High Resolution Time Series Observations and Modeling of Radiance, Optical Properties, and Physical Processes as Part of RaDyO

Tommy D. Dickey
Ocean Physics Laboratory, Department of Geography
University of California at Santa Barbara
Santa Barbara, CA 93106
phone: (805) 893- 4580 fax: (805) 893-3146 email: tommy.dickey@opl.ucsb.edu

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LONG-TERM GOALS

The overall goal of the University of California Santa Barbara (UCSB) Ocean Physics Laboratory (OPL) Radiance in a Dynamic Ocean (RaDyO) project is to contribute to the understanding and prediction of variations in radiance distributions as they are affected by physical forcing and physical and optical conditions of the surface boundary layer (SBL) and the upper ocean. The purpose of our research is to obtain, analyze, and model time series and vertical profile data; specifically, inherent optical properties (IOPs) and physical variables in the SBL and the upper oceanic layer as forced by atmospheric conditions and as affected by other environmental conditions.

OBJECTIVES

Two major field experiments are being used to accomplish the goals listed above. The first took place in the Santa Barbara Channel in August 2008 and the second in August-September 2009 south of the Big Island of Hawaii. Our specific observational, analytical, and modeling objectives follow:

Santa Barbara Channel Experiment:

1. To obtain time series measurements of IOPs and physical variables at ~30 m depth using a package mounted to the spar hull of R/P FLIP, which served as a “pseudo-mooring” for our observational program. Measurements included: hyperspectral absorption and attenuation coefficients (ac-s) [~90 wavelength] (with inference of hyperspectral total scattering coefficients) and spectral optical backscattering [3 wavelengths] for dissolved matter and particle characteristics, chlorophyll, turbidity, dissolved oxygen, temperature, and conductivity (for salinity). These data are being used for quantifying the temporal variability of key optical and physical variables enabling time series and statistical (i.e., spectral, coherence, etc.) analyses that will be utilized to increase our understanding of relationships among environmental and near- and subsurface optical parameters. These data are being shared with other RaDyO investigators for additional collaborative analytical and modeling efforts.

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2. To obtain vertical profile data, which complement the data set described in 1. above. Specifically, a profiler package was deployed from a long boom (20 m length) mounted on R/P FLIP. The variables sampled were similar to those of our hull-mounted measurement package. The profiler measured the following: hyperspectral absorption and attenuation coefficients (ac-s) [~90 wavelength] (with inference of hyperspectral total scattering coefficients) and spectral optical backscattering [9 wavelengths] for dissolved matter and particle characteristics, chlorophyll, turbidity, near forward angle scattering, temperature and conductivity (for salinity). These data are valuable for quantifying the vertical spatial variability of key optical and physical variables enabling statistical analyses that are being utilized to increase our understanding of relationships among environmental and near- and subsurface optical parameters.

3. To collect and distribute a variety of environmental underway data sets that were collected onboard the stable SWATH vessel R/V Kilo Moana (KM) during the Santa Barbara Channel experiment. The data included: a full suite of meteorological measurements including wind speed and direction, incident solar radiation, relative humidity, air and sea surface temperature, vertical profiles of horizontal components of current data from the KM's ADCP, and CTD data. The CTD was equipped with auxiliary instruments to enable observations of chlorophyll fluorescence, particle beam attenuation or backscattering, angular dependent optical scattering, and dissolved oxygen as well as temperature and salinity data. This is a particularly valuable data set for all RaDyO investigators allowing them to interpret and set the context of their measurements as well as to discern the physical mechanisms that likely influence all optical measurements to a significant degree.

4. To solicit and facilitate collaborations with other relevant investigators who study the oceanography of the Santa Barbara Channel. The point of these collaborations is to maximize the scientific value of our RaDyO data sets and those of regional oceanographers. The collaborators include observationalists, remote sensors, and modelers. Background information on the Santa Barbara Channel field experiment and modeling efforts by RaDyO investigators has been made available to over 20 individuals with several positive responses.

