential vorticity (e.g., Olson, 1980; Simpson, 1984). This equation is derived by taking the curl of the momentum equations and then the scalar product of the resulting vorticity equation and the gradient of potential density (e.g., Pedlosky, 1979). In cylindrical coordinates, the conservation of potential vorticity can be expressed as

$$\frac{D}{Dt} \left[ \frac{\partial \rho}{\partial r} \left( \frac{1}{r} \frac{\partial w}{\partial \theta} - \frac{\partial C_\theta}{\partial z} \right) + \frac{1}{r} \frac{\partial \rho}{\partial \theta} \left( \frac{\partial C_r}{\partial z} - \frac{\partial w}{\partial r} \right) + \frac{\partial \rho}{\partial z} \left( \frac{C_\theta}{r} + \frac{\partial C_\theta}{\partial r} - \frac{1}{r} \frac{\partial C_r}{\partial \theta} + f \right) \right] = 0 \quad (4)$$

The quantity inside the brackets is the potential vorticity normal to isopycnal surfaces. The terms in parentheses are the components of the relative ($\zeta$) and planetary ($f$) vorticity assuming a $\beta$-plane approximation. These terms are modulated by the spatial derivatives of the potential density which provide an effective length scale of the vortex.

ADCP and CTD observations were used to estimate the order of magnitude of the terms in equation 4. The Coriolis parameter $f$ was chosen to be $4.9 \times 10^{-5} \text{ s}^{-1}$ (average value for the latitudinal extent of the eddy), and is taken to be constant because of the relatively short north-south scale of Opal (i.e., $\beta$-plane approximation). Rough estimates of vertical velocities ($w$) were computed by integrating the continuity equation. According to the scaling results, the potential vorticity of cyclone Opal ($\pi$) can be expressed...
to a first order of approximation by the equation

\[ \pi = \frac{\partial \rho}{\partial z} \left( \frac{C_\theta}{r} + \frac{\partial C_\theta}{\partial r} + f \right) \]  

(5)

where \( \frac{\partial \rho}{\partial z} \) is the vertical gradient of density; \( \frac{C_\theta}{r} \) the angular velocity; and \( \frac{\partial C_\theta}{\partial r} \) the radial gradient of tangential velocity. This approximation was used to compute potential vorticity \( \pi \) for each transect.

Values of tangential velocities were obtained from the analysis of ADCP data discussed in the previous section and density profiles were obtained from the CTD data. Here \( f = 4.9 \times 10^{-5} \text{ s}^{-1} \) (average value for the latitudinal extent of the eddy), and is taken to be constant because of the relatively short north-south scale of Opal (i.e., f-plane approximation). Velocity and density fields are characterized by different horizontal and vertical resolutions. For this reason, the first step in the analysis was to interpolate one of the two variables over the grid of the other one. CTD data are very well resolved in the vertical but have poor horizontal resolution. On the other hand, ADCP data are characterized by slightly coarser vertical resolution, but much finer horizontal resolution. In order to maintain a good horizontal resolution in the data, we chose to interpolate the density measurements over the grids of the ADCP measurements. The vertical gradients of potential density and the radial gradients of tangential velocity were then computed by finite differencing the partial derivatives in equation 5. These
gradients, being staggered with respect to the velocity grid, were then interpolated again over the ADCP data grid in order to multiply each term within the parentheses by the vertical density gradient and then to sum them together.

