An Oceanic Cyclonic Eddy on the Lee Side of Lanai Island, Hawai‘i

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A young cold-core cyclonic eddy displaying a significant increase in surface chlorophyll was observed offshore Lanai Island, Hawaiʻi, where the Marine Optical Buoy (MOBY) is located. During one of its deployments, MOBY broke free from its mooring. In the course of its 3-day free drifting period, MOBY followed a cyclonic eddy, which is manifested by satellite remote sensing data: chlorophyll data from MODIS and sea surface temperature (SST) from a Geostationary Operational Environmental Satellite (GOES). The time series of the SST show that the cold-core eddy was in a formative stage. It existed as a stand-alone eddy for about 9 days before it merged with cold water south of Oahu Island. A high-resolution numerical model simulation reproduces similar eddies in terms of location, size and intensity. An eddy-detection algorithm is described and applied to locate and track the modeled eddies. The results demonstrates that mesoscale and submesoscale eddies are frequently generated on and pass through the lee side of Lanai Island and the statistical analysis quantifies the general features of eddies in the area.
1 Introduction

Lee sides of islands (headlands) are areas rich in eddy activities in terms of the direction of either winds or oceanic currents (e.g., Patzert, 1969; Signell and Geyer, 1991; Aristegui et al., 1994; Lumpkin, 1998; Barton et al., 2000; Barton, 2001; Chavanne et al., 2002; Dong and MacWilliams, 2007; Calil et al., 2008; Dong and MacWilliams, 2007). There are two mechanisms for the eddy formation in the wake of islands: the one involves the oceanic response to wind stress curls and the other is oceanic island current wakes. For the former one, wind blocking due to the presence of islands can introduce positive (negative) wind stress curls on the right (left) side of the island while looking downstream, which causes the upwelling (downwelling) (See illustration in Chavanne, et al., 2002). For the latter, as oceanic flow passes an island, the horizontal shear and inhomogeneity in bottom stress can induce vorticity. The mixture of two processes associated with the sheltering of wind from the island (Caldeira and Marchesiello, 2002) takes place with almost all islands, which makes the scenario much more complicated. The Hawaiian Islands are located in the path of trade winds (quite steady northeasterly winds in this region) and the North Equatorial Current, so in principle, these two processes could be operative on the lee side of the island chain. In fact, eddies are ubiquitous on the lee side of the Hawaiian Islands (e.g., Patzert; 1969; Lumpkin, 1998; Chavanne et al., 2002; Dickey et al., 2008). Cold-core eddies are active agents promoting nutrient flux from depth to the euphoric zone, especially in the subtropic ocean, such as the area around the Hawaiian Islands, a so-called oceanic ”desert” due to the existence of a subtropical gyre. These eddies are thus usually associated with high biological activity as reported in several papers within the past decade (e.g., Benitez-Nelson et al., 2007; Dickey et al., 2008; Rii et al., 2008; Nencioli et al., 2008; Kuwahara et al., 2008; Brown et al., 2008; Landry et al., 2008; Bidigare et al., 2003; Seki et al., 2001, 2002; Vaillencourt et al., 2003). However the eddies’ roles in the biological and biogeochemical processes remain enigmatic, partially because of the challenges of in-situ eddy measurements due to the spontaneity in eddy generation and present technological
limitations (Dickey and Bidigare, 2005). Benitez-Nelson et al (2007) and a Special Volume of Deep-sea Research (2008) reported an extensive set of measurements of eddies on the lee side of the Big Hawaii Island in 2005. In particular, two eddies were extensively studied during their cruises on the lee side of the Big Island of Hawaii, an eddy-rich area (see Dickey et al., 2008).

In this paper, we describe a cyclonic eddy observed around the mooring location of the Marine Optical Buoy (MOBY) offshore of Lanai Island, Hawai‘i. The MOBY accidently broke from its mooring and floated as a drifter for about 4 days in December, 2007. The drifting locations of MOBY were recorded by its Argos, a satellite-based location system, and show that MODY traveled in an anti-clockwise (cyclonic) path offshore of Lanai Island. The tracking data and other satellite observations, such as the sea surface temperature (SST) and the chlorophyll concentration, are analyzed and all of them confirm that MOBY was following a cyclonic eddy in the lee side of Lanai Island. Altimetric sea surface height data are not used since the satellite tracks passed only over the edge of the eddy. A high-resolution numerical model is applied to the study and the numerical results show that eddies frequently occur on the lee side of Lanai Island. Finally, a statistical analysis of the numerical solution is reported.