5. To coordinate the Santa Barbara Channel field experiment and to maintain an active website for the program (website: www.opl.ucsb.edu/radyo/). This website provides contact information for investigators, up-to-date project information and notices, detailed field experiment information, meeting agendas, reports, and presentations, guides to data sets, extensive bibliographies for the experiments, publications by investigators, and photographs of experimental operations.

Hawaii Experiment Objectives:

The objectives of the Hawaii experiment are very similar to those of the Santa Barbara Channel experiment. The Hawaii experimental site was selected because of the desire to sample an environment with strong wind forcing and large sea states as well as clear waters. Our group was responsible for the R/V Kilo Moana data collection, particularly the CTD, underway, and ADCP data. Our measurements from R/P FLIP were modified from the previous experiment. For this experiment, no optical profiling measurements were done in the interest of allowing more personnel from other groups to deploy their instrumentation. However, we expanded our "virtual mooring" instrument suite with sensors and systems mounted on the hull of R/P FLIP. These included: temperature sensors at 1, 2, 3, 7, 20, 25, 35, 55, 60, 65, 75, 80, and 85 m; temperature and pressure sensors at 15, 30, 45 and 50 m; temperature and conductivity sensors at 6, 13, 40, and 68.5 m; and temperature, chlorophyll fluorescence, and turbidity sensors at 13, 20, 40, 68.5 m.

We have again coordinated the experiment and worked with several collaborators who have joined in the field effort and brought additional modeling tools to the project. We continue to lead special volume publications and meetings as well.

Questions:

1) What is the statistical nature of the time-dependent underwater radiance distribution within the SBL and upper ocean layer?
2) What are the dominant scales of variability in the underwater optical field and how does the sun's zenith angle (i.e., time of day, latitude), wind and wave conditions, and water's IOPs affect these scales? How do all of these variables correlate?
3) To what degrees do physical (atmospheric and oceanic) and bio-optical processes contribute to the variability in underwater radiance? As a corollary, how can the dominant processes be best parameterized and modeled?
4) How do physical and bio-optical variables statistically relate to each other? For example, what are the various scales of coherence?
5) Which atmospheric and surface wave conditions and IOPs are most important in modeling and predicting variability of underwater radiance and AOPs?
6) How is the underwater light field affected by near surface layering in density (i.e., stratification), optically active materials (i.e., CDOM, phytoplankton, detritus), bubbles, foam, and transient and persistent clouds?
7) How do different bio-optical and physical regimes affect high frequency variability in underwater radiance? For example, in coastal waters: phytoplankton (including red tide) blooms, seasonal and episodic runoff, upwelling, sediment resuspension, shelf-break fronts, coastal jets, hurricanes and storms, internal solitary waves, and Langmuir circulations; in the open ocean: seasonal and episodic phytoplankton blooms (including coccolithophore blooms), mesoscale eddies, Langmuir circulation, wind and dust events, and hurricanes and storms. Longer-term interannual (i.e., ENSO) and decadal (NAO, PDO) variability is also important and must be considered.
8) How can optical, acoustical, and physical data sets best be synthesized to analyze and model variability of the underwater light field?

Hypothesis 1:

Time series of meteorological, physical, and bio-optical mooring data, e.g., winds, solar insolation, incident spectral radiation, temperature, salinity, currents, chlorophyll, IOPs [including $a(\lambda)$, $b(\lambda)$, $c(\lambda)$, $b_b(\lambda)$, volume scattering function (VSF), etc.], and AOPs [including $K_d(\lambda)$, $K_L(\lambda)$, $R(\lambda)$, $R_{rs}(\lambda)$], can be used to produce time series that will allow inferences of dominant time scales of variability and determination, parameterization, and modeling of key environmental processes affecting the distribution of subsurface radiance and image propagation across the air-sea interface.

Hypothesis 2:

Time series of meteorological, physical, and bio-optical mooring data obtained in open ocean and coastal waters can be used to ascertain a limited set of key *in situ* optical and physical measurements and to determine appropriate instrumentation that can be used to efficiently predict underwater radiance and to model image propagation (i.e., imaging above-surface objects from sensors placed beneath the sea surface). This hypothesis is important for operational applications.