Figures 20a and 21a show vertical sections of potential vorticity for Transects 3 and 4, respectively. In both figures, the potential vorticity fields show a certain degree of noisiness. As evident from inspection of equation 5, potential vorticity values are highly dependent upon the tangential velocity field. Part of the noise is probably due to the errors associated with the ADCP velocity decomposition into radial and tangential components (i.e., due to an approximate estimate of the position of Opal's center). The several data interpolations performed to compute potential vorticity might have introduced some noise as well. Despite the noisiness, some general common features can be identified in both vertical sections. The field is clearly dominated by the vertical gradient of potential density, since this term is several orders of magnitude greater than the other terms within the parentheses in equation 5. An area of maximum potential vorticity (values >12 Kg m$^{-4}$ s$^{-1}$) occurs where the angular velocity and the horizontal tangential velocity shear reach their maximum values, and is located within a distance of about 20 – 25 Km from the center and down to depths of about 70 to 80 m. This area is surrounded by two lobes where the potential vorticity decreases to values between 7 and 12 Kg m$^{-4}$ s$^{-1}$. Within these lobes, values of potential vorticity are lower because the contributions of the angular velocity and the horizontal tangential velocity shear become negligible, whereas the values of the vertical gradient of potential density are still high due to the presence of the pycnocline. The two lobes get deeper moving away from the center of the eddy as they follow the deepening of the pycnocline. Below and above these areas, potential vorticity values reach their minima (<5 Kg m$^{-4}$ s$^{-1}$) since both contributions from the velocity and the density field are much smaller.

In principle, potential vorticity should be conserved by a parcel of fluid as it moves around the eddy (Olson, 1980). For this reason, knowledge of the relative orientations of isopleths of potential vorticity with respect to isopycnals is extremely important to infer where radial movement of water might have occurred within the eddy. In regions where isopleths of potential vorticity and isopycnals are parallel to each other, parcels of fluid can move radially along density surfaces, while in regions where the two lines intersect diagonally or orthogonally the radial flow is inhibited.

Solid lines in Figures 20b and 21b are contours of potential vorticity, and dashed lines are contours of potential density. The isopleths of potential density delimiting the area of maximum vorticity are almost orthogonal to the isopycnals. Radial movement of fluid in and out from this area is therefore
inhibited and the water mass within it is therefore isolated from the surrounding water masses. This area corresponds to the solid body rotation portion of the eddy. On the other hand, the isopleths delimiting the two lobes around the solid body rotation region are roughly parallel to the isopycnals, indicating that radial exchange between waters from inside the eddy at a depth of 70-90 m and deep waters outside the eddy at depths of 130-150 m was possible along isopycnal surfaces ranging roughly from $\sigma_{23.6}$ to $\sigma_{24.4}$. This radial exchange of fluid may explain the anomalous T-S diagram features in Figure 5 that characterize the peripheral CTD casts of the transects. The effective isolation of eddy core water properties (i.e., biological and chemical, as well as physical) and the mixing and advection of these properties external to the core likely dictate the processes controlling the observed distributions of biogeochemical properties as discussed in the following section.

4. Discussion and Conclusions

The E-Flux III field experiment (March 10-28, 2005) focused on a cyclonic mesoscale feature, Cyclone Opal, that spun up in the lee of Maui and the Big Island of Hawai‘i as a result of strong and persistent trade wind conditions (Dickey et al., 2007). The intensive, interdisciplinary sampling approach adopted for the experiment provided a very comprehensive, quasi-synoptic data set characterizing the physical, biogeochemical, and biological characteristics and dynamics of Opal. In this paper we have presented observations of key physical variables, including temperature, salinity, density and velocity, as well as observations from those biogeochemical variables, such as nutrients, total chlorophyll $a$ and oxygen concentrations, which are fundamentally relevant for the investigation of the physical-biogeochemical-biological interactions occurring within the eddy. The present observational results have stimulated the formulation of new hypotheses that might lead to a better understanding of the effects produced by the physical-biogeochemical-biological interactions associated with cyclonic mesoscale eddies in the lee of the Hawaiian archipelago.

4.1. Physical-Biogeochemical coupling

Hydrographic observation revealed that Opal was characterized by an intense doming of isotherms, isohalines and isopycnals, with maximum vertical shifts of about 80 - 100 m at its center. Vertical sections of temperature, salinity and density indicate that the doming was roughly 100 km in radius, while vertical transects of the properties suggest a vertical expression of the eddy down to depths of at least 600 – 700 m. Analyses of the biogeochemical measurements clearly indicate that the eddy induced uplift of isopycnals had a major impact on the distribution of biogeochemical properties within
the eddy. Isopleths of nitrate + nitrite and oxygen concentrations closely followed the doming of the isopycnal surfaces, while the DCML was shallower and more intense close to the center of the eddy. ADCP velocity observations indicate that *Opal* was characterized by maximum tangential velocities of about 60 cm sec$^{-1}$, occurring at roughly 25 km from the eddy's center. Comparison with other wind generated mesoscale eddies previously observed in the region indicate *Opal*'s physical characteristics to be quite typical (Lobel and Robinson, 1986; Patzert, 1969; Falkowski et al., 1991; Allen et al., 1996; Lumpkin, 1998; Seki et al., 2001, 2002; Bidigare et al., 2003; Vaillancourt et al., 2003).

