

Variability In Surface Reflectance And The Attenuation of Solar Radiation in Coastal Marine Waters.

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LONG-TERM GOALS

Optical observation of the ocean has taken a central role in marine science, and environmental optics has now become established as a key discipline in oceanography. Ocean color is now measured routinely from numerous platforms, and tools for measuring spectral attenuation of solar radiation in surface waters are widely available. In particular, several approaches to the quantitative interpretation of spectral reflectance ("ocean color") have been established: data products include estimates of chlorophyll *a*, colored dissolved organic matter (CDOM), and suspended sediment near the surface. Complementing this work have been studies relating ocean color to diffuse attenuation of solar radiation in visible and ultraviolet wavelengths, and the development of new approaches for relating spectral attenuation in the water column to a broad range of biological effects. A particularly intriguing aspect has been the finding that deviations from the central trends in relationships between ocean color and diffuse attenuation can reveal influences of phytoplankton community structure on ocean optics. We consider analysis of the relationships between ocean color and attenuation to be an especially promising avenue of research that should find broad application in coming years as hyperspectral ocean color sensors and autonomous measurements of multi-spectral diffuse attenuation from moorings, drifters and autonomous vehicles become commonplace. Our long term goal is to develop capabilities to make measurements routinely, with automatic generation of robust interpretations of optical variability in surface waters of the oceans, particularly in the coastal zone.

OBJECTIVES

This program of research is aimed at developing and testing new ways to interpret water-leaving radiance and downwelling irradiance as measured by optical sensors in surface waters of the ocean and complemented by remote sensing. Consistent with established research directions, efforts will be focused on developing improved estimates of the contributions of phytoplankton, CDOM and suspended matter to spectral reflectance and attenuation; however, the major focus will be on describing relationships *between* these optical properties and developing new data products based on

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these relationships. The ultimate objective is to develop a second generation of optical data products that relate optical measurements directly to biological and photochemical properties and processes.

Efforts will be directed toward:

- (1) developing and evaluating new approaches for relating measurements of ocean color and attenuation directly to biological and photochemical properties and processes in surface waters;
- (2) continuing efforts to discern phytoplankton community structure from ocean color and spectral diffuse attenuation;
- (3) exploring new interpretations of sun-induced chlorophyll fluorescence as an indicator of environmental influences on phytoplankton communities; and
- (4) supporting efforts to extract information from autonomous profiling radiometers.

APPROACH

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 (see “Related Projects”). This ONR project provides funding for additional technical support from Satlantic which complements Dalhousie-based efforts.

Data from deployments of optical moorings and research cruises are used to develop and evaluate models and bio-optical algorithms for estimating optical and biological properties of surface waters from measurements of water-leaving radiance. Measurements of downwelling irradiance at several depths (K-chain) are used for validation and also for relating subsurface patterns in optical/biological variability to surface signals.

Data from a range of environments will be obtained and analyzed in the quest for new ways to estimate biological and photochemical properties and processes from derived optical variables such as weighted transparency. The work plan includes the collection of new data and the systematic development of analytical procedures, from theoretical framework to approaches tested through comparison to field observations. Special effort will be devoted to estimating key derived variables from routine optical observations that are collected through remote sensing and other autonomous observation systems. All data and derived products will be archived in the WOODS database supported by ONR.

WORK COMPLETED

Optical moorings in coastal waters. We supported the development, deployment and servicing of four optical mooring systems in coastal waters of Nova Scotia. These moorings include hyperspectral observations of upwelling radiance, and downwelling irradiance; they also include multi-spectral K-chains, physical observations (currents, temperature, salinity profiles) and observations of meteorological variables. The systems communicate via wireless broadband to shore based computers at Dalhousie. Three moored systems have functioned very well, providing data for a total of about 10 months during two deployments in Lunenburg Bay during 2002 and 2003. Ground-truth data were acquired approximately weekly: vertical profiles of irradiance, fluorescence, spectral backscatter, dissolved and particulate absorption; and samples for chlorophyll, HPLC pigments, nutrients and particulate and dissolved absorption). A fourth mooring was deployed this year in Ship Harbour, NS, for a study of optical monitoring near aquaculture sites. It has been operating for most of the summer.

Cullen, assisted by grad student Yannick Huot, presented a full day tutorial on chlorophyll fluorescence at Ocean Optics XVI.