The paper is organized as follows: Section 2 demonstrates that MOBY followed a cyclonic eddy based upon the MOBY Argos location data and satellite data, the eddy’s intensity is analyzed and its generation mechanism are discussed. Section 3 presents a numerical solution and its statistical eddy analysis based on an eddy-detection scheme. The discussion and summary are presented in Section 5.

2 Observations

2.1 A Cyclonic Eddy

MOBY is the critical measurement platform for calibration of several ocean color sensing satellites including the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Sea-viewing
Wide Field-of-view Sensor (SeaWiFS). Approximately 50 feet long, the spar buoy is the world’s largest marine optical device. A physical oceanography group from the Moss Landing Marine Laboratories constructed MOBY in 1991 and it (and a replacement twin MOBY) continues to be maintained at a site about 24 km offshore Lanai Island, Hawai’i. The site was chosen for its relatively clear sky conditions, low turbidity ocean waters, and moderate winds and waves (an island shadow zone with respect to prevailing northeast trade winds) (Clark et al., 1997).

Because of maintenance requirements, a MOBY platform has to be recovered and a replacement is re-deployed at approximately 3-month intervals. A serial number is assigned for each individual deployment. The deployment number for the one of interest here from Sep. 10 to Dec. 20, 2007, is MOBY239; for more information about the MOBY, please refer to the website http://physoce.mlml.calstate.edu/moby/ (also Clark et al., 1997 and Clark et al., 2003). MOBY broke free from its mooring at 13h 52m, Dec. 18 (GMT) and then drifted before it was recovered at 3h 3m, Dec. 22. The period of the MOBY drifting time is 85.18 hours. The number of the MOBY positions recorded by Argos is 116. The time intervals of position records are uneven, from 0.02 hours to 1.98 hours and the average time interval is 0.74 hours. The MOBY drifting trajectory is plotted in Fig. 1, and shows that the free drifting MOBY traveled first northwestward, then turned southwestward on December 19, and continued its journey southeastward before it was recovered early December 22. MOBY made half an anti-clockwise circle with a diameter of about 50 km during the drifting period.

To determine if MOBY’s trajectory followed that of a streamline for a cyclonic eddy, the daily sea surface temperature (SST) data from the GOES with the horizontal spatial resolution of 5 km are used. The two-day averaged GOES SST data are plotted Fig. 1, and overlays the MOBY path. In the center of the incomplete anti-clockwise circle of MOBY’s trajectory lies cooler waters and the trajectory of the freed MOBY appears to generally follow the edge of the cold water, the expression of the cyclonic eddy. This suggests that the MOBY was indeed tracking a cyclonic
eddy with a diameter of at least 50 km. A cyclonic eddy likely upwells cold water from below to the surface in the vicinity of the eddy center (e.g., see realization in Dickey et al., 2008). However, due to the thermocline depth and intensity of the eddy as well as possible surface overprints of warm waters, cool waters are not necessarily seen at the surface in the presence of a cyclonic eddy, thus, the age of a given cyclonic eddy is likely biased toward a lower estimate. Nonetheless, in this case, cooler surface waters are clearly evident.

A time series of the mappings of SST in the area is shown in Fig. 2 in order to further demonstrate that we have observed a cyclonic eddy and to investigate the lifetime history of the eddy. The two-day averaged data are presented to reduce the impact of missing data (e.g., cloud obscuration issues). On Dec. 15-16, the area where MODY would pass a few days later was still occupied by warm waters. On Dec. 16-17, a patch of slightly cooler water started to appear at the surface. On Dec. 17-18, distinctively cooler water could be seen in the area. On Dec. 18-19, when MOBY broke from its mooring, the circular cooler water patch was well developed and its evolution continued during Dec. 19-20. Its northwestern portion spreads northward on Dec. 20-21, and broke into pieces one day later. During Dec. 22-24, it started to move westward and northward and then merged with cooler water south of Oahu Island which was there since the beginning of the period. The development of the cyclonic eddy suggests that the cold water is formed locally, i.e. upwelled.