APPROACH

Our experimental approach has been to obtain key data sets in relatively benign and high sea state conditions during field experiments in the Santa Barbara Channel and relatively intense atmospheric forcing and wave conditions off the Big Island of Hawaii, respectively. These data are being analyzed according to the procedures listed above, and hypotheses. Prior to both field experiments, preliminary testing of instrumentation was completed using the Scripps Pier in January 2008. Details of this work were presented in previous annual reports.

WORK COMPLETED

The primary work completed within the past two years has involved the RaDyO Santa Barbara Channel (SBC) experiment and the RaDyO Hawaii field experiment. Preliminary results from the SBC experiment were summarized in the previous annual report. Details will appear in an overview paper that is presently in preparation and in several more detailed papers with RaDyO colleagues. Figures describing the results are available on the RaDyO website and in the SBC RaDyO overview paper on request.

Here, we focus on the third and final RaDyO field experiment, which took place south of the Big Island of Hawaii from August 24 through September 15, 2009. This location was selected because of its climatologically higher persistent wind speeds and sea states, its optically clear waters, and its open ocean character with good access to a deep-water port. The specific area of operations, which lies in the North Equatorial Current (NEC), is characterized by relatively modest mesoscale eddy activity and relatively less important island wind and wave shadowing effects (e.g., Dickey et al., 2008). The field experiments are described in more detail below and on the website http://www.opl.ucsb.edu/radyo/

Again, the multi-faceted, multi-scale nature of RaDyO problems necessitated a multiple platform, multi-disciplinary sampling approach. The need for a variety of different sampling platforms equipped with multi-disciplinary sensors and systems has been discussed in detail in several earlier references (e.g., Dickey, 2003, 2009; Dickey and Bidigare, 2005; Dickey et al., 2006, 2009; Chang and Dickey, 2008; Schofield et al., 2008). The primary platforms used for the RaDyO Hawaii experiment included: R/P FLIP, R/V Kilo Moana, and a REMUS AUV. The scales of interest were on the order of a few hundred meter radius of the R/P FLIP and the R/V Kilo Moana, which was positioned nearby the R/P FLIP for the primary sampling period.

Next, we describe the oceanographic conditions in the study area from YD 242 through YD 258 (August 30 – September 15). The R/P FLIP drifts in response to wind and current forcing. The exact proportion of the two mechanisms cannot be directly determined. However, for the present experimental region, the winds and currents historically are generally directed toward the west and R/P

FLIP's drift followed a westward course as expected (Figure 1).   Remotely sensed sea surface temperature and color imagery (Figure 1) were used to set the spatial context of the observations. R/P FILIP drifted westward into somewhat warmer surface waters which appear to have also been somewhat more elevated in chlorophyll concentrations.

