Interdisciplinary Applications of Autonomous Observation Systems

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LONG-TERM GOALS

Our long-term goal is to develop improved autonomous observation systems and analytical capabilities for describing the distributions and activities of marine microbes in relation to their physical, chemical and optical environment in support of multidisciplinary, data-assimilating predictive models of optical and biological processes in the world ocean.

OBJECTIVES

Our primary objectives are:

- To develop and test new interdisciplinary sensor arrays on a variety of *in situ* platforms to describe biological variability in relation to the optical, physical and chemical environment of the ocean; and

- To use data from these sensor systems in multidisciplinary models of physically and chemically driven ocean biology.

APPROACH

Data from deployments of coastal ocean observatories and research cruises are used to develop and evaluate models and bio-optical algorithms for estimating optical and biological properties of surface waters using measurements from a variety of optical instruments. An extensive program of sampling

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from research vessels at our coastal observatories provides a large set of data for development and validation of bio-optical models for case 2 waters.

Several of our bio-optical analyses utilize chlorophyll fluorescence — sun-induced, or stimulated by a variety of fluorometers — to describe variability in the biomass or physiological status of phytoplankton. Consequently, we study the environmental influences on chlorophyll fluorescence in controlled laboratory experiments using different taxonomic groups of phytoplankton. The research employs Satlantic's Fluorescence Induction and Relaxation (FIRe) fluorometer as well as other commercially available fluorometers. We are also working on reconciling spatial and temporal patterns in sun-induced fluorescence yield (assessable from space) with patterns of relative fluorescence yield detected with fluorometers at the surface and in the ocean interior. The objective is to link assessments of phytoplankton physiology from space to autonomous measurements from instruments such as ocean gliders, and the physical/biological interactions that they describe.

More broadly, we are working within our own research group and with others in the ocean-observation community to develop effective new ways to make ocean observatory data easily accessible to a broad range of users and to explore new technologies for ocean monitoring.
This work is closely coordinated with the NSERC/Satlantic Industrial Research Chair in Environmental Observation Technology, a partnership between John Cullen (the Chair), Dalhousie University and Satlantic. The Research Chair facilitates a broad range of collaborative research, including coastal observatories in Nova Scotia (see "Related Projects"). This ONR project provides funding for additional support from Satlantic which complements Dalhousie-based efforts.

WORK COMPLETED

Ecosystem modeling supported by data from a coastal observatory. Three moored buoys with interdisciplinary sensor suites were deployed from 2002 - 2007 in Lunenburg Bay (except during winter haul-out and some interruptions), providing real time data supported by nearly weekly sampling for ground-truth data. Graduate student Arnaud Laurent has analyzed the data — including bio-optical assessments of phytoplankton dynamics — with statistical approaches, and he has also modeled the system using a box-model approach and detailed simulations with a nested implementation of the Regional Ocean Modeling System (ROMS). A complete draft of his thesis is in revision. Guided by Katja Fennel and John Cullen, graduate student Diego Ibarra used ROMS in the development of a hybrid modeling framework with an individual-based model for macrobiota embedded in a tracer-based model for plankton dynamics. The modeling system has potential for predicting effects of fixed macrobiota on optical properties of coastal waters.

Redeployment of an optical mooring. As part of a project coordinated by Susanne Craig, the Bedford Basin Ocean Monitoring Buoy (BBOMB) was refurbished and enhanced, then deployed in Bedford Basin, Nova Scotia, in partnership with the Bedford Basin Plankton Monitoring Program, a nearly-20-year time series, conducted by Dr.W.K.W. Li of the Bedford Institute of Oceanography. Comprehensive weekly sampling included bio-optical profiling and collection of samples for ground-truthing. The buoy operated from October 2009 through April 2011, when it taken out of the water for servicing (bbomb.ceotr.ca).

Retrieval of physiological information using measurements from conventional fluorometers. Adam Comeau completed his M.Sc. thesis, analyzing data from conventional fluorometers deployed on commonly used oceanographic profiling systems and novel systems (SeaHorse autonomous profiler

and Satlantic's LOBO observatory) to retrieve estimates of the irradiance at which fluorescence yield of phytoplankton in a light gradient is maximal — a useful measure of photosynthetic physiology. He related his metric of photosynthetic physiology quantitatively to the saturation irradiance for photosynthesis, measured in our laboratory by Audrey Barnett.