Chlorophyll data collected during the period are examined to discern any response in the marine biological (nutrient generated new primary productivity) associated with the eddy. Such data can provide additional observational evidence of the eddy. Again, the upwelling occurring from beneath the central portion of the cyclonic eddy would bring nutrients from below to the euphoric zone and the concentration of the chlorophyll could increase. Upwelling of the chlorophyll lying in the subsurface chlorophyll maximum could also come into play. The daily chlorophyll data observed from MODIS with spatial resolution of 9 km are used. The time series of the SST distributions in Fig. 2 show that the eddy stayed near its original formation location for almost one
week (Dec. 17-22). This allows us to use multiple-day averaged chlorophyll data to avoid the cloud contamination problem. The eight-day averaged MODIS satellite-based chlorophyll concentration data are shown in Fig. 3. To compare with the SST spatial pattern, the SST distribution is also plotted in Fig. 3 for the same period. The spatial pattern of the SST and the chlorophyll concentration match each other very well: the higher chlorophyll concentration and the lower SST are both south of Oahu Island and west of Lanai Island (in the cyclonic eddy area).

In summary, both the SST and chlorophyll data suggest that eddy-related upwelling took place within an area described by an anti-clockwise trajectory (radially inward) of the freed MOBY made. This clearly demonstrates that the freed MOBY was following a mesoscale sized cyclonic eddy with a radius of at least 25 km.

2.2 Eddy Intensity

To estimate the eddy intensity, the velocity of the eddy is calculated from the MOBY trajectory data. In Fig. 4, the upper-left panel shows the drifting speed of MOBY. Before it turned eastward from westward, its speed was $46 \text{cms}^{-1}$. After its turning point, its speed decreased by a half and became $22 \text{cms}^{-1}$. When a drifter follows a streamline of a coherent eddy at a fixed radial distance from the eddy’s center, its tangential speed should be constant (i.e., approximate solid-body rotation at a given distance from the axis of rotation). To understand the dramatic change in the Lagrangian speed, the motion of MOBY is projected onto the zonal and meridional directions. From the upper-right and lower-left panels in Fig. 4, it can be clearly seen how the change takes place. Along the zonal direction, the MOBY speed before and after it passed the west-east turning point decreased dramatically from $40.19 \text{cms}^{-1}$ to $13.77 \text{cms}^{-1}$, however the speeds along the meridional direction do not change before and after the west-east turning point though there is small change at the turning point from the northward to southward. To understand this dramatic change in the speed, the velocity derived from the drift location data is decomposed into several
terms according to its different momentum sources.

MOBY was not designed to be a Lagrangian drifter, so points devoted to its forced motion bear discussion. After MOBY broke from the mooring, it oscillated at the air-sea interface. The wind, oceanic waves and eddy currents could all have varying degrees of direct effects on MOBY’s motion. The Lagrangian current, derived from the Argos location data, can be decomposed as follows,

\[ \mathbf{U}_{\text{lagran}} = \mathbf{U}_{\text{euler}} + \mathbf{U}_{\text{stokes}} = \mathbf{U}_{\text{ekman}} + \mathbf{U}_{\text{geost}} + \mathbf{U}_{\text{res}} + \mathbf{U}_{\text{eddy}} + \mathbf{U}_{\text{stokes}} \]  

where \( \mathbf{U}_{\text{lagran}} \), \( \mathbf{U}_{\text{euler}} \) and \( \mathbf{U}_{\text{stokes}} \) are the Lagrangian, Eulerian and Stokes current, respectively. The Eulerian current \( \mathbf{U}_{\text{euler}} \) includes three parts: the one is the Ekman drift \( \mathbf{U}_{\text{ekman}} \) due to the sea surface wind, the sea surface geostrophic current \( \mathbf{U}_{\text{geost}} \) due to the surface pressure, \( \mathbf{U}_{\text{res}} \) due to the nonlinearity, and \( \mathbf{U}_{\text{eddy}} \) is the azimuthal current around the eddy given the eddy shape is circular. The current for the eddy, \( i.e., \), the azimuthal velocity, is almost constant along the circular eddy at the presumed constant radial distance from the eddy’s center.