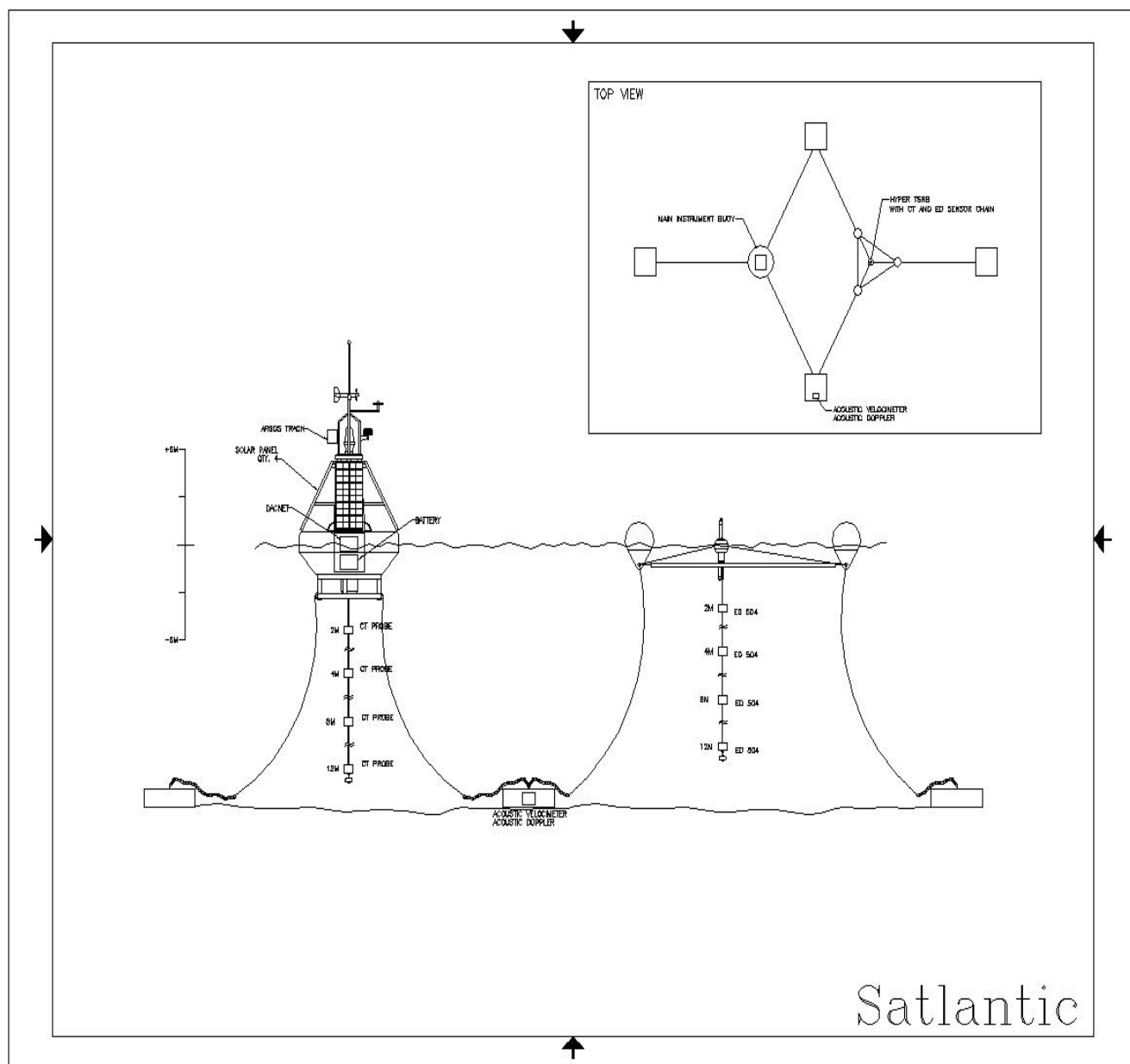


Figure 1. Schematic diagram of Optical Buoy Array as deployed in Lunenburg Harbour, Nova Scotia. The physical and meteorological instruments are on the primary platform, which is connected to the optical package on a separate mooring. A bottom-mounted package provides currents and bottom stress measurements.

The Habwatch workshop (A Workshop on **Real-time Coastal Observing Systems for Ecosystem Dynamics and Harmful Algal Blooms**, co-Chaired by J. Cullen and M. Babin) was an enthusiastic success; it included a strong participation by both Satlantic and Dalhousie investigators, who presented

lectures, carried out tutorials, and guided participants through practical deployment of instruments during the workshop, held in Villefranche-sur-mer from 11-21 June, 2003.

