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

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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 Island of Hawai‘i, focusing on the physical–biogeochemical interactions. 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 experiment, Cyclone Opal moved over 160 km, generally southward. Thus, the sampling design had to be constantly adjusted in order to obtain quasi-synoptic observations of the eddy. Analyses 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. Isopleths of nutrient concentrations were roughly parallel to isopycnals, indicating the upwelling of deep nutrient-rich water. The deep chlorophyll maximum layer (DCML) shoaled from a depth of about 130 m in the outer regions of the eddy to about 60 m in the core. Chlorophyll concentrations reached their maximum values in Opal’s core region (about 40 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 s⁻¹ at roughly 25 km from the center, and then slowly decayed. 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. Potential vorticity analysis suggests that only a relatively small (about 50 km in diameter) and shallow (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 σ₂ = σ₂₃.₆ (σ₂₃.₆ = 23.6 kg m⁻³) and σ₂ = σ₂₄.₄ (σ₂₄.₄ = 24.4 kg m⁻³). Thus the biogeochemistry of the system might have been greatly influenced by these lateral exchanges of water at depth, especially during Opal’s southward migration. While the eddy was translating, deep water in front of the eddy might have been upwelled into the core region, leading 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.

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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 Island of Hawai‘i according to studies including those by Patzert (1969), Lumpkin (1998), Chavanne et al. (2002), Calil et al. (2008), and Dickey et al. (2008). These studies suggest that the Ekman transports associated with wind-curl fields of trade winds on 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 regularly to the southwest of the

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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 Island of Hawai‘i is therefore characterized and significantly influenced by the almost ubiquitous presence of these mesoscale features. Interestingly, Calil et al. (2008) have described satellite altimeter data that indicate that the region of focus during the E-Flux I and III field experiments (to the west of Hawai‘i) 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 (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). Hawaiian lee eddies typically have a radius between 40–150 km and exhibit velocities up to 100 cm s⁻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 (Dickey et al., 2008). 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 (Lumpkin, 1998; Calil et al., 2008); however, our present studies (summarized in Dickey et al., 2008, as well as some other reports (Patzert, 1969)) indicate that 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 triggers the succession of larger phytoplankton species, with subsequent increases in higher trophic level production. Concomitant possible increases in carbon remineralization, particle fluxes, and carbon export are the foci of other papers in this volume (Brown et al., 2008; Maiti et al., 2008; Rii et al., 2008).

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 investigate intensively 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 physical and bio-optical results are provided in Dickey et al. (2008). 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 in order 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 (Brown et al., 2008; Landry et al., 2008; Maiti et al., 2008; Rii et al., 2008). Several details concerning the E-Flux I study of Cyclone Noah and its similarities and differences with respect to Cyclone Opal are given in Kuwahara et al. (2008).

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. (2008).

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., 2008, 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 OperationalEnvironmental Satellite (GOES) and NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. Daily and eight-day composite surface chlorophyll a imagery derived from MODIS Aqua optical imagery was provided by the NASA Ocean Color group. Again, satellite SSHA data were found to be of limited value for most of our purposes.

Cyclone Opal became visible on satellite SST data between February 18 and 25, 2005. It might have formed 1–2 weeks earlier to the southwest of the Alenuihaha Channel, 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., 2008). Opal remained evident in the SST imagery until April 2005. 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 10–15), a series of five shipboard transects averaging roughly 150 km in length were conducted across the eddy. A sixth shipboard transect also was performed at the beginning of the third week (March 22–23). 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., 2008, and Kuwahara et al., 2008). 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. Fig. 1B shows the movement 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., 2008). The sampling scheme was constantly adjusted so that each transect would pass through the best estimated coordinates of the center of the eddy. As shown in Fig. 1A, the resulting sampling pattern only partially resembled the planned star-like structure. The method used for tracking the

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**Fig. 1.** Spatial arrangement of the six transects during E-Flux III (A), and position of IN- and OUT-stations (B). The planned star-like pattern (see Fig. 12a in Dickey et al., 2008) 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 four CTD casts were collected during Transect 1.
center of the eddy is discussed in Dickey et al. (2008), whereas the method to provide the most accurate post-cruise estimate of the eddy's center used in the analyses for this paper is discussed in detail in the ADCP data section (Section 3.3).

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 24–27). 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 Fig. 1B.

