

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

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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 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 is currently underway (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.

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 is responsible for the R/V Kilo Moana's data sets, particularly the CTD, underway, and ADCP data sets as described above. Our measurements from R/P FLIP were modified from the previous experiment. For this experiment, no optical profiling measurements are being done in the interest of allowing more personnel from other groups to deploy their instrumentation. However, we have expanded our "virtual mooring" instrument suite with sensors and systems mounted on the hull of R/P FLIP. These include:

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 are again coordinating the experiment and working with several collaborators who are joining in the field effort and bringing additional modeling tools to the project. We will lead future 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 is to obtain key data sets in relatively benign and high sea state conditions during field experiments in the Santa Barbara Channel and off the Big Island of Hawaii, respectively, as outlined above. These data will be analyzed according to the procedures listed above and hypotheses, also given above, will be tested. Prior to the field experiments, preliminary testing of instrumentation was completed using the Scripps Pier in January 2008. Details of this work were presented last year's report.

WORK COMPLETED

The primary work completed within the past year involves the RaDyO Santa Barbara Channel (SBC) experiment and preparations for the RaDyO Hawaii field experiment. Some of the results from the SBC experiment are briefly summarized next. Details will appear in an overview paper that is presently in preparation and 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.

The R/V Kilo Moana's underway data were collected from the time of departure from Port Hueneme, CA harbor on the morning of September 4 until its return there on the morning of September 22, 2008. The CTD data were collected to approximately full water column depth (~150-160 m) and were used on site for identifying features including the depths of the mixed layer, deep chlorophyll maximum layer, and particle maximum. The CTD measurement operations were conducted from September 9 through September 22 and were made primarily around mid-day and at night when specialized optical profiling systems were not being deployed. Vertical profiles of currents were provided by the R/V Kilo Moana's 38 kHz and 300 KHz ADCP systems (RDI) whose transducers were mounted at 8 m depth. The 38 KHz system obtained data from about 10 m to the ocean floor for our study and the 300 KHz system obtained data from about 10 m to about 100 m. Data were recorded as 5-min averages and vertical binning of the data was accomplished after the cruise. Both systems collected data from the time of the R/V Kilo Moana's departure from Port Hueneme until its return as indicated earlier.

R/P FLIP, which was moored for this experiment, was used to collect data from September 11 until September 22, 2008 at 34 12.3⁰N, 119 37.7⁰W. For reference, R/V Kilo Moana sampled on station about 2 km north of R/P FLIP except during evening treks away from the site to discharge its tanks. The Bluefin and REMUS AUVs conducted their mapping surveys between R/P FLIP and R/V Kilo Moana as well as in their vicinities. Measurement systems deployed from the R/V Kilo Moana and R/P FLIP during the RaDyO Santa Barbara Channel experiment are described in detail on the RaDyO website and in the overview paper.

The wind patterns during September 2008 were quite regular and persistently directed toward the southeast along the California coast and thus almost always oceanographically upwelling favorable based on QuikScat satellite wind stress data shown for the coastal central and southern California region (31-37⁰N, 116-122⁰W) for the periods of September 6-12 (YD 249-256), September 13- 20 (YD 257-264), and September 21-28 (YD 265-272). This wind set up over the region is caused by

relatively high atmospheric pressure (anticyclone) in the eastern North Pacific and relatively low (thermal) pressure over the southwest U.S. in the late summer and early autumn. The synoptic-scale variability (scales of days) is attributable to strengthening and weakening as well as some movement of the off coast high pressure system and the continental (southwestern U.S.) low pressure system. No major low pressure systems passed through the site, which is consistent with seasonal climatology. To summarize the meteorological conditions, three fairly well-defined periods of mid- to high- to low-wind speeds occurred during the experiment with average wind speeds for September 8-16 (YD 252-260) of 4.9 m/sec, for September 16-20 (YD 260-264) of 7.6 m/sec, and for September 20-24 (YD 264-268) of 3.7 m/sec. These three periods, which likely resulted from the strengthening and weakening of the relative atmospheric pressure systems over the Pacific and southwest U.S., suggest inspection of the oceanographic responses according to the three periods. The greatest wind speeds for the study occurred during the afternoon of September 16 (YD 260). The diurnal variations reached values of 5 to 10 m/sec with peak winds typically occurring in the early afternoons.