The Workshop was dedicated to an international audience with a broad range of backgrounds, and was intended to provide the participants with both the theory relevant to understanding the basic principles of real-time observation and modeling tools, and tutorials to allow the use of these tools. Participation was limited (89) to allow tutorials in small groups and to maximize interactions. Experts were invited to present overview lectures accompanied by peer-reviewed chapters in a book. Others were invited to present demonstrations and tutorials. The remaining participants/contributors were selected from a large pool of applicants using criteria designed to favor students and potential end users of coastal observation systems. Industrial exhibitors were able to display, deploy and discuss their instruments and observation tools. With Marcel Babin and Collin Roesler, Cullen is co-editing a book with chapters corresponding to the invited lectures. Lewis and Cullen delivered lectures, and submitted book chapters, and Cullen presented 17 hours of tutorials to small groups of participants.

RESULTS

A new inverse model has been developed by ourselves, largely by students Kitty Brown and Yannick Huot. This new model has been applied to data from the Lunenburg mooring (and to the REMUS AUV system – see report in OP31, Lewis et al.). Initial results are shown in Figure 2 below.

The data stream from the moorings is being processed now in near to real-time; it is being used to address a new inverse model of reflectance as above, and as well as to understand the role of coastal meteorological events on optical variability in these water bodies. We are specifically interested in the variations in the upwelling/downwelling offshore wind stress, and its effect on flushing/stagnation of the waters in coastal inlets, and the consequent bio-optical effects. For example, in summer of 2003, persistent southwesterly winds resulted in a strong upwelling, that reduced surface temperatures by as much as 10 degrees over a three day period. This was followed by a bloom of coccolithophorids in the embayments, which extended seaward by several 10's of kilometers. This event appears to be coherent along the entire Eastern seaboard of North America, with cold water temperatures reported as far south as the Carolinas. This meteorological band forcing appears to account for much of the variance in coastal optical properties at scales less than the annual; this hypothesis will be explicitly tested in the upcoming year.

One of the more “interesting” meteorological events took place at the end of the fiscal year, when Hurricane Juan made landfall directly on Halifax, with the highest winds ever measured historically occurring as a result. The significant height of the waves just offshore was in excess of 10 meters, with several waves greater than 20 meters, which is rather remarkable. Even more remarkable was the survival of all moorings, which continued to function and provide data throughout the intense storm.

IMPACT/APPLICATIONS

The successful deployment and operations of the mooring array have provided an unprecedented opportunity to resolve optically significant variations over meteorological time-scales, which dominate the optical variance spectrum for scales less than one year. The “lessons-learned” in the development of these systems have applicability to other autonomous deployments, and several (wired observatory in Newfoundland, MERIS cal/val buoy in the Med) have relied on this technology. The new inversion model promises wide applicability as well.