E-Flux III hydrographic casts were performed using a SeaBird 9/11+ CTD/rosette package equipped with 12 10-l sampling bottles. Continuous vertical profiles were usually conducted to depths of approximately 500 m, and temperature, conductivity, dissolved oxygen, chlorophyll a (chlorophyll fluorescence) and beam transmission were measured. Downcast CTD data were processed and binned into 1-m depth bins (see Dickey et al., 2008, concerning instrumentation and data processing and calibration). Sampling bottles were used at selected stations to collect 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 total chlorophyll a (see Rii et al., 2008, 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 in near-real time during the entire cruise. The profile depths ranged from 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 shipbased and drifter observations, dynamic and rapidly evolving mesoscale eddies cannot presently be sampled synoptically (Dickey and Bidigare, 2005). Again, the fast movement of Opal represented a major challenge for synoptic sampling. However, the continuous modifications of the original sampling pattern allowed the 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 Transects 3 and 4 are shown and their analyses are discussed in detail. Transect 3 encompassed Cast 13–25 (March 13–14). Bottle measurements from Cast 19 were discarded from the data set because of sampling problems. Transect 3 was selected because it was the most intensively sampled of all transects and several biogeochemical variables were measured and analyzed from the collected water samples. Transect 4 included Cast 26–36 (March 14–15). 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 Figs. 2 and 3, respectively. Vertical dotted lines in the plots indicate the positions where CTD data were collected. As can be noticed from Fig. 2, during Transect 3 an extra CTD cast (Cast 20) was performed to sample at the estimated center of Cyclone Opal. However, 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 (Simpson et al., 1984) are defined as:

$$DPA(r, z) = \text{STAR}_{\text{cast}}(r, z) - \text{OUT}_{\text{avg}}(z)$$

where $\text{STAR}_{\text{cast}}(r, z)$ 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 $\text{OUT}_{\text{avg}}(z)$ 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$_{\text{avg}}$ 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 (Figs. 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 $\sigma_{-24}$ 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 Figs. 2 and 3 Opal's diameter can be conservatively estimated to be roughly 160–180 km. The maximum vertical displacements of the $\sigma_{-24}$ isopycnal indicate the approximate positions of the center of the eddy at about 105 km off Transect 3, and at about 80 km off Transect 4. In both cases, the maximum eddy-induced uplift is roughly 80–100 m, with the $\sigma_{-24}$ 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 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 $-3 \, ^\circ\text{C}$ for temperature, and up to 1 kg m$^{-2}$ for density; these anomalies clearly indicate the areas where the vertical uplift was most intense. Contour plots of...
differential density anomaly in Figs. 2 and 3 deserve particular attention. For both transects, the area of high anomalies can be roughly characterized by the $0.5 \text{ kg m}^{-3}$ 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 horizontally much narrower, roughly 40 km, and relatively less extensive in the vertical and deeper, ranging from 50 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. 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 Fig. 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 Figs. 2 and 3 show slightly different features. There is evidence of a region of high negative differentials (about $-0.4 \text{ psu}$) below a shallower region of high positive differentials (about 0.2 psu). The presence of these two regions is a direct consequence of the deep salinity maximum ($>35 \text{ psu}$) that characterizes the vertical contours of salinity.

Fig. 2. Vertical sections of temperature, salinity and density and their anomalies for Transect 3. Vertical dotted lines indicate the position along the transect where CTD cast data were collected. Anomalies were computed using Eq. (1). An extra cast was collected during the transect to sample the estimated center of the eddy.
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.

Fig. 4 shows mean vertical profiles to 1000 m of (A) temperature, (B) salinity, and (C) density from both Opal’s core region (INavg) and away from the influence of the eddy (OUTavg). Again, the OUTavg profiles were computed using the 26 OUT-stations (Casts 105–130), while the INavg 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-station sampling. As a result, some of the IN-station data were collected too far from the center to be useful for the analyses 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 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 greater 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 s\(^{-1}\) as a reasonable threshold value. According to this criterion nine 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 INavg.
The dotted lines at the sides of each profile in Fig. 4 indicate the 1 standard deviation interval associated with the averaged property at each depth. Clearly standard deviations for all the properties from both INavg and OUTavg are minimal.