The strong correlation between the distributions of physical and biogeochemical properties is a clear indication of strong physical-biogeochemical-biological coupling occurring within the eddy. The importance of mesoscale eddies in regulating the biogeochemical processes of oligotrophic regions of the oceans was recognized by McGillicuddy and Robinson (1998). Recently, Sweeney (2003) introduced a conceptual model that hypothesizes three main stages of the life cycle of a cyclonic eddy, on the basis of data collected at the Bermuda Atlantic Time-series Study (BATS) site in the Sargasso Sea. This model tacitly assumes mesoscale eddies to be fundamentally closed systems with respect to horizontal material exchanges with the surrounding waters. Figure 22 illustrates the three stages which comprise the model. The first stage, or “intensification or upwelling” phase, occurs when the eddy is spinning up. Isopycnal doming associated with the spin-up process causes an upwelling of nutrients into the euphotic zone. The enhanced availability of nutrients above the 1% light level depth in the vicinity of the center of the eddy stimulate a biological response (i.e. increase in production rate), which results in an increase in biomass. The second stage is the “mature” phase, which is characterized by maximum production rates and highest phytoplankton concentrations at the DCML. During this phase shifts in phytoplankton communities may occur, so that the bloom is often dominated by larger size phytoplankton (i.e. diatoms). The third stage, or “decay” phase, is initiated when the isopycnal doming begins to subside or relax. This phase is characterized by a reduced availability of nutrients at the center of the eddy within the euphotic layer and a consequent decay of the phytoplankton bloom. Due to the increase in phytoplankton biomass and the shift in the phytoplankton community induced by the eddy, it has often been hypothesized that an increase in the export of organic carbon below the main thermocline may occur during its “decay” stage (Goldman, 1993; Seki et al., 2001; Bidigare et al., 2003). Interestingly, the direct observations from the E-Flux III field experiment indicated that only moderate increases in carbon export were associated with cyclone *Opal* (Benitez-Nelson et al., 2007).

According to this model, biogeochemical characteristics of mesoscale eddies are strongly dependent
on their age, and the “mature” stage is always characterized by the presence of diatoms whereas the “decay” stage by the presence of an enhanced carbon export. The results obtained from E-Flux III are not necessarily consistent with this conceptual model, since the diatom bloom that characterized Opal during the first week of the experiment decayed after few days, when the eddy was still physically “mature” (Brown et al., 2007; Rii et al., 2007). Cyclonic eddies which were previously studied in the lee region of the Hawaiian Islands revealed further inconsistencies with this model. As examples we report here the results from the analyses of cyclones Mikalele, Loretta and Haulani (see also Brown et al., 2007 and Rii et al., 2007). Loretta and Mikalele were both sampled during November 1999 (Seki et al., 2001). Loretta revealed physical characteristics similar to Opal, and, despite being 6-months old, was characterized by an intense phytoplankton bloom. Despite this bloom was not diatom dominated, total chlorophyll a concentrations at the DCML were similar to the ones observed for Cyclone Opal, which decayed within two weeks from the beginning of the E-Flux III experiment, when the eddy was slightly older than 1 month. Cyclone Mikalele (Seki et al., 2001) was a slightly smaller eddy than Opal, and was sampled when it was about 1 month old. The phytoplankton bloom associated with this eddy was not diatom dominated as was the one observed for Opal, despite the fact that both eddies had approximately the same age when they were observed. Haulani was sampled during November 2000 when it was 2 months old (Bidigare et al., 2003; Villancourt et al., 2003). It was clearly not in its hypothesized “decay” stage, since it remained visible in satellite imagery for several months after it was studied; despite that, it was the only eddy studied to date that showed an increase in carbon export.

