

showed substantial increases above the euphotic depth whereas nutrient increases above this depth were not apparent in *Noah*. One similar attribute of the two eddies is the distribution of dissolved oxygen within the water column. Both eddies exhibited enhanced dissolved oxygen above the euphotic zone and differential anomalies of negative values just below the subsurface DCML. Negative oxygen anomalies located at similar depths of negative chlorophyll anomalies (below the euphotic zone and positive density core) may be associated with enhanced microbial remineralization processes and zooplankton below the subsurface chlorophyll *a* maximum. The positive oxygen anomalies above the subsurface chlorophyll *a* maximum could be associated with remnants from earlier oxygen increases and phytoplankton productivity prior to hypothesized eddy relaxation (spin-down) phase.

The strongest nutrient enrichment within *Noah* occurs between 250 and 700 m depth (Fig. 7). Moderately enhanced dissolved inorganic macronutrient concentrations above 150 m reaching the euphotic layer (~110 m) supported increases in biological activity as well (Bibby et al., 2008; McAndrew et al., 2008; Rii et al., 2008). Although enhancements of nutrients appear minimal in the euphotic layer, even small increases of nutrients can enable phytoplankton to bloom. The hydrography and ADCP velocity observations correlate well with these results. However, enhancements below 250 m suggest that the physical interior of *Noah* may have affected much greater depths prior to the *in situ* survey conducted during this study. Current velocity and hydrographic measurements did not reveal anomalous doming layers below ~300 m, suggesting that post-relaxation of isopycnal layers does not necessitate reduction of injected nutrients to the upper layer. Seki et al. (2001) describe isothermal doming and enhanced macronutrient signatures between the layers of 200 and 500 m depth during their survey of Cyclones *Mikalele* and *Loretta*, while Nencioli et al. (2008) present upward shifts of isopycnal layers to ~700 m depth during the survey of *Opal*. The combined results suggest that wind-induced cyclonic eddies in Hawai'i have relatively deep physical perturbations reaching depths below 300 m during mature phases with the potential for steady nutrient enhancement effects (Lewis, 2002). *Noah* displayed ~50 m doming of isopycnal layers across a 90–144 km horizontal plane with modest increases in nutrients and phytoplankton. The correlation between the distributions of physical and biogeochemical properties indicates moderate physical–biogeochemical–biological coupling within *Noah*.

A major difference between the two eddies was their translations. *Opal* moved rapidly southward by about 165 km from the beginning of the tracking period to the end of the field survey (approximately 2.5 weeks), whereas *Noah* was relatively stationary during the entire *in situ* survey (Dickey et al., 2008; Nencioli et al., 2008). One hypothesis is that a fast moving eddy system like Cyclone *Opal* could partially distribute initially entrained upper layer biogeochemical–biological processes (open-bottom hypothesis; Nencioli et al., 2008) during migration, while a relatively stationary eddy may exert less lateral exchange below the most dynamic layers of rotation (also see Rii et al., 2008 for alternate hypothesis). The near-stationary position of *Noah* may have significantly influenced the biological and biogeochemical characteristics observed within the eddy. According to the hypothesis proposed by Nencioli et al. (2008), nutrient injections within mesoscale eddies might not be limited to a single injection at the time of an eddy's physical spin-up phase, but rather multiple or continuous injections could take place during an eddy's lifetime. The eddy velocity field and the eddy translation speed are likely two of the main factors controlling nutrient fluxes within mesoscale features. Potential vorticity sections derived from *Noah*'s velocity field are quite similar to the ones observed

for Cyclone *Opal*. However, in the case of *Noah*, contributions of nutrients to the eddy core via lateral exchange of water are most likely limited because of the relatively stationary position of the eddy. This juxtaposition might in part explain the much more moderate phytoplankton bloom, which characterized Cyclone *Noah* relative to that of *Opal* (Rii et al., 2008).

## 5. Summary and conclusions

Surveys of the physical and biogeochemical features of a cold-core cyclonic eddy, *Noah*, were examined using several interdisciplinary observational methods during E-Flux I in an effort to understand the effects of frequently occurring mesoscale eddies that are spawned in the lee of the Hawai'iian archipelago. Our *in situ* observations revealed that vertical shifts of isopleths of physical, chemical and biological properties occurred within the radial distance (with respect to eddy's center) of maximum velocity jets. Vertical contours of the density ( $\sigma_t = 23 \text{ kg m}^{-3}$  isopycnal surface) structure suggest that *Noah* was ~144 km along its estimated major axis. The eddy-induced uplift of isopycnals resulted in relatively minimal enhancements of nutrients and chlorophyll *a* in the euphotic zone. *Noah* was likely nearly elliptical in shape at depths shallower than ~100 m, but nearly circular at greater depths and perhaps in near geostrophic balance. The nearly elliptical shape may result in part from shear effects through flow interaction with the coastline of Hawai'i. Perhaps wind forcing caused a major perturbation of the upper layer as well. In either case, it appears that *Noah* may have begun to physically spin-down with the upper layer shifting away from geostrophic balance. Our investigations of Cyclone *Noah* show that wind-induced upper ocean perturbations that act to spawn cyclonic eddies can cause significant changes to the physical, biogeochemical, and biological structure of the water column. The importance of mesoscale eddies regulating biogeochemical processes in other oligotrophic regions is under continuing debate (McGillicuddy and Robinson, 1997; McGillicuddy et al., 1998, 1999; McNeil et al., 1999). The difference in biogeochemical–biological response between 'pinched' jet-stream generated eddies and wind-stress curl generated Hawaiian lee eddies remains to be fully understood. Of particular future interest are the differences in physical induction parameters that regulate and sustain the doming of isopleths, the resolution of closed-system (encapsulated) eddies versus hypothesized shallow-water quasi-open-bottom system eddies (see Nencioli et al., 2008) and the decoupling of physical–biogeochemical–biological parameters as they relate to eddy life-cycle phases.

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## References

- Allen, C.B., Kanda, J., Laws, E.A., 1996. New production and photosynthetic rates within and outside a cyclonic mesoscale eddy in the North Pacific subtropical gyre. *Deep-Sea Research I* 43, 917–936.