Comparisons of the mean profiles of temperature, density and salinity shown in Fig. 4 are consistent with the presentation of data in Figs. 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 Fig. 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 Fig. 5. Fig. 5 shows T–S diagrams (A) for the 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 Fig. 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 (<4 °C); the North Pacific Deep Waters (NPDW), characterized by moderate-to-low salinity (34.5 down to 34.2) but still relatively cold waters (4–6 °C); the North Pacific Intermediate Waters (NPIW), characterized by low salinity (<34.2) and relatively higher temperature (6–12 °C); the Subtropical Subsurface Waters (SSW) characterized by high salinity (>34.5) and much warmer temperatures (~20 °C); and the shallowest near-surface waters characterized by high temperatures (~25 °C) and lower salinity being largely influenced by precipitation (Wyrtki and Kilonsky, 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 Fig. 4B. The NPDW water masses extend from below 1000 m up to depths between 700 and 800 m, and the NPIW water masses are confined between 300 and 600 m depths. The SSW water masses are found between 100 and 200 m depths, and the near surface waters are limited to the upper 20 m of the water column. The NPBW water masses are much deeper than 1000 m and therefore not shown in the plot.

The T–S diagram data shown for the IN-stations in Fig. 5B are 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. Fig. 5C shows slightly different features compared to those of the previous two diagrams. The T–S curves in the diagram that are still identical to the ones evident in Fig. 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 less saline SWWs even though NPIWs and near surface waters show quite typical temperature and salinity values. These data 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

Fig. 4. Mean vertical profiles of temperature, salinity and density for Opal’s core region (INavg) and the far-field (OUTavg). The lines at the sides of each profile indicate the 1 standard deviation interval.
salinity maximum is particularly evident at the beginning of Transect 3 (Fig. 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 Fig. 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., 2008). 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. Fig. 7 shows the same data for Transect 4 except nitrate + nitrite. The black dots in the vertical section of nitrate + nitrite in Fig. 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 Transsects 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, so that 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., 2008). Nonetheless, individual profiles obtained during E-Flux III may be compared.

As indicated by the data displayed in Fig. 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 depths, 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 \( \sigma - t_{24.2} \) and the \( \sigma - t_{24.4} \) density surfaces (Rii et al., 2008). The transect sections shown in Figs. 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. The 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 and 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\(^{-3}\)).

Fig. 6. Vertical sections of nitrate + nitrite, total chlorophyll \( a \) and oxygen concentration and their anomalies for Transect 3. Isopycnal contourlines 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 positions along the transect where CTD cast data were collected. Anomalies were computed using Eq. (1). Chlorophyll \( a \) was derived from fluorometer measurements using a regression curve.
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 the case for analogous data displayed in Figs. 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 Fig. 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., 2008; Landry et al., 2008; Rii et al., 2008).

Vertical sections of dissolved oxygen concentrations exhibit a pronounced doming of oxygen isopleths closely related to the doming of isopycnal surfaces, 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 Figs. 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 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 Fig. 8A–F. INavg and OUTavg 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, INavg and OUTavg profiles of nitrate $+$ nitrite were computed by averaging a limited number of IN- and OUT-stations (Cast 20, 63, 67 and 73 for INavg and Cast 111, 119 and 127 for OUTavg). 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 Figs. 4 and 8. Also, this profile is limited to the upper 300 m of the water column. Mean vertical profiles of total 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 INavg 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 Fig. 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 Fig. 6. Particularly interesting are the differences between INavg and OUTavg profiles when they are
plotted against density (Fig. 8B). OUT$_{avg}$ nutrient concentrations start to increase below the $\sigma-t_{23.7}$ density level, whereas the IN$_{avg}$ profile shows low nitrate + nitrite concentrations extending below the $\sigma-t_{24}$ level. These limiting nutrient concentrations above the $\sigma-t_{24}$ surface most likely explain the IN$_{avg}$ DCML occurring at higher density levels than the OUT$_{avg}$ DCML (Fig. 8D). Nitrate + nitrite concentrations at the $\sigma-t_{24.5}$ 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
INavg profile. As shown in Fig. 8D, the density interval within which this gradient occurs is characterized by the presence of the DCML, 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., 2008 for more details). The OUTavg profile of chlorophyll a concentration indicates quite typical values for the region with a DCML 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 INavg 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 Fig. 4, 1000-m vertical profiles of dissolved oxygen (Fig. 8E) 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 Fig. 8E with Fig. 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 INavg 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 \(\sigma - \tau_{24}\) and \(\sigma - \tau_{24.5}\) levels in Fig. 8F. As mentioned above in the discussion of the dissolved oxygen sections shown in Figs. 6 and 7, this observation suggests increased oxygen consumption, which is most likely caused by enhanced remineralization 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 Fig. 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 these 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 did not 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 45–60 min) compared to the ADCP sampling interval (15 min, see Dickey et al., 2008). 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 was 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 \(\times\) 30 km around the minimum velocity zone of each transect was divided into a grid of 30 \(\times\) 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 became more perturbed due to the growing influence of the outer velocity field.