Direct modeling of biological-optical dynamics. Based on a fairly thorough review of the foundations of bio-optical oceanography and ecosystem modeling (Cullen and Fennel 2009, Cullen and Lewis 2010, Cullen 2010), we successfully developed an initial framework for simulating the dynamics of phytoplankton using mechanistically realistic descriptions of light absorption, photosynthesis, acclimation of phytoplankton to irradiance, and growth (Cullen and Fennel 2010). Notably, the model is not based on chlorophyll, the flawed proxy of phytoplankton biomass and light absorption.

Spectral model of photosynthesis. With Yannick Huot and Richard Davis, Cullen described a spectral model of depth-integrated water column photosynthesis and its inhibition by ultraviolet radiation, including its application in assessing the influences of solar irradiance and variations in spectral water transparency on global primary production (Cullen et al. 2010). Previous models of this type could not assess effects of ultraviolet radiation and were inherently incapable of directly predicting effects of variations in spectral attenuation (water color).

Ocean fertilization. Cullen served on the Canadian Science Advisory Secretariat Panel that produced a Science Advisory Report: "Ocean Fertilization: Mitigating Environmental Impacts of Future Scientific Research." The report should contribute to Canadian and international policy development.

RESULTS

A study of an extensive set of optical and ground-truth data from the Bedford Basin Ocean Monitoring Buoy showed that a rather simple Empirical Orthogonal Function (EOF) analysis of hyperspectral upwelling radiance measurements provided an excellent basis for predicting both the concentration of chlorophyll *a* and the contribution of phytoplankton to the absorption coefficient (Craig et al., 2010; Fig. 1). The initial application is to relate continuous measurements of ocean color to the variability of phytoplankton in Bedford Basin. Additional analyses and measurements will evaluate the temporal stability of the algorithms and approaches for regional application in remote sensing.

Successful implementation of the buoy program during 2009 - 2010, including winter months, has led to a strengthened interest in collaborative research on optical, physical, chemical and biological variability in Bedford Basin. The collaboration between Dalhousie, the Bedford Institute of Oceanography, and Satlantic has expanded to include Canadian, American and German researchers in microbial genomics; we have begun sampling to describe molecular ecology in relation to the physical, chemical and optical environment.

Our absorption-based model for primary production and the dynamics of phytoplankton (Cullen and Fennel, 2010) departs from previous plankton modeling systems by eliminating chlorophyll *a* as a variable. Presentation of this approach generated a great deal of interest and numerous comments — not all in agreement — at the Ocean Optics XX meeting in September, 2010. It is very likely that the approach will stimulate further refinements of bio-optical modeling as researchers adopt the new path or defend their decisions to stay with other approaches.

In support of our mechanistic approach to optically based modeling, Adam Comeau showed through rigorous statistical analysis that his method for retrieving a photoacclimation parameter from measurements of stimulated fluorescence could be applied to records from vertical profilers and long-term moorings. If follows that the approach can be used with ocean gliders, and we will be doing that soon.

IMPACT/APPLICATIONS

Our research is converging toward the development of an integrated system for using optically-based ocean observation assets — in particular, moorings, ocean gliders and satellite sensors — to guide multidisciplinary prediction of physical, biological and optical variability in surface layers of the ocean. We know that absorption-based modeling of phytoplankton dynamics has been an aspiration of oceanographers for decades; now we are on the verge of implementing it. In turn, our method for retrieving quantitative information about the physiology of phytoplankton from fluorometers on gliders is ready to go. Simple analyses of hyperspectral radiometry should support the assessment of biological variability from space. A significant impact on the science and systems applications of marine environmental prediction is highly likely. Progress will be rapid if the research is supported directly, but the impacts will be felt nonetheless.

RELATED PROJECTS

1) NSERC/Satlantic Industrial Research Chair: this partnership is the focus of support for Cullen's research activities. Funding for complementary projects, such as this ONR program, are highly leveraged by the research partnership and associated grants. This project (as well as NSERC Research Tools and Instruments) provides much of the support for the Bedford Basin Ocean Monitoring Buoy program (bbomb.ceotr.ca).

2) Ocean Tracking Network (oceantrackingnetwork.org): This project is supporting the purchase of ocean gliders, their deployment on the Scotian Shelf, the analysis of optical data and modeling, but not the specific innovations supported by ONR and NSERC.