The first three terms on the right side of equation (1) are the large scale current, \( i.e., \), the background flow. The nonlinear residual is generally small for the large scale current (Dong et al, 2008). The Ekman drifting current \( \mathbf{U}_{\text{ekman}} \) is theoretically directed 45° towards the right facing towards the wind direction in the northern hemisphere, however in real geostrophic flows, the deflection angle is much less than 45° and is found to range between 5° and 20° (Cushman-Roisin, 1994). The daily blended wind data with the QuikSCAT satellite-based wind product (Zhang et al., 2006) show the wind direction is almost uniform northeasterly (Fig. 5) and constant from Dec. 10 to the end of December at about 75 degree based on the meteorological wind direction convention (Fig. 6). The MOBY Ekman drift is generally in the westward direction with slightly northward by 5 degree based on the above estimate of the deflection angle. The surface Ekman drifting current is \( \mathbf{U}_{\text{ekman}} = \frac{2k \times \tau}{\rho D} \), where \( k \) is the vertical unit vector, \( \tau \) wind stress, \( f \) the local Coriolis coefficient, \( \rho \) the water density, \( D \) is the Ekman layer thickness, which is estimated by \( D = \frac{0.4}{f \sqrt{\rho}} \).
as 76 meters. (Cushman-Roisin, 1994). The coefficient 2 is due to the assumption that the linear change in the velocity in the Ekman layer. Given the wind stress is about 0.1 N/m² from Fig. 6, \( U_{\text{ekman}} = 5.0 \) cm/s. The altimter-measured sea surface height data from the AVISO product (http://www.aviso.oceanobs.com) are used to estimate the geostrophic current, and it is about 5.0 cm/s westward.

The wave-induced mass transport, i.e., Stokes drift velocity can be estimated theoretically: \( u^{St} \), as (e.g., LeBlond and Mysak, 1978):

\[
    u^{St} = \frac{H_{\text{sig}}^2 \omega k \cosh 2k(z + h)}{8 \sinh^2 kh},
\]

along with the linear dispersion relation:

\[
    \omega^2 = g k \tanh kh,
\]

where \( H_{\text{sig}} \) is significant wave height; \( z \) is vertical coordinate (\( z = 0 \) for the surface drift); \( h \) is local water depth; \( \omega \) is wave frequency; \( k \) is wavenumber vector and \( k \) is its magnitude; and \( g \) is the gravitational constant. We make use of the in situ wave data from two NDBC roll-pitch buoys (http://www.ndbc.noaa.gov/) northwest of Kauai Island, HI (NDBC 51001, 23.445 °N & 162.279 °W) and at Christmas Island (NDBC 51028, 0.0 °N & 153.913 °W), both of which measured \( H_{\text{sig}}, \omega \) and \( k/k \) required for the \( u^{St} \) estimation. From Dec. 18 to Dec. 20, the meridional component of 2 cm/s equatorward is much smaller compared with the zonal component, which is about 5 cm/s westward. Since Dec. 20, the southwesterly waves were predominant, both the meridional and zonal components of \( u^{St} \) are in the same magnitude of about 2 cm/s (Fig. 7).

In summary, the dramatic change in the Lagrangian current in the zonal direction before and after the west-east turning point is due to the Ekman drift and geostrophic current (the residual current can be neglected). The small change in the Lagrangian current in the meridional direction in the course of the MOBY drifting is because the Ekman drift and the geostrophic current are neglectable and the Stoke drift is in a small magnitude. In the first order of approximation, before
the east-west turning point (see Fig. 4), the mean zonal speed for the eddy can be estimated as
\[ U_{\text{eddy}} = U_{\text{lagran}} - U_{\text{ekman}} - U_{\text{geost}} - U_{\text{stokes}} = -40.19 + 5.0 + 5.0 + 5.0 = -25.19 \text{ cm/s}. \]
For the mean meridional speed for the eddy is
\[ V_{\text{eddy}} = V_{\text{lagran}} - V_{\text{ekman}} - V_{\text{geost}} - V_{\text{stokes}} = -14.35 + 2.0 = -12.35 \text{ cm/s}, \]
where \( V_{\text{ekman}} \) and \( V_{\text{geost}} \) are negligible. After the east-west turning point, the Lagrangian current \( U_{\text{lagran}} \) decreases to 13.77 cm/s, and based on the similar calculation as above, the eastward \( U_{\text{eddy}} = 28.77 \text{ cm/s}, \) which is very close to the westward Eulerian current before the turning point, reflecting the circular eddy shape. Based on the above estimate, the azimuthal current for the eddy is about 30.0 cm s\(^{-1}\) in magnitude (averaged from westward and eastward currents).