Clearly results from these studies indicate that the correlation between biogeochemical properties of a mesoscale eddy and its age is not as strong as assumed by the model proposed by Sweeney et al. (2003), at least for the wind generated mesoscale eddies that form in the lee of Hawai‘i. At least in this region it is very likely that other factors beside the life stage of cyclonic eddies influence the biogeochemical response within these mesoscale features. Rii et al. (2007) hypothesized that the different phytoplankton communities observed within Hawaiian cyclones result from differences in the rate of nutrient input above the 1% light limitation depth: fast inputs of nutrients most likely determine favorable conditions for diatom blooms, whereas slow inputs of nutrients may establish more favorable conditions for blooms of smaller carbon-rich phytoplankton, such as coccolithophores. In the following section, we forward an alternative hypothesis describing the physical and biogeochemical processes occurring within the eddy based on the analysis of Opal's velocity field. For this hypothesis, the eddy's biogeochemical state does not necessarily depend on the age or stage of the eddy's life cycle. This
could explain why eddies of the same age are characterized by different phytoplankton communities, as well as why intense phytoplankton blooms may occur within relatively old cyclones.

4.2. Closed vs. Open-bottom/Horizontally Leaky eddies

Nutrient availability within the euphotic zone is the factor that ultimately controls the biogeochemical properties within a cyclonic eddy. Sweeney et al. (2003) postulated a mesoscale feature, which is fundamentally closed to horizontal exchanges with the surrounding waters. For this reason, the only mechanism possible for bringing nutrients above the 1% light level within the eddy involves the doming of isopycnal surfaces. This mechanism presumes that nutrient injection occurs only during the hypothesized eddy “intensification” stage. The model's dependence of biogeochemical state upon eddy age results from these constraints. The following analysis of our data set has stimulated an alternative hypothesis to describe the introduction of new nutrients into the euphotic zone in the vicinity of the center of a cyclonic eddy.

Analyses of the ADCP velocity observations indicate that from a dynamical point of view, the major current structure of cyclone Opal was manifest primarily on shorter horizontal scales and over shallower depths than the structure inferred from the analyses of the hydrographic data. In particular, the analyses of angular velocities and the potential vorticity field reveal that the waters within the eddy, that were isolated from the surrounding waters, corresponded roughly to those within the portion that rotated as a solid body. The portion of Opal that was in solid body rotation was only 20 – 25 km in radius and 60-70 m deep. Using analyses of N isotopic fractionation data, Mahaffey et al. (2007) have inferred that cyclone Opal likely acted as a closed system within virtually the same portion of the water column as our region of solid body rotation. This inference is consistent with our analyses of the potential vorticity field with respect to the orientation of isopycnal surfaces as discussed in Section 3.4. Although the waters in solid body rotation appear to be essentially isolated from their surroundings (i.e., closed), there is significant horizontal exchange at greater depths, which causes the eddy to appear as an open-bottom, horizontally leaky system. Specifically, radial exchanges of water likely occurred between 70-90 m depth waters at the eddy's center and waters from the peripheral region between 130-150 m depth waters. This exchange of water would have taken place along density surfaces between $\sigma_{23.6}$ and $\sigma_{24.4}$. For this reason, cyclone Opal, rather than being a deep, horizontally closed or isolated system like the one depicted in Figure 22, was more likely a shallow, open-bottom/horizontally leaky system as depicted in Figure 23. We hypothesize that this characteristic might have significantly influenced the biogeochemistry and biology of the eddy, especially during the periods when its
migration was quite fast (i.e., from March 11 to 13, the eddy translated at an average speed of ~0.6 km h\(^{-1}\) m/s).