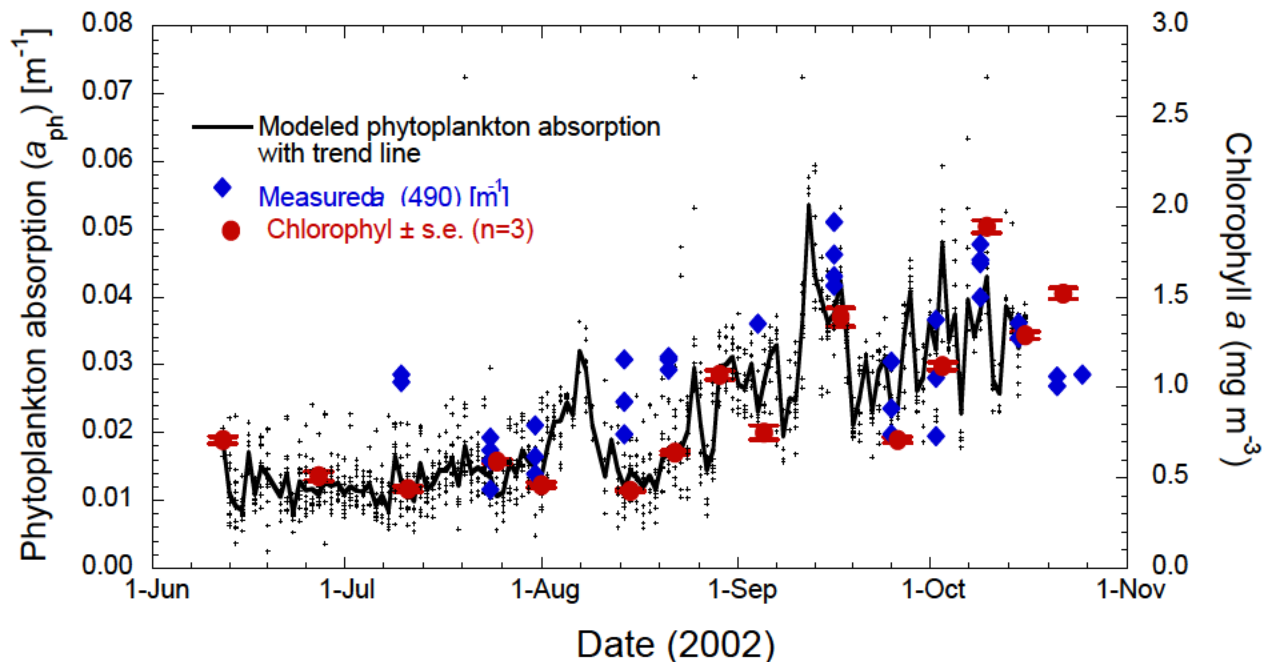


Figure 2. Early results from a coastal observatory. Nearly continuous measurements of hyperspectral ocean color were analyzed by C. Brown et al. (2002 2003) with an inverse model (cf. Roesler and Perry, 1995), generating relative estimates of phytoplankton absorption, corrected for the substantial contribution of CDOM and other constituents of the water (black dots; the black line is a locally weighted least squares regression to indicate trends). Blue symbols show direct measurements of phytoplankton absorption (filter pad method, corrected for detritus) and red symbols are determinations of extracted chlorophyll.

TRANSITIONS

The optical and system technologies developed for the Lunenburg mooring system have been transitioned into standard products by Satlantic, and have been deployed in Bonne Bay, Newfoundland as part of a highly advanced wired (fiber optic and power) underwater observatory, and in the Med as part of the BOUSOULE mooring in support of calibration and validation of the MERIS observatory. It is anticipated that the “lessons-learned” will be of great interest as the field moves towards the vision of the Integrated Ocean Observatory System on an international basis.

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.
- 2) A research project on interdisciplinary marine environmental prediction in the Atlantic coastal zone (Canadian Foundation for Climate and Atmospheric Sciences) is a major source of support for the field program in Lunenburg Bay and the development of optical data products for use in models of the Bay.

3) NOAA-funded work on bio-optical variability in the Bering Sea (J. Cullen and R. Davis) is in the synthesis stage. Funding from ONR allowed us to append extra research on optical properties, including advanced analysis of hyperspectral reflectance spectra..

4) ONR-funded research by Marlon Lewis and colleagues (HyCODE). This project is discussed in a separate report, in which Lewis's activities are described in more detail. We share data and discuss results for these complementary activities.

5) We work with Allan Cembella of the Institute of Marine Biosciences, National Research Council of Canada on optical detection of biological variability near aquaculture sites. The emphasis is on detection and prediction of harmful algal blooms. The data stream from a newly developed mooring, deployed in 2003, will be used in further development of our program.

6) Cullen is a member of PARADIGM (The Partnership for Advancing Interdisciplinary Global Modeling; a NOPP project). The project supports some analysis of data from our coastal observing system with an aim to develop and evaluate novel optical data products that might be used in global data assimilation models of ecosystems dynamics.

REFERENCES

All references are given in the publication list below, except:

Roesler, C. and Perry, M. J. (1995). In situ phytoplankton absorption, fluorescence emission, and particulate backscattering spectra determined from reflectance. *J. Geophys. Res.* 100: 13,279-213,294.