The current for the eddy could be caused by either the flow instability or wind stress curl. Given that the radius of the trajectory from the center of the eddy is about 25 km, the vorticity of the eddy is about \( 1.2 \times 10^{-5} \text{s}^{-1} \), which is comparable with the background rotating rate \( 2.5 \times 10^{-5} \text{s}^{-1} \). The divergence scale of the eddy is also \( 1.2 \times 10^{-5} \text{s}^{-1} \), and thus the upward vertical velocity is about \( 0.9 \times 10^{-3} \text{m/s} \) if the mixing layer is in the same scale of the Ekman layer.

### 2.3 Speculation on Eddy Generation

The time series of the SST from the GOES (Fig. 2) show the cooler temperature at the eddy site is generated locally other than remotely. It implies the eddy could be generated by the local external forcing such as wind stress curl or a local flow instability. Due to the lack of local measurements of the oceanic current or the vertical profile of the density and current, we have no clue if any flow instability took place at the time when the eddy was formed. However the time series of the wind speed (Fig. 6) show a sudden increase in the wind speed on Dec. 15, the date of the onset of the cyclonic eddy, which results in a significant increase of the wind stress curl on the northside of the center of the eddy on Dec. 15, see Fig. 8. The burst of a high wind is coincident with the appearance of the cooler water timely, which suggests the eddy could be induced by the local wind
stress curl.

3 Numerical Simulation

To further examine the eddy activity and dynamics on lee side of Lanai Island, the Regional Oceanic Modeling System (ROMS) is utilized. ROMS solves the rotating primitive equations. It is a split-explicit, free-surface oceanic model, where short time steps are used to advance the surface elevation and barotropic momentum equations, with a larger time step used for temperature, salinity, and baroclinic momentum (Shchepetkin and McWilliams, 2005). A third-order, upstream-biased advection operator allows the generation of steep gradients in the solution, enhancing the effective resolution of the solution for a given grid size when the explicit viscosity is small (Shchepetkin and McWilliams, 1998). The numerical diffusion implicit in the upstream-biased operator allows the explicit viscosity to be set to zero without excessive computational noise or instability. It has been demonstrated that the ROMS can reproduce mesoscale eddies observed on the lee side of the Big Island of Hawai’i (Calil et al., 2008).

We developed two-level offline nesting grids using the Regional Oceanic Model System (ROMS) ($L_1$ is 1/10 degree and $L_2$ is 1/32 degree). The model is forced by the 2007 daily blended wind data with the 25 km resolution (Zhang et al. 2006). The open boundary data are from the monthly SODA data set (Carton et al. 2000a,b). The model is repeated for four years. The last three years are analyzed. The mean circulation of the last three years is compared with the drifter-derived climatological surface current and shows its consistence with the circulation derived from the drifter data (Lumpkin and Garraffo, 2005; the data are available online at http://www.aoml.noaa.gov/phod/dac/drifter-climatology.html, and an analysis by Qiu et al. (1997)). West of the Hawaiian Islands and downstream of generally prevailing northeasterly trade wind, North Equator Current (NEC), cyclonic and anticyclonic eddies are frequently generated and propagate generally northwestward and southeastward, respectively (Calil et al., 2008). In Fig. 9, a cyclonic eddy with a similar location to that
described by our observations and with comparable intensity is selected for comparison and analysis. The similarity allows us to examine the vertical structure and variability of a model-generated cyclonic eddy which is not possible due to data unavailability for the observed eddy. The signature of the eddy can be seen as deep as 300m. This depth of impression is comparable to those of Cyclones Noah and Opal off Hawaii observed during the E-Flux field experiment and reported by Dickey et al. (2008), Kuwahara et al. (2008), and Nencioli et al. (2008).

