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Collaborative Research: Autonomous Measurements of Carbon Fluxes in the North Atlantic Bloom

Mary Jane Perry
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Annual Report for Period: 10/2011 - 09/2012
Submitted on: 10/03/2012
Principal Investigator: Perry, Mary J.
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Organization: University of Maine
Submitted By:
Perry, Mary - Principal Investigator
Title:
Collaborative Research: Autonomous Measurements of Carbon Fluxes in the North Atlantic Bloom

Project Participants

Senior Personnel

Name: Perry, Mary
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: deCharon, Annette
Worked for more than 160 Hours: Yes
Contribution to Project:
education and outreach

Post-doc

Name: Cetinic, Ivona
Worked for more than 160 Hours: Yes
Contribution to Project:
Data analysis and manuscript preparation

Graduate Student

Name: Briggs, Nathan
Worked for more than 160 Hours: Yes
Contribution to Project:
CTD data analysis

Name: Bagniewski, Witold
Worked for more than 160 Hours: Yes
Contribution to Project:

Undergraduate Student

Technician, Programmer

Name: Kallin, Emily
Worked for more than 160 Hours: Yes
Contribution to Project:
Assisted with cruise preparation

Name: Companion, Carla
Worked for more than 160 Hours: Yes
Contribution to Project:
Helps in developing education and outreach component

Name: Steinman, Medea

Worked for more than 160 Hours: Yes

Contribution to Project:

Helps in developing education and outreach component

Other Participant

Name: Sieracki, Michael

Worked for more than 160 Hours: Yes

Contribution to Project:

responsible for flow cytometer and flow cam analysis

Name: Poulton, Nicole

Worked for more than 160 Hours: Yes

Contribution to Project:

responsible for flow cytometer and flow cam analysis

Name: Thompson, Brian

Worked for more than 160 Hours: Yes

Contribution to Project:

Analysis of Flow CAM and flow cytometer data

Name: Fennel, Katja

Worked for more than 160 Hours: Yes

Contribution to Project:

Co-supervised graduate student

Research Experience for Undergraduates

Organizational Partners

University of Washington

This is a formal collaborative research project with University of Washington (Eric D'Asaro and Craig Lee)

Bigelow Laboratory for Ocean Sciences

The organization has a subcontract to work on this project.

Dalhousie University

This organization is an unfunded collaborator on the project.

University of California-San Diego Scripps Inst of Oceanography

Oregon State University

University of Rhode Island Graduate School of Oceanography

National Oceanography Centre, UK

Plymouth Laboratory, UK

University of East Anglia

University of Copenhagen, Denmark

Marine Research Institute, Reykjavik, Ic

Woods Hole Oceanographic Institution

Amala Mahahevan and her post doctoral fellow Melissa Omand are collaborating on data analysis.

Other Collaborators or Contacts

Craig Lee, University of Washington
Eric D'Asaro, University of Washington
Katja Fennel, Dalhousie University, Canada
Kristinn Gudmundsson, Marine Research Institute, Reykjavik, Iceland
Hedinn Valdimarsson, Marine Research Institute, Reykjavik, Iceland
Nicole Bale, Plymouth Laboratory, UK
Jan Kaiser, University of East Anglia, UK
Alba Gonzalez-Posada, University of East Anglia, UK
Richard Lampitt, National Oceanography Centre, South Hampton, UK
Patrick Martin, National Oceanography Centre, South Hampton, UK
Maren Moltke Lyngsgaard, University of Copenhagen, Denmark
Katherine Richardson, University of Copenhagen, Denmark
David Checkley, Scripps Institution of Oceanography
Ryan Rykaczewski, Scripps Institution of Oceanography
Giorgio Dall'Olmo, Oregon State University
Toby Westberry, Oregon State University
Tatiana Rynearson, University of Rhode Island
Rainer Lohmann, University of Rhode Island
Lin Zhang, University of Rhode Island
Michael Sauer, University of Maine
Paul Hill, Dalhousie University, Canada
George Jackson, TA&MU, Texas
Amala Mahadevan, WHOI
Melissa Omand, WHOI

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)
see attached pdf file

Findings: (See PDF version submitted by PI at the end of the report)
see attached pdf file

Training and Development:
see attached pdf file

Outreach Activities:

see attached pdf file

Journal Publications

Bagniewski, W., K. Fennel, M.J. Perry, and E.A. D????Asaro, "Optimizing models of the North Atlantic spring bloom using physical, chemical and bio-optical observations from a Lagrangian float", Biogeosciences 8: 1291-1307, doi:10.5194/bg-8-1291-2011, p. 1291, vol. 8, (2011). Published, 10.5194/bg-8-1291-2011

Briggs, N, M.J. Perry, I. Cetinic, C. Lee, E. D'Asaro, A. M. Gray and E. Rehm, "High-resolution observations of aggregate flux during a sub-polar North Atlantic spring bloom", Deep-Sea Research Part 1, p. 1031, vol. 58, (2011). Published,

Martin, P., R.S. Lampitt, M.J. Perry, R. Sanders, C.M. Lee and E. D???Asaro, "Export and Mesopelagic Particle Flux during a North Atlantic Spring Diatom Bloom", Deep-Sea Res PT 1, p. 338, vol. 58, (2011). Published, 10.1016/j.dsr.2011.01.006