3) A research project funded by Cellana BV is aimed at screening strains of microalgae for their potential to produce next-generation biofuels and protein. The project provides funds for optically based modeling, supporting some conceptual developments, and it leverages fundamental research on fluorescence.

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PUBLICATIONS

The following manuscripts resulted in full or in part from this contract:

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HONORS/AWARDS/PRIZES

Lewis was awarded Fellow of The Oceanography Society in February, 2010.

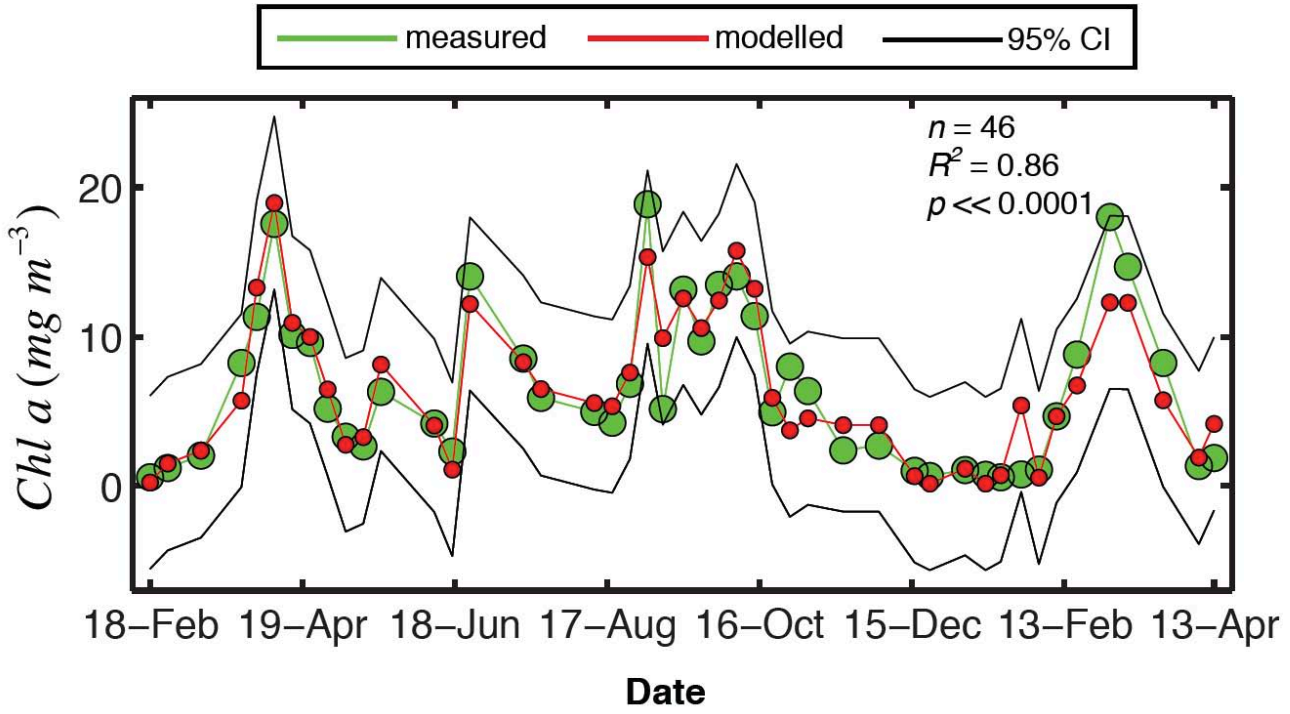

Figure 1. Comparison of a measured concentration of chlorophyll α at 1 m (green circles) vs. estimates from a multiple linear regression model to predict chlorophyll as a function of the first three empirical orthogonal functions (EOFs) of hyperspectral upwelling radiance spectra at 1 m from weekly sampling in Bedford Basin, Nova Scotia from February 2009 – April 2010. Black lines are the 95% confidence intervals on the estimates.

[Graph: The measured concentration of chlorophyll varies from less than 1 mg m^{-3} in the winter to about 20 mg m^{-3} during blooms in the spring and fall. Modeled results from nearly weekly sampling are similar: for 46 comparisons, R2 is 0.86, p<<0.0001.]