Statistical analysis of the eddies in the area of the MOBY drift pattern is performed. In particular, we developed an eddy-detection algorithm to do statistical analysis of the eddies that were generated and passed through the study area. The algorithm directly uses oceanic currents to detect vorticity based on the minimum speed and the reversal in velocity direction (see Appendix and also Nencioli et al. (2009) for the details), which is an algorithm different from other existing approaches: Okubo-Weiss Parameter (Isern-Fontanet et al., 2006; Chelton et al., 2007), the wavelet analysis (Siegel and Weiss, 1997; Doglioli et al., 2007) and the winding-angle method (Sadarjoen and Post, 2000; Chaigneau et al., 2008). Fig. 10 shows the trajectories of eddies generated over the course of three years. An interesting pattern is evident: i.e., on the northern (southern) lee flank of the group of islands in the chain including the Big Island of Hawaii, generally more cyclonic (anticyclonic) eddies are evident in the model results. This is consistent with the argument that there is north-south symmetry in cyclonic and anticyclonic eddy generation on the lee side of an island. When the trade winds (northeasterly generally) pass the islands from the east, the positive (negative) wind stress curl is generated on the north (south) flank of the lee side of the islands, which could induce the cyclonic (anticyclonic) eddies (Dong et al., 2007). When the westward NEC approaches the islands, the current shear instability could enhance such eddy generation (Calil et al., 2008).

We next focus specifically on the lee side of Lanai Island (158.5°W, 156.5°W, 20°N, 21.5°N, see Fig. 10. The statistical results of the eddies in the area are listed in Table 1. The daily eddy number
and eddy sizes detected in the area are similar for cyclonic and anticyclonic eddies. The average lifetime for a cyclonic eddy is somewhat longer than for an anticyclonic eddy. This is in agreement with work reported by Xin et al. (2008). The intensities of cyclonic eddies are also relatively greater than for the anticyclonic eddies in terms of relative vorticity, SST and SSH anomalies.

4 Summary and Discussion

The optical buoy MOBY is a primary in situ observation platform used to calibrate the MODIS and SeaWiFS. MOBY broke free from its mooring off Lanai Island on December 18, 2007 and was recovered on Dec 22, 2007. During MOBY’s about 4-day drift at sea, it tracked a cyclonic eddy on the lee side of Lanai. The cyclonic eddy was evident in the satellite remote sensing data: chlorophyll from MODIS, SST from GOES. The time series of satellite-based SST show that the cold-core eddy was likely young in age: for about 9 days it was clearly a distinctive eddy but then it merged with cold waters south of Oahu Island. An increase in chlorophyll concentration within the young cold-core eddy suggests nutrient export from depth to the surface (upwelling at the eddy center), which is vital to the marine primary productivity in this nutrient-deficient water. The dramatic changes in the Lagrangian velocity of MOBY are due to the westward Ekman drift and background geostrophic current. The estimate of its intensity shows it is a strong eddy.

An offline two-level nesting numerical model (ROMS) was applied to simulate the eddy formation and evolution on the lee side of Lanai Island. The high-resolution numerical simulation shows the frequent existence of mesoscale eddy activities on the lee side of Lanai. To detect the eddies in the area, an eddy-detection algorithm based on the velocity field was developed. The statistical result shows that the populations and sizes of cyclonic and anticyclonic eddies are similar, but the lifetimes of cyclonic eddies are longer than those of anticyclonic eddies and the intensities of cyclonic eddies are greater than those of anticyclonic eddies.

The present analysis of the trajectory of the free-drifting MOBY is incorporated with the satellite
observational data. During the lifetime of the observed eddy, there were no other in-situ data available. Looking forward, it may be possible in the future to utilize surface drifter data by applying automated trajectory-tracked eddy detection schemes to detect eddies (e.g., Lankhorst, 2006; Boebel et al., 2006, Lilly and Gascard, 2006), and then assemble satellite data within eddy areas to quantify eddy features and their physical and biogeochemical impacts in the world ocean given that more and more drifters and satellite data are becoming available (Lumpkin and Pazos, 2007).

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Appendix: Eddy Detection and Tracking Algorithm

This appendix briefly describes the algorithm developed for this study to objectively detect and track mesoscale eddies. A more exhaustive and complete description of the method, which was inspired by E-Flux ship-based operations, will be presented in a separate paper by Nencioli et al. (2009).