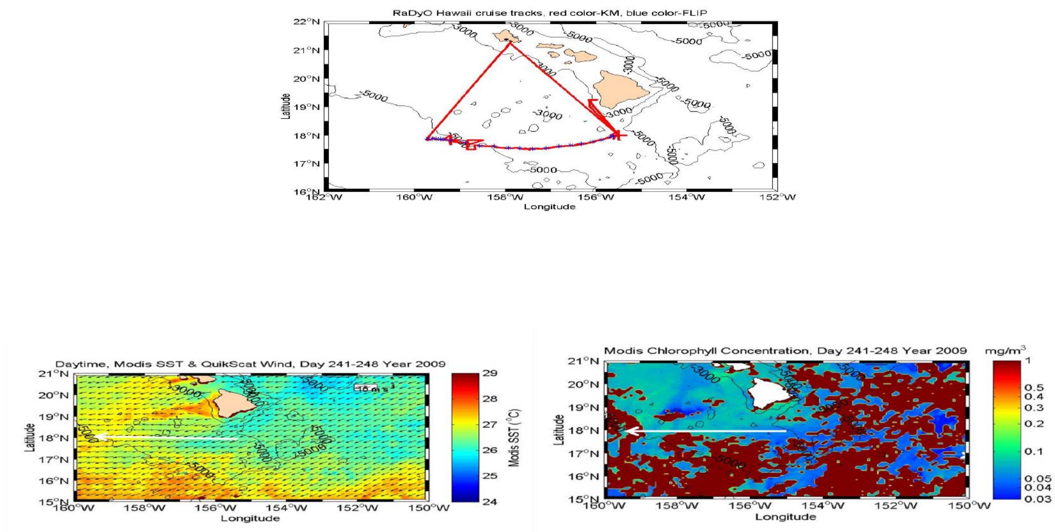

Figure 1.   Left. Map showing the drift path of R/P FLIP during the Hawaii RaDyO experiment. R/V Kilo Moana remained near R/P FLIP once R/P FLIP was flipped at the designated experimental starting location. Center. MODIS sea surface temperature map with Quikscat wind vectors during the Hawaii RaDyO experiment. Right. MODIS chlorophyll map during the Hawaii RaDyO experiment. Images were processed by Songnian Jiang. The white arrows in the right two images indicate the approximate path of R/P FLIP's drift.

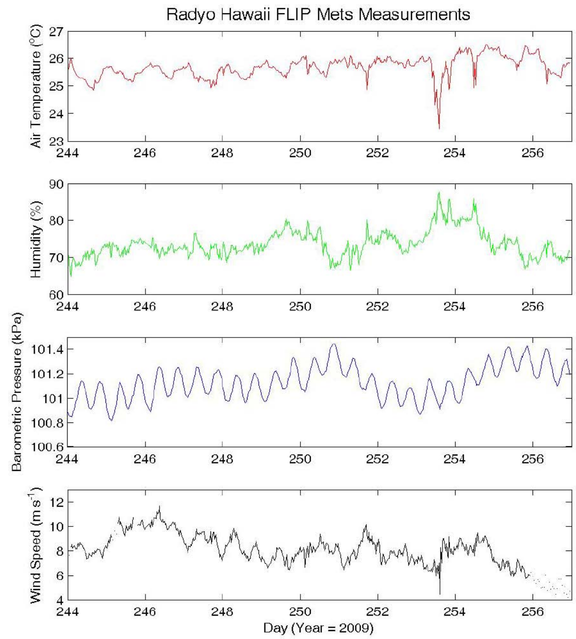

Figure 2. Time series of R/P FLIP meteorological data (provided by Ken Melville and Luc Lenain).

Meteorological time series collected from the drifting R/P FLIP are illustrated in Figure 2. R/V Kilo Moana meteorological data are very similar to these. Note that the R/V Kilo Moana are somewhat longer than those of R/P FLIP since it needed to be flipped and its booms had to be deployed. The wind speeds were greatest during the first part of the experiment and sporadically decreased after peak winds of approximately YD 246. Somewhat surprisingly, these winds were quite comparable to those observed during the SBC RaDyO experiment a year earlier. However, the sea state was greater in Hawaiian waters.