Matthew B. Alkire, Eric D????Asaro, Craig Lee, Mary Jane Perry, Amanda Gray, Ivona Cetini???, Nathan Briggs, Eric Rehm, Emily Kallin, Jan Kaiser, Alba Gonz????lez-Posada, "Estimates of net community production and export using high-resolution, Lagrangian measurements of O2, NO3-, and POC through the evolution of a spring diatom bloom in the North Atlantic", Deep Sea Research Part 1, p. 15, vol. 64, (2012). Published, doi:10.1016/j.dsr.2012.01.012

Rehm, E., and N. McCormick, "Inherent optical property estimation in deep waters", Optics Express, p. 24986, vol. 19, (2011). Published, 10.1364/OE.19.024986

Fennel, K., I. Cetini???, E. D????Asaro, C. Lee, M.J. Perry, "Autonomous Data Describe North Atlantic Spring Bloom", EOS, Transaction American Geophysical Uniion, p. 465, vol. 92, (2011). Published, 10.1029/2011EO500002

Cetinic, Ivona, Mary Jane Perry, Nathan T. Briggs, Emily Kallin, Eric A. DAsaro ,Craig M. Lee, "Particulate organic carbon and inherent optical pnroperties during 2008 North Atlantic Bloom Experiment", J. Geophysical Research, Oceans,, p. , vol. 117, (2012). Published, 10.1029/2011JC007771

Amala Mahadevan, Eric DAsaro, Craig Lee, Mary Jane Perry, "Eddy-driven stratification initiates the North Atlantic Spring phytoplankton bloom", Science, p. 54, vol. 337, (2012). Published, 10.1126/science.1218740

Zhang., L., T. Bidleman, M. J. Perry, and R. Lohmann, "Fate of chiral and achiral organochlorine pesticides in the North Atlantic Bloom Experiment", Environmental Science and Technology, p. 8106, vol. 46, (2012). Published, 10.1021/es3009248

Rehm, E., and C. Mobley, "Estimation of hyperspectral inherent optical properties from in-water radiometry: error analysis and application to in situ data", Applied Optics, p. , vol. , (2012). Submitted,

Books or Other One-time Publications

Web/Internet Site

URL(s):

http://osprey.bcodmo.org/project.cfm?id=102&flag=view

Description:

The site contains the data and technical report submission to the Biological and Chemical Oceanography Data Management Office (BCO-DMO).

Other Specific Products

Product Type:

archived webinar series on NAB

Product Description:

This dynamic webinar series features the research of scientists from the North Atlantic Bloom (NAB) Experiment and focuses on key concepts in ocean science. The five-part series consists of presentations from NAB scientists, and tells the story of the North Atlantic spring phytoplankton bloom and its role in the ocean ecosystem. It describes the multi-faceted nature of this complex experiment and provides participants with a rich body of educational resources, including linked concept maps aligned to National Science Education Standards and access to datasets that have been translated into classroom activities.
Because of the complex nature and breadth of the experiment, this webinar series offers meaningful linkages to most, if not all, of the ?cross-cutting scientific concepts? outlined in the New Framework of the National Science Education Standards. These concepts include ?scale, proportion, and quantity,? ?systems and system models,? ?energy and matter: flows, cycles and conservation,? and ?stability and change,? among others.

Sharing Information:

http://cosee.umaine.edu/programs/webinars/nab/

Contributions

Contributions within Discipline:

see attached pdf file

Contributions to Other Disciplines:

see attached pdf file

Contributions to Human Resource Development:

see attached pdf file

Contributions to Resources for Research and Education:

see attached pdf file

Contributions Beyond Science and Engineering:

see attached pdf file

Conference Proceedings

Special Requirements

Special reporting requirements:

Submission of data to NODC: We have submitted data to the BCO-DMO data base. http://osprey.bcodmo.org/project.cfm?id=102&flag=view

Change in Objectives or Scope: None

Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Book

Any Conference

Collaborative Research: Autonomous Measurements of Carbon Fluxes in the North Atlantic Bloom

Research and education activities

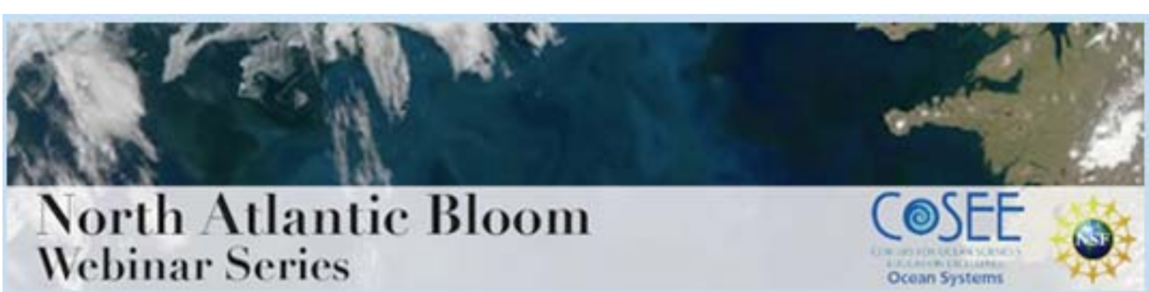
Activities during the last year (October 2011 through September 2012) have focused on further analysis and synthesis of data collected during the 2008 field year and, in particular, on publishing and otherwise communicating these results.