Velocity fields associated with mesoscale cyclones and anticyclones are characterized by common features, such as a velocity minimum in proximity of their centers, and tangential velocities that increase approximately linearly with distance form the center before reaching a maximum value and then decreasing. Furthermore, due to the rotational nature of the motion, the meridional
or v-component of velocity reverses in sign along an east-west section across an eddy center, and
the westward or u-component reverses in sign along a north-south section. A recent study of a
mesoscale cyclone (Cyclone Opal) sampled in the lee of the Big Island of Hawaii showed that
these features can be successfully used to estimate the location of an eddy’s center (Nencioli et al.,
2008). Using the same concept, in this work we develop an algorithm to detect and track mesoscale
eddies, based on the analysis of surface velocity fields. A series of constraints were derived in con-
formance with the general characteristics associated with the eddy’s velocity field. Eddy centers
are determined after all of the constraints are satisfied.

The algorithm first analyzes the v component. It inspects the data for contiguous points of
opposite sign. Among those, only those for which v is still opposite in sign, but higher in magnitude
two points away (7 km for the present model resolution) eastwards and westwards are considered
indicative of the presence of a mesoscale eddy feature, and retained in the analysis. From the east-
west variation of v, it is possible to determine the sense of rotation: if v changes from negative
to positive (progress from the east towards the west), as the center is crossed, then the rotation is
anticyclonic, whereas if it changes from positive to negative, then it is cyclonic.

For the next step, the algorithm analyzes latitudinal sections of u across the points for which the
constraints on v are satisfied. Similar to the v-component, the value of u has to change in sign
across these points and has to increase in magnitude two points away northwards and southwards.
Moreover the sense of rotation of u has to be compatible with the one of v for the same point.
That is, u has to change from negative to positive (progress from south to north) if the rotation is
anticyclonic, and from positive to negative if it is cyclonic.

Points for which both constraints on v and u are satisfied are expected to be relatively close to the
eddy center. Therefore, for each of those points, the algorithm searches for the velocity minimum
within a searching area of 7 numerical grid points (22.5 km). A second search is then performed,
this time with the searching area centered at the grid point where the first minimum was found.
Points for which the second minimum coincides with the first one are local minima of velocity and, therefore, are assumed to be possible locations of an eddy center.

At these points, the algorithm performs a last control on the velocity distribution along the two 45-degree diagonals with respect to the NS-EW axes (i.e., NW to SE and NE to SW): $u$ and $v$ have to change sign consistently with the sense of rotation already determined, and the velocity magnitude has to increase moving two points away from the center in each direction. If all of these constraints are satisfied, then the point is defined to be the center of a mesoscale eddy.

Once the eddy centers are detected and defined, the size of each eddy are determined by streamlines. Eddy limits are defined as the largest closed streamline around the eddy center. As a further constraint, the velocity magnitude has to increase radially across the closed streamline. This condition is included in order to physically define the eddy boundary as the point at which tangential velocity begins to decrease. The radius of each eddy is then computed as the mean distance between the center of the eddy and the eddy limits using this formalisms.

An eddy is tracked by comparing the position of its center at successive time steps (daily output in this case). The track of a given eddy is updated from time step $t$ to time step $t+1$ by looking for eddy centers of the same type (cyclonic or anticyclonic) within a searching area of 15 numerical grid points (48 km) at $t+1$, centered at the location of the eddy at $t$. If a center cannot be located, then the search is performed at $t+2$, and the searching area increased to 21 grid points (68 km) (this is to prevent the algorithm from recording two distinct eddies, the same eddy was not be detected during a particular day because it is too weak or too asymmetric). If even at $t+2$ no centers are detected, then the eddy is considered dissipated and the track for that specific eddy is closed. Again, the eddy tracking illustrated in Fig. 10 followed this methodology.

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Table 1 Cyclonic and anticyclonic eddy statistics averaged over 3 years of simulation. All eddies with lifetime longer than 4 days were included in the computation. Population is the average number of cyclones and anticyclones inside the area at any given day. The fourth column is the average value of the mean amplitude of the temperature gradient within each eddy. The last three rows are the averages of the maximum anomalies found within the eddies. The anomalies were computed with respect to the spatial mean of the day the eddy was detected.
**FIGURE CAPTIONS**

**Fig. 1** The trajectory of MOBY during the period after it broke free from its mooring and before it was recovered (Dec. 18, 13h 55m - Dec. 22, 3h 3m (GMT)). The blue stars are the GPS locations of MOBY and the red arrows depict the Lagrangian velocities estimated from the distance between two recording times. The color contours indicate the SST average for Dec. 19 and 20, 2007 from GOES data with a resolution of about 5 km.