Based upon the aforementioned results and analyses, we hypothesize an alternative conceptual model, which describes the physical and biogeochemical processes of cyclone *Opal*, as depicted in Figure 23. For the present model, the initial, spin-up phase is similar to the one described by Sweeney et al. (2003) and shown in Figure 22; it is characterized by the doming of isopycnal surfaces and the consequent upwelling of nutrients into the euphotic zone. We postulate that as the eddy migrates, the distribution of the potential vorticity field is such that the deep waters approached by the eddy shoaled toward the center. Since these waters were originally below the euphotic zone, they would have been relatively richer in nutrients compared with the waters lying along the same isopycnal surfaces at the center of the eddy, where nutrients had already been consumed by the phytoplankton to a great extent. The upwelling of nutrients at *Opal*'s center, rather than being limited to only a single nutrient injection at the time the eddy spun-up, would thus have most likely been continuously renewed during the eddy's migration. The enigma of long-term nutrient availability during eddy lifetimes has been posed previously by Lewis (2002). Our hypothesis of an input of nutrients, which was not necessarily limited to a single injection event, allows for a decoupling between the biogeochemical state of a mesoscale cyclone and its age, which is fundamental to explain the variability encountered in Hawaiian lee eddies.

It is important to emphasize that an “open-bottom/horizontally leaky” eddy does not necessarily imply a continuous input of nutrients at the eddy's center. There are at least two ways through which the upward transport of nutrients can be reduced. First, it is possible that the solid body rotation portion of the core of the eddy, which is relatively isolated from surrounding waters, could penetrate to sufficiently great depths that radial inflow of nutrients toward the eddy center at depths of 70-90 m are not possible. The second way is through a reduction of the eddy's translational movement, since a stationary eddy is characterized by less favorable conditions for radial exchanges of water (i.e., as was the case for cyclone *Noah*, Kuwahara et al., 2007). The latter is most likely the reason for which the phytoplankton bloom decayed toward the end of the E-Flux III experiment (Benitez-Nelson et al., 2007; Brown et al., 2007; Rii et al. 2007). In fact, during the second week of the experiment when the IN-station data were collected, the eddy's translational speed was noticeably reduced (i.e., only 0.2 km h\(^{-1}\)) compared to that recorded during the early portion of the cruise (i.e. when the eddy was rapidly translating at 0.6 km h\(^{-1}\)). For these reasons, after the spin-up phase, translation speed and specific eddy velocity field are fundamental factors in determining the biogeochemical characteristics of a cyclonic
eddy. Although not considered here, we further speculate that passages of previous eddies (whether cold-core or warm-core) through the same region might well be important factors, since they might precondition the distributions of biological and biogeochemical properties encountered by impinging eddies. These collective factors can vary throughout the lifetime of a cyclone. Depending on these factors, individual eddies at various points in their lifetimes may act more as open or closed systems. Changes from relatively closed to open-bottom/horizontally leaky phases and vice versa, can trigger or reduce a phytoplankton bloom. This viewpoint does not constrain the biogeochemical state of the cyclone to its age or stage of development. This new conceptual model may help to explain the high degree of biogeochemical and biological variability encountered in physically similar mesoscale cyclones in the lee of the Hawaiian Islands.

Returning to Figure 23, as Opal was translating, we observed that deep water in front of the eddy's path presumably shoaled to the center. Then water at the center would have moved and sunk to the rear of the eddy. This movement of water might have resulted in a displacement of part of the DCML from the center of the eddy to the outside. This process could have acted to produce an eddy wake characterized by relatively high chlorophyll concentrations, and possibly a moderate increase in carbon export. Unfortunately, the wake of cyclone Opal was not directly sampled during the E-Flux III experiment because of ship resource limitations. However Transect 2 was sampled from south to north as the eddy was moving relatively fast from the north to the south. A contour plot of chlorophyll \( a \) concentrations superimposed on contour lines of density is shown in Figure 24. To generate the figure, chlorophyll concentrations were simply interpolated against depth and therefore the representation of the DCML is distorted. However, the important feature evidenced by the figure is a deep (~135 m) peak of high chlorophyll concentrations at a distance of 90 km along the transect. This is roughly 40 km from the center of the eddy, which in Transect 2 is located at about 50 km along the transect. Considerations of the relative motion of Opal with respect to ship while the transect was performed suggest that this peak might have been located at even greater distance from the center than it appears in Figure 24. Such a deep and distant peak was not observed for any of the other transects, and for this reason it might be interpreted as an indication of the presence of a wake of relatively high phytoplankton concentrations developed behind the fast moving Opal.