Continuing coordination among NAB participants:

1) The NAB PIs continue to communicate frequently via emails and by tele and/or video conferences.
2) Several small data workshops were held in the last year that variously included the PIs, students, postdocs, and collaborators.
3) Graduate student supervision continues to be highly interactive; Perry and D'Asaro are on the committees of the two remaining graduate students supported by the Collaborative Research grant; Lee is on one committee. All three PIs are involved in discussions with and in mentoring of postdocs supported by NAB or using NAB data – Dr. Ivona Cetinić (at U. Maine), Dr. Matthew Alkire (at U. Washington), and Dr. Meliss Omand (at WHOI).

Major educational activities:

Educational endeavors included mentoring of the four graduate students and three postdocs. Two students (Gray, Bagniewski) have now graduated with Masters', one (Rehm) will graduate with a Ph.D from U. Washington in December 2012, and the fourth student (Briggs at UMaine) is on track to finish his Ph.D. in 2014. One postdoc (Alkire) now has a permanent position at APL, but continues to work NAB; Cetinić is on the research staff at UMaine, and Omand is currently at postdoc at WHOI. In summer 2011, the NAB PIs and collaborators worked with marine educator Annette deCharon and her group at COSEE Ocean Systems to develop and present five webinars along with a concept map and classroom exercise material associated with each webinar. These webinars are available at http://cosee.umaine.edu/programs/webinars/nab/, and a manuscript describing this webinar series is in preparation for publication in the *Oceanography* journal (Companion et al.). Data from NAB has been incorporated data into graduate and undergraduate classes at the University of Washington and University of Maine.



Dissemination of findings – Presentations since September 2011:

Cetinić, I., Perry, M. J., and Thomas, A. *Challenges to validating satellite POC products.* NASA Ocean Color Research Team meeting. http://cce.nasa.gov/meeting_2011/agenda_ocean.htm.

Cetinić, I., *Sampling the under-sampled ocean; North Atlantic Bloom Experiment 2008,* invited talk at Lamont-Doherty Earth Observatory, Columbia University, November 2011.

D'Asaro, E., and C. Lee., *A new look at the North Atlantic bloom: gliders, floats, ships and slumping patches*, MBARI, August 2012.

Lee, C., E. D'Asaro, and M. J. Perry, *A new look at the North Atlantic bloom: gliders, floats, ships and slumping patches*, University of Washington, January 2012.

Perry, M. J., *2008 North Atlantic Spring Bloom Experiment: Autonomous Sampling in a Lagrangian Frame*, invited talk at Woods Hole Oceanographic Institution's Chemistry Department, May 2012.

Perry, M. J., Lee, C. M., D'Asaro, E., *Strategies for Autonomous Sensors: lessons learned from the 2008 autonomous North Atlantic bloom experiment for the Ocean Observatories Initiative (OOI).* Invited talk at NASA and OOI workshop on sensor quality control, Walpole ME, June 2012.

Ocean Sciences presentations:

Alkire, M. B.; D'Asaro, E.; Lee, C.; Perry, M. J.; Gray, A.; Cetinić, I.; Briggs, N.; Rehm, E.; Kaiser, J.; González-Posada, A.; *Estimates of net community production and export via lagrangian measurements of O2, NO3, and POC through the evolution of a spring bloom* (Abstract ID: 9644), February 2012 Ocean Sciences Meeting.

Briggs, N. T.; Slade, W. H.; Perry, M. J.; Boss, E.; Poulton, N.; Sieracki, M.; Lee, C.; D'Asaro, E.*; Estimating phytoplankton size from high- frequency fluctuations in simple optical measurements* (Abstract ID: 11410), February 2012 Ocean Sciences Meeting.

Cetinić, I. M. J. Perry, N. Briggs, E. Kallin, M. Alkire, E. A. D'Asaro, C. Lee, N. Poulton, E. Rehm, and M. Sieracki, *Relationships between the particulate organic carbon, plankton composition and optical properties during North Atlantic Bloom 2008 February*, 2012 Ocean Sciences Meeting.

Cetinić, I.; Companion, C.; deCharon, A.; Herren, C.; D'Asaro, E.; Lee, C.; Mahadevan, A.; Omand, M.; Perry, M. J.; Poulton, N.; *North Atlantic bloom 2008 webinar series* (Abstract ID: 9964), February 2012 Ocean Sciences Meeting.

D'Asaro, E. A.; Perry, M. J.; Lee, C.; Cetinić, I.; Alkire, M.; Poulton, N.; Sieracki, M.; *The evolution of patch of the North Atlantic Bloom* (Abstract ID: 9776), February 2012 Ocean Sciences Meeting.