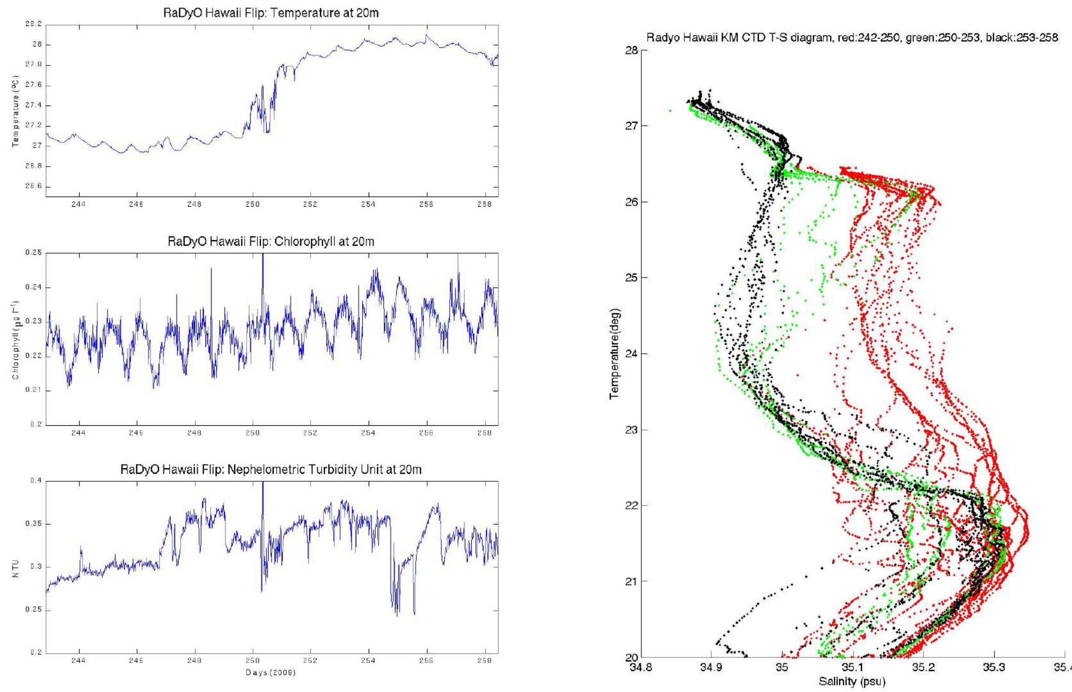

Figure 3. Left. Time series of data for temperature, chlorophyll and turbidity collected from a UCSB package mounted at 20-m depth on R/P FLIP during the Hawaii RaDyO experiment. Right. T-S diagram for depths of 0-200 m. Red color data points for YD 242-250, green data points for YD 250-253, and black YD 253-258.

Data collected from a 20-m UCSB instrument package are displayed in Figure 3. These data suggest that R/P FLIP drifted into warmer waters with higher biomass. The T-S diagram (0-200 m) diagram provides some insights into the differing water masses that R/P FLIP drifted through. Nonetheless, it needs to be mentioned that the wind speeds were declining so that some of the physical and bio-optical changes may be attributable to local as well as spatial effects.

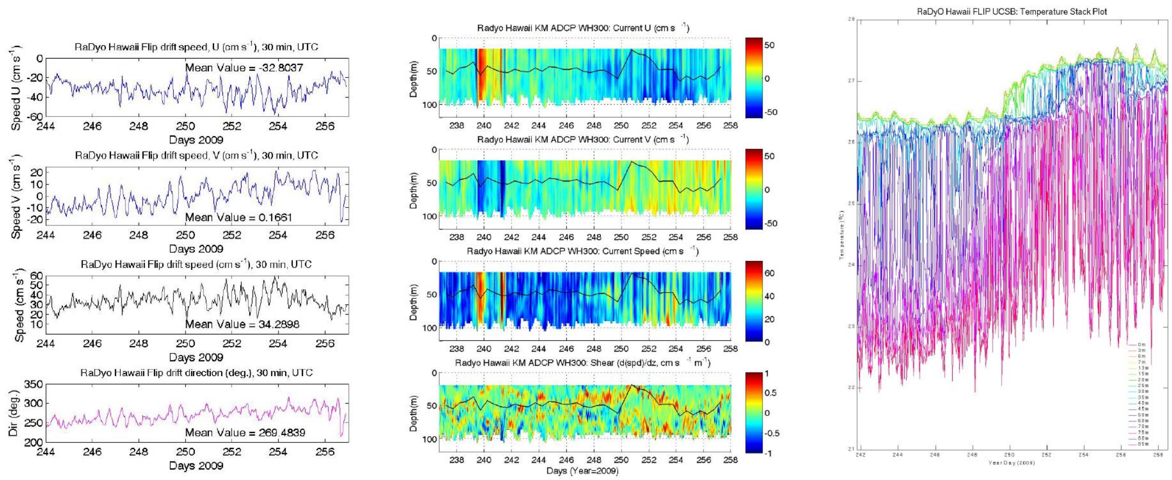

Figure 4. Left. Time series of motion of R/P FLIP during the Hawaii RaDyO experiment. Center. Time series of temperature (from R/P FLIP) from the surface to 85 m. The black curve indicates the mixed layer depth. Right. Time-depth contour plots of currents and vertical shears relative to the drifting R/P FLIP. temperature, salinity, σ_t, and stratification using data collected with the R/V Kilo Moana and MASCOT CTDs. Depth of the mixed layer based on a 0.5^0C criterion is also displayed in white curves. These panels cover 0-70 m depths.