Although there appears to be reasonable evidence supporting the proposed hypothesis, it remains to be tested with additional relevant data sets and analyses. Our studies have demonstrated that the ocean waters in the lee of the Hawaiian Islands are ideal for focused interdisciplinary eddy experiments.
Clearly, numerical simulations using coupled physical-biogeochemical-biological models are needed to test and validate our hypothesis.

**ACKNOWLEDGEMENTS**

We would like to thank all of our E-Flux collaborators, particularly lead-PI Claudia Benitez-Nelson, for their assistance in collecting the data described in this paper and for their intellectual contributions. Eric Firing and Jules Hammond provided considerable assistance with the ADCP data sets. The crews and technicians of the R/V *Wecoma* are thanked for their assistance at sea. This study was funded by the NSF Ocean Chemistry Program.
BIBLIOGRAPHY


Figure 1: Spatial arrangement of the six transects during E-Flux III (a); *Opal* translation track and position of IN- and OUT-stations (b). The planned star-like pattern (see fig 12a in Dickey et al., 2007) was rearranged to have all the transects crossing the center of the eddy as *Opal* was moving north to south. Because of bad weather conditions only 4 CTD casts were collected during Transect 1.
Figure 2: Vertical sections of temperature, salinity and density and their anomaly for Transect 3. Vertical dotted lines indicate the position along the transect where CTD cast were collected. Anomalies were computed using equation 1. An extra cast was collected during the transect to sample the estimated center of the eddy.
Figure 3: Vertical sections of temperature, salinity and density and their anomaly for Transect 4. Vertical dotted lines indicate the position along the transect where CTD cast were collected. Anomalies were computed using equation 1.
Figure 4: Mean vertical profiles of temperature, salinity and density for Opal’s core region (IN$_{avg}$) and the far-field (OUT$_{avg}$). The lines at the sides of each profile indicate the 1 standard deviation interval.
Figure 5: T-S diagrams for OUT-stations, IN-stations and transect stations.
Figure 6: Vertical sections of nitrate + nitrite, total chlorophyll $a$ and oxygen concentration and their anomaly for Transect 3. Isopycnal contours are superimposed on these sections. Dots in the nitrate + nitrite section indicate position and depth at which water samples were collected. Vertical dotted lines in the other sections indicate the position along the transect where CTD cast were collected. Anomalies were computed using equation 1. Chlorophyll $a$ was derived from fluorometer measurements using a regression curve.
Figure 7: Vertical sections total chlorophyll $a$ and oxygen concentration and their anomaly for Transect 4. Isopycnal contour lines are superimposed on these sections. Vertical dotted lines indicate the position along the transect where CTD cast were collected. Anomalies were computed using equation 1. Chlorophyll $a$ was derived from fluorometer measurements using a regression curve. During Transect 4 water samples for nutrient measurements weren’t collected.
Figure 8: Mean vertical profiles of nitrate + nitrite, total chlorophyll $a$ and oxygen concentration for Opal's core region (IN$_{avg}$) and the far-field (OUT$_{avg}$). The lines at the sides of each profile indicate the 1 standard deviation interval. INavg profile of chlorophyll $a$ shows high variability due to variations in depth and intensity of the DCML. Nutrient profiles were reconstructed from water samples.
Figure 9: 40 m ADCP vectors for Transect 3 and 4. The dots indicate the locations where CTD casts were collected. The two circles indicate the best estimated positions of the center of cyclone Opal for the two transects.
Figure 10: Best estimated position of the center of cyclone Opal at 40 m depth (red *) for Transect 3 (a) and Transect 4 (b). The areas evidenced by the contour lines were divided into a 30 by 30 km grid. Tangential components of the blue vectors were computed for each point within the grids. For each transect, the center of the eddy was defined as the point for which the mean tangential velocity was maximal. Isopleths indicates values of equal mean tangential velocity.
Figure 11: Distribution of radial (a) and tangential velocity (b) with respect to radial distance from the center for Transect 3. Distribution of normalized tangential velocity with respect to normalized radial distance (c). The solid line in this figure indicate values of equal angular velocity ($V_{\text{max}}/R_{\text{max}}$).