Johnson, K. S.; Matsumoto, G.; Scheurle, C.; Claustre, H.; Perry, M. J.; Riser, S.; *Understanding ocean chemistry and biology using real-time data from profiling floats* (Abstract ID: 10070), February 2012 Ocean Sciences Meeting.

Lee, C. M.; Briggs, N.; Cetinić, I.; D'Asaro, E. A.; Perry, M.; *Strategies for autonomous sensors* (Abstract ID: 11507), February 2012 Ocean Sciences Meeting.

Perry, M. J.; Gudmundsson, K.; Alkire, M.; D'Asaro , E.; Cetinić , I.; Rehm, E.; Lee, C. M.; *Estimates of net phytoplankton productivity (NPP) and net community productivity (nNCP) from a Lagrangian mix-layer float* (Abstract ID: 11621), February 2012 Ocean Sciences Meeting.

Rynearson, T. A.; Richardson, K.; Lampitt, R. S.; Sieracki, M. E.; Poulton, A.; Perry, M. J.; *What you see is not what you get: relating diatom species composition in surface waters to carbon flux during a spring bloom in the North Atlantic* (Abstract ID: 11790), February 2012 Ocean Sciences Meeting.

Dissemination of findings – Publications since September 2011

Since September 2011 six new papers were published, an educational webinar series was archived and is available one line, and six manuscripts are either in review or soon to be submitted.

Alkire, M. B., E. D'Asaro, C. Lee, M. J. Perry, A. Gray, I. Cetinic, N. Briggs, E. Rehm, E. Kallin, J. Kaiser, and A. González-Posada. (2012) *Estimates of net community production and export using high-resolution, Lagrangian measurements of O2, NO3-, and POC through the evolution of a spring diatom bloom in the North Atlantic.* Deep-Sea Research Part I 64: 157-174; http://dx.doi.org/10.1016/j.dsr.2012.01.012

Budgets of nitrate, dissolved oxygen, and particulate organic carbon (POC) were constructed from data collected on-board a Lagrangian, profiling float deployed between April 4 and May 25, 2008 as part of the North Atlantic Bloom Experiment. These measurements were used to estimate net community production (NCP) and apparent export of POC along the float trajectory. A storm resulting in deep mixing and temporary suspension of net production separated the bloom into early (April 23-27) and main (May 6-13) periods over which ~264 and ~805 mmol C m^{-2} were produced, respectively. Subtraction of the total POC production from the NCP yielded maximum estimates of apparent POC export amounting to ~172 and 574 mmol C m^{-2} during the early and main blooms, respectively. The bloom terminated the following day and ~282 mmol C m^{-2} were lost due to net respiration (70 %) and apparent export (30%). Thus, the majority of the apparent export of POC occurred during the main bloom and a large respiration event occurred during bloom termination. A comparison of the POC flux during the main bloom period with independent estimates at greater depth suggest a rapid rate of remineralization in the upper mesopelagic (60-100 m). We suggest the high rates of export and remineralization in the upper layers could explain the apparent lack of carbon overconsumption (C:N > 6.6) in the North Atlantic during the spring bloom.

Cetinić, I., M. J. Perry, N. Briggs, E. Kallin, E. A. D'Asaro, C. M. Lee. (2012) *Particulate organic carbon and inherent optical properties during the 2008 North Atlantic Bloom Experiment.* Journal of Geophysical Research 117, C06028, 18 pp. doi:10.1029/2011JC00777

The co-variability of particulate backscattering (b_{bp}) and attenuation (c_p) coefficients and particulate organic carbon (POC) provides a basis for estimating POC on spatial and temporal scales that are impossible to obtain with traditional sampling and chemical analysis methods. However, the use of optical proxies for POC in the open ocean is complicated by variable relationships reported in the literature between POC and c_p or b_{bp}. During the 2008 North Atlantic Bloom experiment, we accrued a large dataset consisting of >300 POC samples and simultaneously-measured c_p and b_{bp}. Attention to sampling detail, use of multiple types of POC blanks, cross-calibration of optical instruments, and parallel measurements of other biogeochemical parameters facilitated distinction between natural and methodological based variability. The POC vs. c_p slope varied with plankton community composition but not depth; slopes were 11% lower for the diatom community vs. the recycling community. Analysis of literature POC vs. c_p slopes indicates that plankton composition is responsible for a large component of that variability. The POC vs. b_{bp} slope decreased below the pycnocline by 20%, likely due to changing particle composition associated with remineralization and fewer organic rich particles. The higher b_{bp}/c_p ratios below the mixed layer are also indicative of particles of lower organic density. We also observed a peculiar platform effect that resulted in ~28% higher values for downcast vs. upcast b_{bp} measurements. Reduction in uncertainties and improvement of accuracies of POC retrieved from optical measurements is possible but requires a community consensus to agree on standard protocols for both measurements.

Fennel, K., I. Cetinić, E. D'Asaro, C. Lee, and M. J. Perry. (2011) *Autonomous data describe North Atlantic spring bloom.* Eos Trans. AGU, 92(50), 465; doi:10.1029/2011EO500002

A major accomplishment of the project was the high, rigorous calibration, and detailed documentation of the large and diverse NAB data set that was submitted to the BCO-DMO in 2010 and 2011. The data represented four cruises and five autonomous platforms, along with a series of data providing details of calibration, cross calibration, analytical methodology, data analysis, quality assurance and control procedures for the NAB bottle samples, shipboard measurements and autonomous sensors. The publication announced to the community that the NAB data were freely available at http://osprey.bcodmo.org/project.cfm?flag=viewd&id=102&sortby=project .