Time series of the drift velocities of R/P FLIP are shown in Figure 4. These data are interesting and show that the drift was predominantly to the west. However, semi-diurnal tidal effects appear to modulate the motion. The subsurface currents shown in the center panel of Figure 4 are intertpreted as being relative to the vessels. The first few days of the time series in the upper 100 m show modest currents relative to the R/V Kilo Moana and R/P FLIP, generally directed eastward with some rotation, likely due to semi-diurnal tides. A strengthening of westward-northwestward currents appears to be correlated with the onset of relatively strong winds around YD 246. From this point forward, the deeper current time series indicate a propagation of energy deeper into the ocean, some of which is likely near the inertial period of 39.3 h. The currents measured during our experiment are consistent with those reported by other investigators and with those simulated using various numerical models. The most interesting aspect is the shift in our currents about mid-way through the experiment, which may result from a combination of decreased wind forcing and movement of our platforms into a different water mass with a differing current regime. The right panel of Figure 4 shows high vertical resolution time series temperature data in the upper 70 m. A near surface diurnal signal is apparent, however the most striking feature is the increase in sea surface temperature and stratification about midway in the time series. These subsurface observations are consistent with the spatial pattern of east to west trending increases in sea surface temperature displayed in the satellite data of Figure 1 as well as decreased wind forcing noted earlier.

