Author's personal copy

warm-core anti-cyclones that are so often evident downstream of the Hawaiian Islands during persistent trade wind conditions. Note that the wind-stress-curl field and thus distribution of vertical velocities before and during E-Flux II (Figs. 16C and D) is rather featureless. This lack of wind shear, small wind-stress curl, and weak localized upwelling and downwelling velocities supports the argument that eddies are likely produced via the wind forcing mechanism rather than others such as oceanic flow. Calil et al. (2008) have recently done detailed numerical modeling simulations of the ocean response to realistic wind forcing in the lee of the Hawaiian Island chain, which are valuable for improving our understanding of the physical processes reported in our study. Also, Chavanne et al. (2002) did studies of wind forcing and oceanic responses for the Cabo Verde archipelago off the west coast of Africa.

Considerable research concerning island effects on ocean flows and biological processes has been conducted in the region of the Canary Islands (Barton, 2001; Aristegui et al., 1994, 1997; Barton et al., 2000, 2004; Basterretxea et al., 2002). The Canaries are high volcanic islands that are located where strong southwestward trade winds blow. The geophysical setting has several similarities to the Hawaiian Islands. Both the current flow and wind stress gradient mechanisms have been invoked to explain eddies in the wakes of the Canary Islands (Barton, 2001). One complication presented for Canary Island studies is the coastal effect of filaments that can interact with eddies (Barton et al., 2004). Nonetheless, comparative studies of physical and biological phenomena occurring in the Hawaiian, Canary, and Cabo Verde Islands should prove to be quite valuable, especially when model simulations can be done in conjunction with comprehensive field experiments.

5. Summary

The two major eddies that occurred to the west of Hawai'i during the period of May 2004 to April 2005 coincided with periods of strong trade winds. Cyclone *Noah* likely formed to the southwest of the 'Alenuihaha Channel in mid-August, over 2 1/2 months before the first E-Flux field experiment. Cyclone *Noah* appears to have formed shortly after another cold-core cyclone (unnamed) had drifted westward away from the 'Alenuihaha Channel area. Both of these features occurred during prolonged and strong trade wind conditions. The former unnamed eddy appears to have a lifetime of about 4–6 weeks whereas *Noah*, which existed for at least four months, was the longest-lived cyclone observed off Hawai'i during the study year. The E-Flux I field sampling began about three months after Noah's spin-up, indicating that the mature to perhaps decaying phase was observed. The strong currents ($\sim$80 cm s^{-1}) and well-developed doming of isotherms, isopycnals, nutrient isopleths, and chlorophyll *a* isopleths along with outcropping of some of the isopleths in the environs of the center of the eddy all suggest that *Noah* was still a well-developed and active eddy.

Following a hiatus of eddy activity from mid-December 2004 through early February 2005, Cyclone *Opal* appeared almost concurrently with the return of trade winds, which were not as steady as those that produced the first two cyclones of the year. However, there were strong pulses of trade winds during this period that may have reenergized Cyclone *Opal* and possibly contributed to its southward movement (i.e. possibly via induced inertial motions and Ekman transport) as observed in dramatic fashion during the ship-based sampling of E-Flux III. Like Cyclone *Noah*, Cyclone *Opal* displayed impressive upward doming of isotherms, isopycnal surfaces, chlorophyll *a* isopleths, and nutrient isopleths. Both cyclones also displayed inner-core regions of order of 10–30 km radius where chlorophyll *a* was elevated between two isopycnal surfaces. However, Cyclone *Opal* was nearly twice as large as Cyclone *Noah*. Nonetheless, both showed maximum tangential current speeds of about 60 cm s^{-1} in the upper 40 m of the water column. The E-Flux III cruise took place about 4–5 weeks following the spin-up of Cyclone *Opal*, which was very nearly circular, whereas the elliptically shaped Cyclone *Noah* was not observed by our ship-based sampling until about 2 1/2 months after its formation and likely at a later life-stage. Thus, it appears that we observed an earlier phase of evolution of a cyclone during E-Flux III. Other papers in this volume suggest that Cyclone *Opal* was decaying in terms of biological indicators (Brown et al., 2008; Landry et al., 2008a, b; Rii et al., 2008); however, during the cruise the physical parameters were relatively unchanged despite the eddy's relatively rapid southward movement. The lack of movement of Cyclone *Noah* and the rapid southward translation of Cyclone *Opal* are apparently unusual according the statistical analyses of multiple data sets by Lumpkin (1998), who suggested that cyclonic lee eddies typically move westward at near the speed of a first baroclinic mode Rossby wave.

Several strong correlations are evident between physical, chemical, and biological variables within the two cyclones that we studied. For example, isopleths of nutrients and chlorophyll *a* generally lie on isopycnal surfaces. That is, when isopycnal surfaces rise toward the centers of the eddies, so do isopleths of nutrients and chlorophyll *a*. This suggests that physics is controlling the availability of nutrients to the euphotic layer and that phytoplankton can thrive under these optimal conditions. Biological production and grazing rates, described in other papers in this volume (Brown et al., 2008; Landry et al., 2008a, b), certainly are important as well in regulating the concentrations of nutrients and chlorophyll within the eddy.

The estimation of upwelling velocities for eddy features is most difficult because of current technological limitations (i.e., few means are available to directly measure vertical velocities). Estimates based on rates of change of isopycnal surfaces are very problematic because our observations were done from a ship that was not