The surface current flow pattern for the period of September 8-17 (YD 252-260) is typified by an eddy centered near the deepest portion of the SBC. The eddy extended nearly across the Channel (over 20 km north-south and east-west). Eastward flow was seen north of Santa Rosa and Santa Cruz Islands. The surface currents at the RaDyO site were generally rather weak during this period, but appeared to be directed generally toward the east. On September 8 and 9 (YD 252-253), the surface current at the site was toward the southeast and did not appear to be strongly connected with the eddy or island current. The flow was toward the east September 10-13 (254-257), toward the south or southeast on September 14 (258), and near zero on September 15 and 16 (259-260). The greatest wind forcing for the experiment occurred during the next period (September 17-20; YD 261-264). The eddy over the proximate center of the basin (somewhat to the west of the geographic center) remained during the period; however, the flow to the north of Santa Rosa and Santa Cruz Islands intensified and importantly appeared to extend eastward affecting the current conditions at the RaDyO study site. In addition, surface flow exited the east end of the SBC. At the RaDyO site, currents appeared to be related to the strong island current suggesting possible advection of materials from well to the west. The direction of the surface currents at the site were toward the north-northeast on September 17 (YD 261), the northeast on September 18 (YD 262), the southeast on September 19 (YD 263), and were near zero on September 20 (YD 264).

The final period of the experiment, September 20-24 (YD 264-268) was marked by the weakest wind forcing. The surface current patterns suggested a transitional flow regime as the strong basin-scale eddy lost its definition and flow changed direction from eastward to westward through the east end of the SBC. Inspection of the sequence of current images suggested the possibility of a submesoscale eddy developing and propagating westward in the eastern portion of the Channel. Perhaps because of the transitory surface currents, the direction of currents at the RaDyO site were highly variable: near zero on September 21 (YD 265), for the second day, strong toward the north on September 22 (YD 266), strong toward the north-northeast on September 23 (YD 267), and finally switching toward the south on September 24 (YD 268).

The time series of ADCP currents (Figure 1) show strong semi-diurnal and diurnal tidal (and perhaps wind-forced) signals (roughly 10-20 cm/sec in amplitude). Because of the apparent three wind regimes, average currents were computed for the periods of September 8-17 (moderate winds averaging 4.9 m/sec; YD 252-260), September 17-20 (strongest winds averaging 7.6 m/sec; YD 260-264), and September 20-24 (weakest winds averaging 3.7 m/sec). The respective average currents at 17 m were 11.3 cm/sec directed toward the west-northwest at 311° , 18.0 cm/sec directed northward at 2° , and 19.7 cm/sec directed northwestward at 344° . It should also be noted that there is little correlation between the HF radar determined surface currents and the 17-m ADCP currents.

The currents at the RaDyO site were relatively weak as the site lay to the east of the dominant cyclonic flow. However, toward the end of the experiment there was a strengthening of currents that may have resulted from the extension of the eastward current lying to the north of the islands. Another possibility is that the strong winds occurring around September 17 (YD 260) may have been important. Finally, the strong diurnal (land-sea breeze) forcing and tides played roles in the current variability at the site as well. The site of RaDyO ($34^{\circ} 13'N$, $119^{\circ} 37'W$), which lay in the eastern portion of the SBC, appears to have been in a relatively quiescent location with subsurface currents directed roughly northwestward through about September 17 (YD 260) and possibly more influenced by local forcing. However, after this date, currents picked up at about the same time that local peak daily winds roughly doubled.

The upper layer temperatures were relatively warm (Figure 1) and the mixed layer depth was around 15 m through about September 17 (YD 260). There is diurnal variation in the MLD as forced by the combination of the daily solar cycle and a strong land-sea breeze signal. The thermocline extends downward from the base of the mixed layer by about 15-20 m for the first period of wind forcing. The strong winds initiated around September 17 (YD 260) appear to have resulted in deepening of the mixed layer to about 25 m, cooling of the surface layer waters, and sharpening of the thermocline and pycnocline for about 2 days after which the mixed layer shoaled to values of ~ 10 m, even less than those observed at the beginning of the experiment.

Time series of temperature and salinity collected at 8 m depth from the R/V Kilo Moana's underway system and from a package mounted at 30 m depth on R/P FLIP show that 8-m temperature remained fairly constant until around September 15 or 16 (YD 258 or 259) and then decreased (by over $1^{\circ}C$) for about 4-6 days as the winds increased dramatically and the mixed layer deepened by about 10 m. At approximately the same time, the temperature record from the 30-m R/P FLIP package showed an increase of up to $4^{\circ}C$. This surface decrease in temperature and the concurrent subsurface increase is consistent with mixing and entrainment of waters from below and mixing of warmer waters to depth. After this point (about September 20, YD 264), the temperatures at 8 and 30 m remained roughly constant on average, but with continuing diurnal oscillations. The salinity at 8 and 30 m generally tracked the temperature variability. Density is largely controlled by the temperature variability; however the subsurface salinity minimum zone does reduce the stratification from roughly the mixed layer depth down to about 60 m.

Time series of dissolved oxygen versus depth (Figure 1) show that it was relatively uniform in the upper 40-65 m with some influence by the increased winds during the period of September 17-20 (YD 260-264). The maximum vertical gradient in dissolved oxygen lags that of the MLD by about 1 day. The chlorophyll maximum generally resided near the mixed layer, but there are some significant

departures. The most impressive feature occurs between depths of about 10 and 40 m around September 20-22 (YD 264-266). The origin of this high chlorophyll event is not certain. It is possible that it may result from advection as there was a change in current patterns around this time. However, another possibility is that the prior wind event may have been sufficient to entrain some of the subsurface chlorophyll maximum waters and higher nutrient waters from depth and thus stimulated a phytoplankton bloom with a time lag of a couple of days being plausible.