PUBLICATIONS

Manuscripts published or accepted for publication resulting in full or in part from this contract:

Browman, H.I., R.D. Vetter, C.A. Rodriguez, J.J. Cullen, R.F. Davis, E. Lynn, J.-F. St-Pierre. 2003. Ultraviolet (280 - 400 nm) Induced DNA Damage in the eggs and larvae of *Calanus finmarchicus* G. (Copepoda) and Atlantic Cod (*Gadus morhua*). *Photochem. Photobiol.* 77: 397-404 [published, peer-reviewed]

Cullen, J.J. and R.F. Davis. 2003. The blank can make a big difference in oceanographic measurements. *Limnol. Oceanogr. Bull.* 12: 29-35. [published, peer-reviewed]

Johannessen, S.C., W.L. Miller and J.J. Cullen. 2003. Calculation of UV attenuation and CDOM absorbance spectra from satellite measurements of ocean color. *J. Geophys. Res. (Oceans)*. (in press, peer-reviewed)

P.A. Stæhr and J.J. Cullen. 2003. Detection of *Karenia mikimotoi* by spectral absorption signatures. *J. Plankton Res.* (in press, peer-reviewed)

Presentations:

Cullen, J.J., Cembella, A.D., Ibarra, D.A., Kirchhoff, S. and Davis, R.F. Optical monitoring of biological variability in coastal waters. ASLO Winter Meeting, Salt Lake City. February 2003.

J.J. Cullen. "Observation and prediction of harmful algal blooms. Workshop on Real-Time Coastal Observing Systems for Ecosystems Dynamics and Harmful Algal Blooms. Villefranche-sur-mer, France, June 2003. (www.habwatch.org)

Brown, C.A., Y. Huot, R. F. Davis, S. Kirchhoff, C. M. Ryan, M. R. Lewis, and J. J. Cullen. Ocean colour inversion model optimized for a coastal inlet: including the near UV and fluorescence quantum yield. Poster: Workshop on Real-Time Coastal Observing Systems for Ecosystems Dynamics and Harmful Algal Blooms. Villefranche-sur-mer, France, June 2003. (www.habwatch.org)

Ibarra, D.A., A. D. Cembella, J. Grant and J.J. Cullen. Diffuse attenuation (490 nm) from multiple optical moorings to quantify chlorophyll depletion by mussels in a coastal aquaculture operation. Poster: Workshop on Real-Time Coastal Observing Systems for Ecosystems Dynamics and Harmful Algal Blooms. Villefranche-sur-mer, France, June 2003.

Ocean Optics Presentations with Extended Abstracts:

Brown, C.A., Y. Huot, M.J. Purcell, M.R. Lewis and J.J. Cullen. 2002. Mapping coastal bio-optical properties with an autonomous underwater vehicle (AUV) and a spectral inversion model. Ocean Optics XVI, Santa Fe, NM. CD-ROM. (Honorable mention student paper award).

Cullen, J.J. and R.F. Davis. 2002. Optical measurements in oceanography: when the blank makes a difference. Ocean Optics XVI, Santa Fe, NM. CD-ROM.

Huot, Y. and J.J. Cullen. 2002. MODIS chlorophyll fluorescence efficiency: A bio-optical model comparison. Ocean Optics XVI, Santa Fe, NM. CD-ROM.

Schallenberg, C. M.R. Lewis, D.E. Kelley and J.J. Cullen. 2002. Variability in the quantum yield of sun-induced fluorescence in the Bering Sea: effects of light and nutrients. Ocean Optics XVI, Santa Fe, NM. CD-ROM.

Book review:

Cullen, J.J. 2002. Phytoplankton Productivity: Carbon Assimilation in Marine and Freshwater Ecosystems. J. Phycol. 38: 1273-1275.

Cullen invited:

Short course at Ocean Optics XVI, Santa Fe, NM, Nov 2002: "Fluorescence of chlorophyll in surface waters: measurement and interpretation."

Tutorials at the Real-time coastal observing systems workshop:

These tutorials, generally one hour each, were presented to eight small groups over two days. Cullen presented tutorials (2) on measurement and interpretation of fluorescence and apparent optical properties.

Yannick Huot presented tutorials (2) on sun induced fluorescence and above-water measurements of reflectance.

Richard Davis presented at sea demonstrations and tutorials on the measurement of apparent optical properties.

Manuscripts Submitted (peer-reviewed):

Cullen, J.J. 2003. Observation and prediction of harmful algal blooms. In: Babin, M. Cullen, J.J. and Roesler, C.S., Eds. "Real-Time Coastal Observing Systems for Ecosystems Dynamics and Harmful Algal Blooms" UNESCO. (invited)

Lehmann, M.L., R.F. Davis, Y. Huot, and J.J. Cullen. 2003 Biologically weighted transparency: A predictor for water-column photosynthesis and its inhibition by ultraviolet radiation. Marine Ecol. Prog. Ser. (favorably reviewed and in revision)