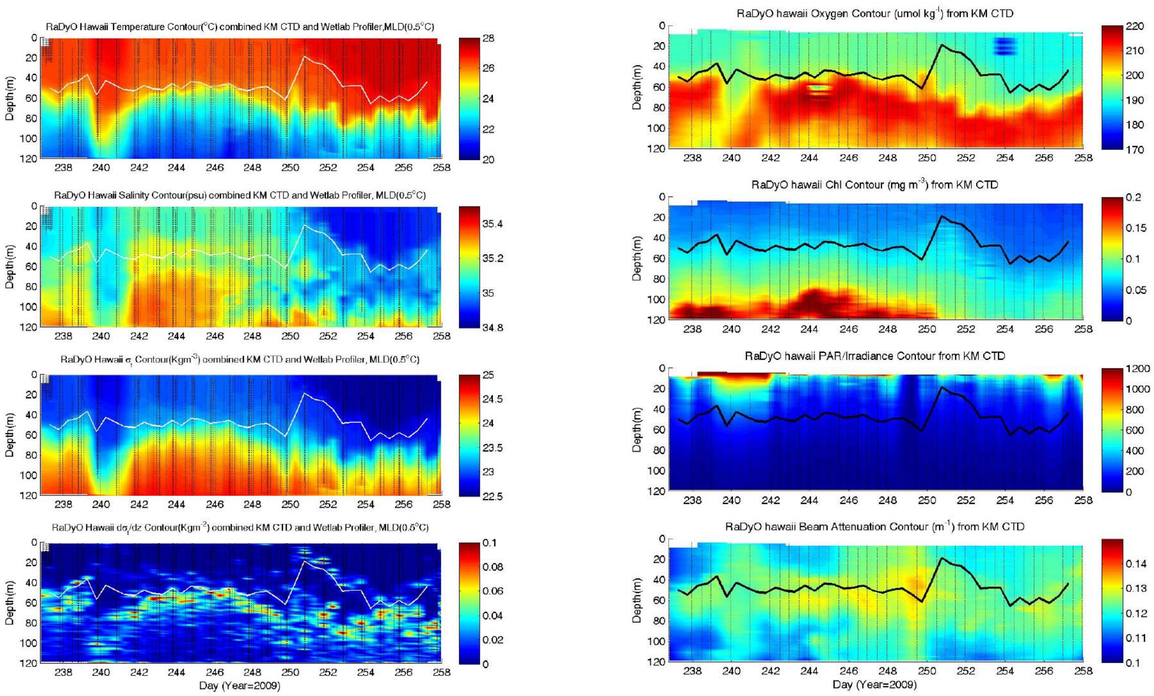

Figure 5. Left. Time-depth contour plots of physical variables during the Hawaii RaDyO experiment. Right. Dissolved oxygen and optical time-depth contour plots during the Hawaii RaDyO experiment. The time-depth contour plots were derived from merged MASCOT (Twardowski et al.) and R/V Kilo Moana CTD package data. The white curves on the left and black curves on the right indicate the mixed layer depth.

Finally, the physical and optical time-depth contour data sets are displayed in Figure 5. The general westward or temporal trends toward warmer waters following a possible wind event early in the time series of the upper 80 m are consistent with the reduced wind forcing and drift into a warmer, less saline water mass. A subsurface beam attenuation (proxy for particles) layer is apparent and it appears to show greatest concentrations toward the mid-portions of the time series and to hover around the base of the mixed layer. A deeper chlorophyll maximum layer is also apparent and deepens significantly toward the latter third of the time series and even nearly disappears around YD 252 (this is more evident in the 0-500 plots not shown here). The decreases in both beam attenuation coefficient and chlorophyll concentration near the end of the sampling period is curious and not readily explained. However, because of the depths involved and lack of appreciable wind forcing variations, water masses appear to be important.

Although analyses of the comprehensive Hawaii data sets are still underway and incomplete, it appears that we now have two very interesting data sets that will be valuable for gaining new insights and for modeling the coupling of near and upper ocean physical and optical processes.

IMPACT/APPLICATIONS

Impacts of our RaDyO efforts are expected to include better understanding and prediction of time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes, construction of a radiance-based SBL model, validation of the model with field observations, and investigation of the feasibility of inverting the model to yield SBL conditions. These activities bear on understanding and predicting impacts of SBL processes and ocean biogeochemistry and ecology on the underwater light field and imaging, and thus operational problems involving naval operations. The feasibility of construction of ocean surface estimates using underwater camera data will be resolved.

TRANSITIONS

We anticipate that major transitions of will occur in the form of testing and commercialization of new sensors by RaDyO collaborators (e.g., MASCOT). We expect that the RaDyO project will accelerate interdisciplinary ocean measurement technology capabilities by 1) increasing the variety of variables which can be measured autonomously, and 2) improving the robustness and reliability of interdisciplinary sampling systems. In addition, this work will enable development of more accurate and robust numerical models of the ocean environment, which will include optical as well as physical components.

RELATED PROJECTS

There were several projects taking place in the Santa Barbara Channel that relate the RaDyO program. Spatial surface current data (using CODAR) were collected by Libe Washburn's UCSB group (http://www.icess.ucsb.edu/iog/realtime/index.php) and will be useful for characterizing major current features and passages of sub-mesoscale features and eddies; ship-based bio-optical data collected by the Plumes and Blooms Program (Dave Siegel, lead-PI; http://www.icess.ucsb.edu/PnB/PnB.html) will facilitate interpretation of the RaDyO bio-optical data; surface hydrocarbon slicks and slick dynamics are being investigated (Ira Leifer and Jordan Clark, PIs; http://www.bubbleology.com/). Satellite sea surface temperature and ocean color data were collected by our group, Dave Siegel's group and Ben Holt (Jet Propulsion Laboratory, JPL) collected synthetic aperture radar (SAR) data. These remote sensing data sets along with others provide spatial context. By combining and synthesizing these data sets with ours, we will be able to describe and quantify the three-dimensional evolution of several key water quality parameters on time scales of a day to the interannual.

PUBLICATIONS

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HONORS/AWARDS/PRIZES

Professor Dickey was named Outstanding Professor by University of California Santa Barbara Residence Hall Association and Office of Residential Life (2009).