Figure 12: Distribution of radial (a) and tangential velocity (b) with respect to radial distance from the center for Transect 4. Distribution of normalized tangential velocity with respect to normalized radial distance (c). The solid line in this figure indicate values of equal angular velocity ($V_{\text{max}}/R_{\text{max}}$).
Figure 13: Perspective view of cyclone Opal. Top panel: 40 m depth velocity vectors superimposed to a contour plot of temperature at the same depth. Bottom panel: depth of the $\sigma_{t_3}$ isopycnal surface. The yellow x's indicate the position of the casts in transect 3 and 4.
Figure 14: 120 m (a) and 200 m depth (b) ADCP velocity vectors for Transects 3 and 4.
Figure 15: Vertical sections of tangential and radial velocity for Transect 3. Black dots indicate position and depth of the data used to generate the figure. Data close to the center of the eddy (located at ~110 km) were not included because small and not coherent with the cyclonic motion of the eddy. Black crosses at 0 m depth indicate the position of the hydrographic stations along the transect.
Figure 16: Vertical sections of tangential and radial velocity for Transect 4. Black dots indicate position and depth of the data used to generate the figure. The point along the transect closest to the center of the eddy occurs at ~90 km. Black crosses at 0 m depth indicate the position of the hydrographic stations along the transect. Lack of data at the end of the transect is due to instrument failure.
Figure 17: Vertical sections of vertical and horizontal velocity shear for Transect 3. Contourlines of density are superimposed on the sections. Shears were computed using equations 2 and 3. Black crosses at 0 m depth indicate the position of the hydrographic stations along the transect.
Figure 18: Vertical sections of vertical and horizontal velocity shear for Transect 4. Contourlines of density are superimposed on the sections. Shears were computed using equations 2 and 3. Black crosses at 0 m depth indicate the position of the hydrographic stations along the transect.
Figure 19: Vertical section of angular velocity \((V_\theta/r)\) for Transects 3 (a) and 4 (b). Black crosses at 0 m depth indicate the position of the hydrographic stations along the transect.
Figure 20: (a) Vertical section of potential vorticity for Transect3. Dots indicate the position of the data used in the analysis. (b) Contour lines of potential vorticity (solid) and potential density (dashed) for Transect3.
Figure 21: (a) Vertical section of potential vorticity for Transect 4. The dots indicate the position of the data used in the analysis. (b) Contour lines of potential vorticity (solid) and potential density (dashed) for Transect 4.
Figure 22: Schematic representation of the three phase model proposed by Sweeney et al. (2003): In the first stage, or “intensification phase”, the eddy induced nutrient upwelling above the euphotic depth determines an enhancement in the production rate within the eddy, which result in an increase in biomass. During the second stage, or “mature” phase, production rates and phytoplankton concentrations reach their maximum. The phytoplankton bloom is often dominated by larger size phytoplankton. The third stage, or “decay” phase, begins when the isopycnal doming begin to relax. The phytoplankton bloom decays due to the reduced availability of nutrients in the euphotic zone. It has been hypothesized that an increase in carbon export can occur during this phase.
Figure 23: Schematic representation of the proposed open-bottom/horizontally leaky model: at the time of eddy formation a first injection of nutrients is associated with eddy induced isopycnal uplift. Depending on the eddy velocity field, further upwelling of nutrients can occur when the eddy translates. At the same time, part of the phytoplankton community at the DCML at the center of the eddy can be displaced at the rear of the eddy, forming a wake characterized by relatively high chlorophyll concentrations, and possibly moderate increase in carbon export.
Figure 24: Fluorescence derived total chlorophyll $a$ concentrations (shaded) superimposed to isopycnals (contour lines) for Transect 2. Chlorophyll data were interpolated relative to depth, therefore the DCML representation in this particular section is distorted.