Mahadevan, A., E. D'Asaro, C. Lee, and M. J. Perry. (2012) *Eddy-driven stratification initiates a North Atlantic Spring phytoplankton bloom.* Science 337: 54-58; doi: 10.1126/science.1218740

Springtime phytoplankton blooms photosynthetically fix carbon and export it from the surface ocean at globally important rates. These blooms are triggered by increased light exposure of the phytoplankton due to both seasonal light increase and the development of a near-surface vertical density gradient (stratification) that inhibits vertical mixing of the phytoplankton. Classically and in current climate models, that stratification is ascribed to a springtime warming of the sea surface. Here, using observations from the subpolar North Atlantic and a three-dimensional biophysical model, we show that the initial stratification and resulting bloom are instead caused by eddy-driven slumping of the basin-scale north-south density gradient, resulting in a patchy bloom beginning 20 to 30 days earlier than would occur by warming. The publication was accompanied by a Science 'Perspective' – Martin, A., (2012) The Seasonal Smorgasbord of the Seas. Science 337, 46; doi: 10.1126/science.1223881.

Rehm, E., and N. J. McCormick. (2011). *Inherent optical property estimation in deep waters*, Optics Express 19: 24986-25005, doi.org/10.1364/OE.19.024986.

Two algorithms were developed for determining two inherent optical properties (IOPs) from radiometric measurements in vertically homogeneous waters. The first algorithm is for estimation of the ratio of the backscattering to absorption coefficients from measurements of only the vertically upward radiance and the downward planar irradiance at depths where the light field is in the asymptotic regime. The second algorithm enables estimation of the absorption coefficient from measurement of the diffuse attenuation coefficient in the asymptotic regime after use of the first algorithm. Multiplication of the two estimates leads to an estimate for the backscattering coefficient. The algorithms, based upon the use of a simplified phase function and the asymptotic eigenmode, are shown to potentially provide good starting conditions for iteratively determining the absorption and backscattering coefficients of a wide variety of waters. The uncertainty in the estimates defines a subspace for IOPs that may reduce ambiguity in such iterative solutions. Because of the ease of estimating the backscattering to absorption ratio from in-water measurements, this IOP deserves further investigation as a proxy for biogeochemical quantities in the open ocean.

Zhang., L., T. Bidleman, M. J. Perry, and R. Lohmann (2012). *Fate of chiral and achiral organochlorine pesticides in the North Atlantic Bloom Experiment.* Environmental Science and Technology 46: 8106-14. DOI: 10.1021/es3009248.

Organochlorine pesticides (OCPs) were measured in the surface seawater and lower atmosphere during the North Atlantic Bloom Experiment in the spring 2008 from samples collected on the R/V Knorr. The gaseous concentration profiles resulted from both long-range transport (LRT) from the Arctic by polar easterlies and local biogeochemical processes. Relatively constant α/γ-hexachlorocyclohexane (HCH) ratios and enantiomer fractions of α-HCH indicated that a single water mass was sampled throughout the cruise. Changes in dissolved phase concentrations were dominated by bloom processes (air-water exchange, partitioning to organic particles, and subsequent sinking) rather than LRT. α-HCH and dissolved phase trans-chlordanes showed depletion of (+) enantiomer, whereas depletion of the (-) enantiomer was observed for heptachlor exo-epoxide (HEPX) and cis-chlordanes. Fugacity ratio calculations suggest that hexachlorobenzene (HCB) and γ-HCH were depositing from air to water whereas heavier OCPs (chlordanes, HEPX) were evaporating. Dissolved phase concentrations did not decrease with time during the three-week bloom period; neither were lipophilic OCPs drawn down from air to water as previous studies hypothesized. Comparison with Arctic measurements suggested that the Arctic returned higher concentrations of α-HCH and HCB through both the atmospheric (polar easterlies) as well as oceanic transport (East Greenland Current) to the lower latitudes.

deCharon, A., C. Companion, I. Cetinić, C. Lee, A. Mahadevan, E. D'Asaro, N. Poulton, M. J. Perry (2011). *North Atlantic Bloom series webinar.* http://cosee.umaine.edu/programs/webinars/nab/

The series of five webinar features the research of NAB scientists and focuses on key concepts in ocean science, telling the story of the North Atlantic spring phytoplankton bloom and its role in the ocean ecosystem. It describes the multi-faceted nature of this complex experiment and provides participants with a rich body of educational resources, including linked concept maps aligned to National Science Education Standards and access to datasets that have been translated into classroom activities. Because of the complex nature and breadth of the experiment, this webinar series offers meaningful linkages to most, if not all, of the "cross-cutting scientific concepts" outlined in the New Framework of the National Science Education Standards. These concepts include "scale, proportion, and quantity," "systems and system models," "energy and matter: flows, cycles and conservation," and "stability and change," among others.