Fig. 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 \(\times\) 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 that 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., 2008). For this reason the center position determined at the 40-m depth can be taken as a good approximation of the center position throughout the whole water column.

The center of the eddy also could 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 were 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 Fig. 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 casts 13 to 20), while red crosses referring to data collected after the center was crossed (from casts 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 Fig. 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 seem 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 Fig. 12), 2, and 6 (not shown here), do not 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 (\(V_{max}\)) against radial distances normalized by the radius at which the maximum tangential velocity was found (\(R_{max}\) (Olson, 1980). Normalized tangential velocities and radial distances for Transect 3 are plotted in Fig. 11C. The solid line in the figure represents values of constant angular velocity \(V_{max}/R_{max}\). 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; $C_\theta/R$) 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 $\approx 60$ cm s$^{-1}$ and $R_{\text{max}}$ is $\approx 25$ km, the angular velocity is $\approx 2.4 \times 10^{-3}$ rad s$^{-1}$, and the corresponding orbital period of the solid core is $\approx 3$ 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 the exchange processes of the system.

In Fig. 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 Fig. 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 only within $\approx 10$ 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 Fig. 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 $\approx 35$ cm s$^{-1}$. A possible explanation for these anomalies can be found in the location of the first portion of Transect 4. First of all, the initial section of this transect is relatively close to the Island of Hawai’i, 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 Island of Hawai’i is characterized by eddies that develop due to the shear between the southernmost tip of the Island of Hawai’i itself and the westward North Equatorial Current that is partially blocked by the island (Qiu et al., 1997; Calil et al., 2008). 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 Island of Hawai’i (from Cast 30 to Cast 36; red crosses in Fig. 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 Fig. 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 seem 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.

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 Fig. 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 $\sigma - \tau_{\text{c}}$ 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 Fig. 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 Fig. 14A and B as vector maps analogous to the one shown in Fig. 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 Fig. 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 as 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 as 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 Fig. 15 are locations along the transect where CTD casts were made. 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 Fig. 15A that velocities are usually very small close to the center of the eddy, and even at a depth of 40 m they can decrease 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 Figs. 15–18, with the exception of Fig. 16. 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 points were removed up to a distance of 10 km from the center.

The vertical section of tangential velocity in Fig. 15A shows a typical eddy 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 a quite rapid increase 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 to the upper 150 m. For this reason, Cyclone Opal can be considered from a dynamical prospective to be a
relatively shallow feature. Radial velocities in Fig. 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 m.

Fig. 14. (A) 120 m and (B) 200 m depth ADCP velocity vectors for Transects 3 and 4.

Fig. 15C and D 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
Fig. 15. Vertical sections of tangential and radial velocity for Transect 3, (A) and (B), and Transect 4, (C) and (D). Black dots indicate position and depth of the data used to generate the figure. In Transect 3 data close to the center of the eddy (located at \( \approx 110 \) km) were not included because small and not coherent with the cyclonic motion of the eddy. In Transect 4 the closest point 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 Transect 4 is due to instrument failure.

Fig. 16. Vertical sections of vertical and horizontal velocity shear for Transect 3, (A) and (B), and Transect 4, (C) and (D). Contourlines of density are superimposed on the sections. Shears were computed using Eqs. (2) and (3). Black crosses at 0 m depth indicate the positions of the hydrographic stations along the transect.
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 Fig. 12, 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 s\(^{-1}\), 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 s\(^{-1}\) at depths shallower than 90 m. On the other hand, limitations of 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 Island of Hawai‘i. 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 rapidly 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:

\[
\frac{\partial \bar{U}}{\partial z} = \left( \left( \frac{\partial C_y}{\partial z} \right)^2 + \left( \frac{\partial C_r}{\partial z} \right)^2 \right)^{1/2} \tag{2}
\]

\[
\frac{\partial \bar{U}}{\partial r} = \left( \left( \frac{\partial C_y}{\partial r} \right)^2 + \left( \frac{\partial C_r}{\partial r} \right)^2 \right)^{1/2} \tag{3}
\]

where \( C_y \) 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 Fig. 16A to D. 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. Fig. 16A and C shows 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 \( \alpha \) 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 Fig. 16B and D do not display any major structures. However, there are two narrow areas of high values limited to the upper 100 m 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 Fig. 16D, it is apparent that these two peaks arise from sharp variations of the radial component of velocity rather than from variations of the tangential component.