The beam attenuation coefficient data (Figure 1) show higher levels within and just below the mixed layer and falling off in values quickly below for the first two periods of the experiment. However, beam attenuation coefficient shows similar changes as those noted for chlorophyll (Figure 1) around September 20-22 (YD 264-266). In this case, the beam attenuation coefficient maximum lies very near the base of the MLD whereas the chlorophyll maximum was deeper by about 10 m. Whether this feature was caused locally or resulted from advection will be explored using general circulation models.

The forcing and responses discussed here (depicted in Figure 1) may be explained primarily by local forcing; however, as noted above, there may be some influence from a change in current patterns. This question will be addressed using a physical numerical model, which should allow us to partition the observed physical variability between local and advective effects.

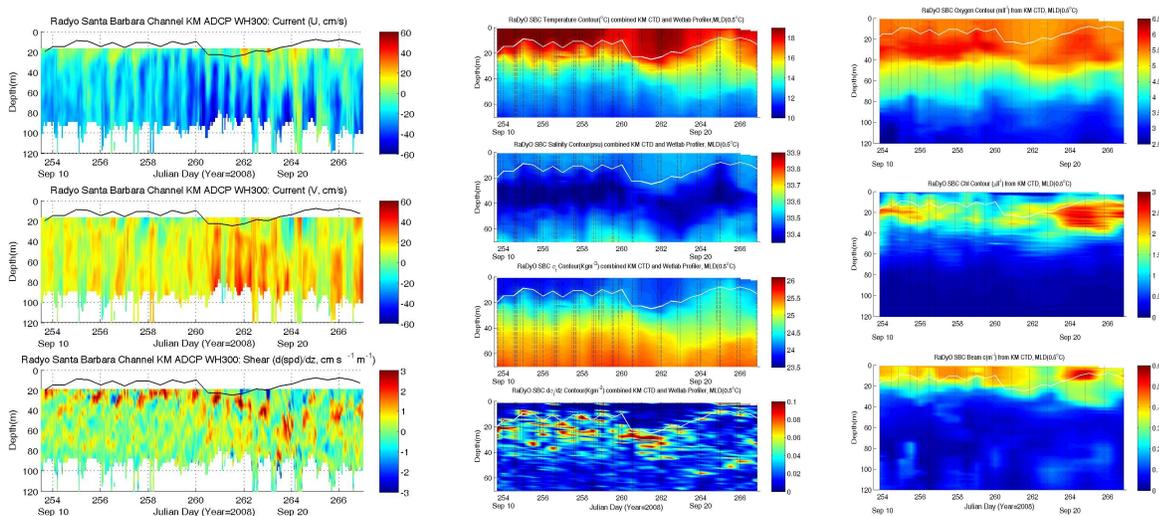


Figure 1. Depth-time contour plots of data collected during the RaDyO Santa Barbara Channel field experiment in August 2008. Three wind forcing regimes were apparent. The second period (about halfway through the observational period) with strong winds resulted in deepening of the mixed layer, increased currents, and modification of the vertical structure of dissolved oxygen and optical properties.

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

The RaDyO program is still in the early field stages, therefore there are no transitions yet. However, we anticipate that major transitions 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.icesb.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.icesb.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

Dickey, T., M.-C. Alboussiere, M. Banner, P. Bhandari, T. Boyd, L. Carvalho, G. Chang, Y. Chao, M. Cimono, H. Czerski, M. Darecki, C. Dong, D. Farmer, E. Firing, S. Freeman, J. Gemmrich, N. Hall-Patch, B. Holt, J. Hummon, J. Jaffe, S. Jiang, C. Jones, G. Kattawar, L. Lenain, M. Lewis, Y. Liu, L. Logan, D. Manov, K. Melville, M. Moline, R. Morison, F. Nencioli, S. Pegau, B. Reineman, I. Robbins, R. Roettgers, H. Schultz, D. Siegel, L. Shen, M. Shinki, M. Slivkoff, M. Sokolski, P. Sutherland, F. Spada, N. Statom, D. Stramski, M. Twardowski, S. Vagle, R. Van Dommelen, K. Voss, L. Washburn, J. Wei, H. Wijesekera, O. Wurl, S. Yildiz, Y. You, D. Yue, R. Zaneveld, and C. Zappa, An introduction to the Radiance in a Dynamic Ocean (RaDyO) Santa Barbara field experiment: Physical and optical setting, to be submitted to *Journal of Geophysical Research*.

HONORS/AWARDS/PRIZES

Professor Dickey was named a Secretary of the Navy/Chief of Naval Operations Chair in Oceanography in 2008.

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