Rehm, E., and C. D. Mobley (in review). *Estimation of hyperspectral inherent optical properties from in-water radiometry: error analysis and application to in situ data,* submitted to Applied Optics.

An inverse algorithm is developed to retrieve hyperspectral absorption and backscattering coefficients from measurements of hyperspectral upwelling radiance and downwelling irradiance in vertically homogeneous waters. The forward model is the azimuthally-averaged radiative transfer equation, efficiently solved by a EcoLight radiative transfer model which includes the effects of inelastic scattering (EcoLight). Although this inversion problem is ill-posed (the solution is ambiguous for retrieval of total scattering coefficients), unique and stable solutions can be found for absorption and backscattering coefficients. The inversion uses attenuation and backscattering coefficients at one wavelength to constrain the inversion, increasing the algorithm's stability and accuracy. Two complementary methods, Monte Carlo simulation and first-order error propagation, are used to develop uncertainty estimates for the retrieved absorption and backscattering coefficients. The algorithm is tested using simulated light fields from a chlorophyll-based case I bio-optical model and radiometric field data from the 2008 North Atlantic Bloom Experiment. The influence of uncertainty in the radiometric quantities and additional model parameters on the inverse solution for absorption and backscattering is studied using a Monte Carlo approach and an uncertainty budget is developed for retrievals. All of the required radiometric and IOP measurements can be made from power-limited autonomous platforms. We conclude that hyperspectral measurements of downwelling irradiance and upwelling radiance, with a single-wavelength measurement of attenuation, can be used to estimate hyperspectral absorption to an accuracy of $\pm0.01\ m^{-1}$ and hyperspectral backscattering to an accuracy of $\pm0.0005\ m^{-1}$ over wavelengths for which the contributions of inelastic scattering are small.

Alkire, M., et al. (manuscript). *Net community production and export from Seaglider measurements in the North Atlantic after the spring bloom.*

Mean rates of net community production (NCP) and particulate organic carbon (POC) export were estimated from sensor measurements of dissolved oxygen, chlorophyll fluorescence (chl F), and particulate backscatter (b_{bp}700) collected from three Seagliders that surveyed a 20 x 20 km area in the North Atlantic subsequent to a large diatom bloom. During this period, ratios of chlorophyll fluorescence-to-particulate backscatter (chl:b_{bp}700) were lower than values encountered during the spring diatom bloom, suggesting the phytoplankton community was predominately composed of smaller cells (pico- and nanoplankton) and/or coccolithophorids. However, coupled budgets of oxygen and POC indicated a net community production of 1.1-1.6 mol C m^{-2} and carbon export of 0.5-1.0 mol C m-2 (40-60 %), respectively over a period of 21 days. Thus, the production and export of carbon that occurred over a month-long period was comparable to that encountered during the shorter diatom bloom and efficient.

Briggs, N., et al. (manuscript). *Inversion of optical properties to estimate mean particle size.*

Particle size plays a critical role in the cycling of carbon in the ocean by constraining both trophic interactions and sinking rates. Widespread measurements of size can therefore enhance understanding of the carbon cycle. Inversions of high-frequency fluctuations in timeseries of optical measurements of marine particles, i.e., backscattering, attenuation and chlorophyll *a* fluorescence measured autonomous floats and gliders, are used to derive mean phytoplankton and particle size. The method is based on the variance-to-mean ratio, which increases as a function of mean particle size. The approach is similar to that of Shifrin (1995), who estimated particle size from fluctuations in beam transmissometer measurements. The present inversion was evaluated with data from two laboratory clay aggregation experiments, and was found to derive consistent results with a particle size range of 10 - 80 μm.

Cetinić, I., et al. (manuscript). *Follow the North Atlantic Spring Bloom.*

This dataset, with containing activities, was developed as an accompaniment to North Atlantic Bloom Experiment 2008 (NAB08) webinar series. The goal of these activities is to allow students to develop a holistic view of North Atlantic spring bloom, exploring the biological and environmental settings, approaches for measurements, and potential impacts of climate change on this system. The Phytoplankton Growth and Light exercise emphasizes negative and positive exponential functions, including attenuation of light with depth and growth of phytoplankton with time. The Physics of the Bloom exercise demonstrates concepts pertaining to the physics of the ocean, specifically how changes in mixed layer depth impact phytoplankton growth. The Temporal and Spatial Scales exercise focuses on different oceanic processes that occur on scales of a day, week, month (temporal scales) and processes that occur on scales of a millimeter, meter and kilometer. Students are asked to think about which of these scales are important for a phytoplankton cell, a copepod, a fish and a whale? The Nutrients and Community Change exercise introduces another controlling factor in bloom formation - nutrients. In this exercise students learn how the changes in nutrient concentration impact the absolute concentrations of phytoplankton, and also drive the change in the dominant phytoplankton group, as they see in the NAB08 dataset that decline in silica concentrations changed the absolute concentrations of chlorophyll, but also a shift from diatoms to picoeukaryotes.