Vertical sections of angular velocity (\( C_y/r \)) from Transects 3 and 4 are shown in Fig. 17A and B, respectively. Values of angular velocity are highly sensitive to radial distance, and even small tangential velocities result in very large values of angular velocity when divided by small radial distances. For this reason, the tangential velocities from which angular velocities were computed are the same ones used in Fig. 15A and C. Vertical sections of angular velocity show similar structure to those 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 of minimum values that occur close to the center of the eddy where tangential velocities decay to very small values. An analogous minimum region is not evident in the angular velocity distribution of Transect 4; as expected, less symmetry is seen in the angular velocity of Transect 4. The less accurate estimated position of the eddy center for Transect 4, which results from the offset of the transect from the true center of the eddy, likely explains part of the asymmetry. 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 analyses of the various terms that contribute to the equation for conservation of potential vorticity (e.g., Olson, 1980; Simpson et al., 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 (Pedlosky, 1979). In cylindrical coordinates, the conservation of potential vorticity can be expressed as

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

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 Eq. (4). The Coriolis parameter \( f \) was chosen to be \( 4.9 \times 10^{-5} s^{-1} \) (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). Rough estimates of vertical velocities (\( w \)) were computed by integrating the continuity equation. According to the scaling results, the potential vorticity, \( \pi \), of Cyclone Opal can be expressed to a first order of approximation by the equation

\[
\pi = \frac{\partial r}{\partial z} \left( \frac{C_y}{r} + \frac{\partial C_y}{\partial r} + f \right) \tag{5}
\]

where \( \partial r/\partial z \) is the vertical gradient of density; \( C_y/r \) the angular velocity; and \( \partial C_y/\partial r \) the radial gradient of tangential velocity. This approximation was used to compute \( \pi \) for each transect.

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 Eq. (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.
Fig. 18A and C shows 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 Eq. (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 Eq. (5). An area of maximum potential vorticity (values $> 12 \text{ kg m}^{-4} \text{s}^{-1}$) 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 70–80 m. This area is surrounded by two lobes where the potential vorticity decreases to values between 7 and $12 \text{ kg m}^{-4} \text{s}^{-1}$. 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 ($< 5 \text{ kg m}^{-4} \text{s}^{-1}$) 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 Fig. 18B and D 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 of 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 $\sigma_t \approx 23.6$ to $\sigma_t \approx 24.4$. This radial exchange of fluid may explain the anomalous T–S diagram features in Fig. 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 Island of Hawai’i as a result of strong and persistent trade wind conditions (Dickey et al., 2008). 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 observations 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 s$^{-1}$, occurring at roughly 25 km from the eddy’s center. Comparison with other wind generated mesoscale eddies observed in the region indicate Opal’s physical characteristics to be quite typical (Patzert, 1969; 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).

The high 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 et al. (1998). More recently, Sweeney et al. (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. Fig. 19 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 stimulates a biological response (i.e. increase in primary 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.
Cyclones Mikalele, Loretta and Haulani (see also Brown et al., 2008 and Rii et al., 2008). 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. Although this bloom was not dominated by diatoms, total chlorophyll a concentrations at the DCML were similar to the ones observed for Cyclone Opal, which decayed within 2 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 dominated by diatoms 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; Vaillancourt 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.

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 Hawaii. For 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. (2008) 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, which were isolated from the surrounding
winters, 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. 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 possible exchange of water would have taken place along density surfaces between $\sigma -t_{23.5}$ and $\sigma -t_{24.4}$. For this reason, Cyclone Opal, rather than being a deep, horizontally closed or isolated system like the one depicted in Fig. 19, was potentially a shallow, open-bottom/horizontally leaky system as depicted in Fig. 20. 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 $\sim 0.6 \text{ km h}^{-1}$).

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 Fig. 20. For the present model, the initial, spin-up phase is similar to the one described by Sweeney et al. (2003) and shown in Fig. 19; 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 (2007). 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., 2008). The latter is most likely the reason that the phytoplankton bloom decayed toward the end of the E-Flux III experiment (Benitez-Nelson et al., 2007; Brown et al., 2008; Rii et al., 2008). 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 likely 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, so that 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 Fig. 20, 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 Fig. 21. To generate this figure,
increased silica export in the subtropical Pacific Ocean. Science 316, 1017–1020.