**Fig. 2** SST time series (unit: °C): Two-day-average from the GOES data.

**Fig. 3** Upper panel: The MODIS chlorophyll concentration (averaged over the period of Dec. 18-24, 2007) at the sea surface during the period when the cyclonic eddy formed and developed. The colorbar is shown with a logarithmic scale and the data in the unit of mgm$^{-3}$. The data are based the MODIS/Aqua 9 km daily data; Lower panel: the SST (also averaged over the period of Dec. 18-24, 2007) from the GOES with resolution of 5 km. The spatial correlation between the chlorophyll concentration and SST is 0.76.

**Fig. 4** The upper-left panel: the black line is the drifting distance of MOBY from the breaking point (black) vs. time, and the red lines are the linear regressions for two periods separated by the red star at the turning point where MOBY drifted from westward to the eastward; The upper-right panel: the black line is the drifting distance projected on the zonal direction vs. the time, and the red lines are the linear regressions for the two periods separated by the red square indicating the turning point; The lower-left panel: the same as the upper-right panel except for the distance projected on the meridional direction and the separated point is marked by the red triangle at the turning point from northward to southward; The lower-right panel is the trajectory of MOBY. The numbers are the slopes of the linear regression lines, which reflect the velocity or speed of MOBY for specified period.

**Fig. 5** Daily-averaged Merged Wind (Zhang *et al.*, 2006) on Dec. 15, when the onset of the cyclonic eddy. The blue vectors is the wind vectors and the wind stress curls are plotted in color.
contours (unit is Pa/100km). Blue crosses are the locations MOBY, black solid line is the transec-
tion across the center of the eddy during the MOBY drifting period. The black circles on the solid
line denoted as wind data points (see Fig. 8). and the red cross indicates the center of the eddy. The
wind direction is about 75.0° (the direction of the wind is coming from in degrees clockwise from
true north according to the meteorological convention). The wind direction persist in this direction
from Dec. 10 to Dec. 26 with the standard deviation of about 5.0°. see Fig. 6.

**Fig: 6** Time series of the daily wind direction (blue) and speed (green) at the point which is the
closest wind data point to the center of the eddy. The wind direction in

**Fig: 7** Stokes drift velocities inferred from the NDBC buoys. Two buoys which are the closest
NDBC buoys providing the wave data are used: 51028 (0.0 °N & 153.913 °W) and 51001 (23.445
°N & 162.279 °W).

**Fig: 8** Time series of the daily wind stress curl along the transect (shown in Fig. 5). The unit
is Pa/100 km. The white line denotes the location of the eddy center during the MOBY drifting
period. On Dec. 15, the positive wind stress curl burst on the northern side of the eddy center.
The wind stress curl remains positive on the northern side of the eddy center after the date 15 of

**Fig: 9** A typical example of cyclonic eddies evident offshore Lanai Island using results from
the ROMS numerical simulation. During the three-year repeated runs, the cyclonic eddies could
appear at different times during the different years. In the upper panels are the surface current and
temperature and in the lower panels are the vertical profiles of the temperature (lower-left) and the
meridional velocity (lower-right).

**Fig: 10** Trajectories of modeled eddies on lee side of the Hawaii Islands in the repeated three
years of ROMS simulation. The modeled current data are sampled daily. Dots denote the eddy
generation sites: red dots indicate anticyclonic eddies and blue dots show cyclonic eddies. The
thin lines are the trajectories of eddies (again red for anticyclonic and blue for cyclonic). The
patterns shows that on the northern (southern) lee flank of the Big Island of Hawaii, there are more cyclonic (anticyclonic) eddies generated. The box of solid black lines is the area where the statistic analysis is applied. On the northern (southern) lee flank of the group of middle islands, there are more cyclonic (anticyclonic) eddies. This is consistent with the argument that there is symmetry in cyclonic and anticyclonic eddy generation on the lee side of an island.
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<table>
<thead>
<tr>
<th>Property</th>
<th>Cyclonic</th>
<th>Anticyclonic</th>
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<td>population</td>
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<tr>
<td>$SST'(\text{oC})$</td>
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<td>0.15</td>
</tr>
<tr>
<td>$SSH'(\text{m})$</td>
<td>-0.094</td>
<td>0.059</td>
</tr>
</tbody>
</table>
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