Cetinić, I., et al. (manuscript). *Optical community index to assess spatial patchiness during the 2008 North Atlantic Bloom.*

Phytoplankton composition changed over the bloom and these changes could be documented and tracked using an optical 'community index', i.e., the ratio of chlorophyll fluorescence to optical backscatter. This ratio is similar to the ratio of beam attenuation to chlorophyll developed by Nencioli et al. (2010) in the OPAL experiment near Hawaii. In diatom-dominated bloom communities the chlorophyll fluorescence to backscatter ratio (with values of 100-150) was almost a factor of two higher than in the post-bloom picoplankton-dominated community (with values of ~50). This optical index is used to map patchiness in community composition over broad spatial and temporal scales. Data from the four gliders indicate a high degree of patchiness from late April through late May not only in phytoplankton biomass but also in community composition. These findings corroborate Mahadevan et al. (2012)'s prediction that the bloom is intrinsically patchy.

Rynearson, et al. (manuscript). *Diatom resting spores disproportionally contribute to carbon flux during the sub-polar North Atlantic spring bloom.*

The mass sinking of phytoplankton cells following blooms is thought to be an important source of carbon to the ocean's interior, with some species potentially contributing more to carbon flux than others. Significant differences in species composition both at the genus and species levels were found between trap material and surface samples. Cells and resting spores in the genus *Chaetoceros* contributed 50–95% (mean 81%) of phytoplankton cell flux into the sediment traps, with resting spores of one species, identified as *Chaetoceros diadema*, dominating (35–92%). Microplankton other than diatoms always comprised < 0.25% of cells in the traps although they were often more abundant at the surface. Spores of *C. diadema* were rarely observed in surface waters and, when present, were only found at low concentrations (1-4 x 10^3 spores l^{-1}). On the one taxonomic profile taken below the mixed layer, however, the concentration of free spores increased with depth with the highest concentration (3.9 x 10^4 spores l^{-1}) found at 200 m. Spores contained within vegetative cell frustules were also observed and were most abundant between 80 and 200 m, suggesting that spore formation may occur primarily in the more nutrient rich waters of the mesopelagic, while cells are sinking. Carbon flux associated with sinking resting spores ranged between 2–63 mg C m^{-2} d^{-1}, contributing between 9–64% of daily total particulate organic carbon flux measured in the traps. These data emphasize the ephemeral nature of organic carbon flux events in the open ocean and show how non-dominant species and transient life stages can contribute more to carbon flux than their more abundant counterparts.

Training and Development

The project has supported four graduate students. Mentoring was collaborative with the other NAB PIs. Committee meetings were held as needed, varying from weekly meetings for a period of several months prior to the Master's defense to a meeting frequency of 2 to 4 months; meetings were held either by teleconference call or video conferencing and when possible, in person at the mini-workshops.

Three students have completed and defended their MS degrees:

1) Witold Bagniewski (UMaine) – "Optimizing models of the North Atlantic spring bloom using physical, chemical and bio-optical observations from a Lagrangian float"; a paper has been published in Biogeosciences.

2) Amanda Gray (UW) – "North Atlantic Spring Bloom Experiment 2008: Observations of a Diatom Bloom in an Eddy Field".

3) Nathan Briggs (UMaine) – "Analysis of optical spikes reveals dynamics of aggregates in the twilight zone"; a paper has been published in Deep Sea Research. Nathan is continuing for his Ph.D., expected 2014, with further analyses of NAB08 data.

The fourth student, Eric Rehm (UW) continues to make good progress on his Ph.D. dissertation and will defend in December 2012. One paper has published, a second submitted, and a third in preparation.

The project has supported two postdoctoral fellows and provided significant interactions with a third: Dr. Ivona Cetinić (UMaine), Dr. Matthew Alkire (APL/UW), and Dr. Melissa Omand, a postdoctoral fellow with colleague Dr. Amala Mahadevan.

Data from the North Atlantic Bloom experiment have been incorporated into undergraduate class (SMS 204: Integrated Marine Science II – Chemistry; SMS 303 – field oceanography) and graduate classes (SMS 501: Biological Oceanography) at the University of Maine.

Outreach Activities

Data and experiences from the NAB program were used in lectures to high school students (UMaine's 'Dive-In' program and Waynflete Academy's 'Sustainable Ocean Studies' program) and for various K-12 school groups that come to the Darling Center during the academic year.

In collaboration with COSEE-Ocean Systems (OS), we produced a series of webinars http://cosee.umaine.edu/programs/webinars/nab/ aimed at secondary school teachers that told the story of the North Atlantic spring bloom and its role in that ocean ecosystem. Simplified NAB08 data sets and Excel-based activities are provided on the website for classroom activities and a manuscript is in advanced stage of preparation (Cetinić et al.). The webinars attracted 68 unique participants from 21 states and 3 non-U.S. countries (Canada, Iceland and Germany). Webinar audiences included 51% educators and 31% scientists/graduate students; 30% of participants attended three or more live webinars; 90% of those who completed post evaluation surveys reported they were "likely to use the presentation content" in their own work. The NAB webinars' archived material – including transcribed webinar video, data sets, and interactive concept maps with images, animations, and teaching resources – have over 600 visits per month, making it the second most visited section of the COSEE-OS website (cosee.umaine.edu). The concepts in the Webinar series directly map to New Proposed Framework for NSES Standards, i.e. Patterns, similarity, and diversity; Cause and effect: mechanism and prediction; Scale, proportion, and quantity; Systems and system models; Energy and matter: flows, cycles and conservation; Form and function; and Stability and change.

Contributions within Discipline

We have demonstrated that an array of autonomous platforms, floats and gliders can successfully sample the space and time variability of biogeochemical processes over time spans of several months. By combining optical data from floats and gliders with more traditional ship-based biological and chemical measurements, it is possible to determine phytoplankton aggregate size and diatom aggregate sinking. The use of optical spikes observed from gliders provided unprecedented coupled vertical and temporal resolution measurements of an aggregate flux event.

We have demonstrated that array of autonomous instruments can make spatially coherent and quantitatively meaningful measurements of carbon production and export, of associated changes in community structure, and of the space and time variations of these over many months. Moreover, we have demonstrated that the resulting data can tightly constrain many components of a biogeochemical model, particularly when the data is taken in a Lagrangian coordinate system.

Our analysis have demonstrated the important role of lateral processes in governing spring bloom initiation in the Icelandic Basin, the importance of diatoms in carbon export and the role of silicate in controlling this, and the importance of small space and time scales in the production and export of carbon and in the community structure that supports these fluxes.

This project illustrated the importance of carefully considered calibration efforts in autonomous sampling schemes and began to explore the scope that will be required of such endeavors. Toward this goal, NAB08 developed techniques for in situ calibration of sensors carried on autonomous platforms, and for extensive intercalibration of sensors within a modest-sized array of mobile (drifting and gliding) assets.

Contributions to Other Disciplines

Our measurement techniques have application to global measurement of biogeochemical aspects of climate change and ecosystem response to climate variability.

Contributions to Human Resource Development

This project has supported four graduate students and two postdocs, and has developed a series of Webinars for educators that uses our 'story' of the spring bloom.

Contributions to Resources for Research and Education

The graduate students acquired a data base that will enable them to enhance their computational, modeling and visualization skills. Data and experiences from the project have enriched undergraduate and graduate curricula, as well enriched lectures and activities with visiting high school groups. The NAB webinars, archived on line, present content and data for K-12 plus college educators.

Contributions Beyond Science and Engineering

The initial outcomes of this project are 1) demonstration of the power of new technologies (gliders and floats) to operate autonomously for three months and to observe ephemeral events in open ocean environments and 2) the observation of a rapid carbon flux that suggests that chain forming diatoms plays a critical role in the rapid transfer of carbon from the ocean surface to the seafloor. The 'know-how' for using and calibration autonomous sensors acquired for this project will be available for future NSF projects.

Production and Export

Three papers focus on the production and export processes during NAB08. These demonstrate the ability of autonomous platforms to estimate production and export rates. They confirm previous observations of intense export throughout the Spring diatom bloom, quantify these rates for our observations, show the key role of aggregation and sinking, the acceleration of these rates as the silicate is exhausted, and show strong remineralization in the upper layers during this export.

A fourth paper shows that these processes can be successfully modeled, that the NAB08 data is sufficient to constrain most of the parameters of this model and, consistent with the observations, that such models are most successful if the acceleration of diatom sinking at the time of silicate exhaustion is included.

Estimates of net community production and export using high-resolution, Lagrangian measurements of O_2, NO_3^-, and POC through the evolution of a spring diatom bloom in the North Atlantic, Matthew B. Alkire, Ph.D.; Eric D'Asaro; Craig Lee; Mary Jane Perry; Amanda Gray; Ivona Cetinić; Nathan Briggs; Eric Rehm; Emily Kallin; Jan Kaiser; Alba González-Posada, (2011) *Deep-Sea Research Part I*, *resubmitted after review*

Budgets of nitrate, dissolved oxygen, and particulate organic carbon (POC) were constructed from data collected on-board a Lagrangian, profiling float deployed between April 4 and May 25, 2008 as part of the North Atlantic Bloom Experiment. These measurements were used to estimate net community production (NCP) and apparent export of POC along the float trajectory. A storm resulting in deep mixing and temporary suspension of net production separated the bloom into early (April 23-27) and main (May 6-13) periods over which ~264 and ~805 mmol C m^{-2} were produced, respectively. Subtraction of the total POC production from the NCP yielded maximum estimates of apparent POC export amounting to ~172 and 574 mmol C m^{-2} during the early and main blooms, respectively. The bloom terminated the following day and ~282 mmol C m^{-2} were lost due to net respiration (70 %) and apparent export (30%). Thus, the majority of the apparent export of POC occurred during the main bloom and a large respiration event occurred during bloom termination. A comparison of the POC flux during the main bloom period with independent estimates at greater depth suggest a rapid rate of remineralization in the upper mesopelagic (60-100 m). We suggest the high rates of export and remineralization in the upper layers could explain the apparent lack of carbon overconsumption (C:N > 6.6) in the North Atlantic during the spring bloom.

Export and mesopelagic particle flux during a North Atlantic spring diatom bloom, Patrick Martin, Richard S. Lampitt, Mary Jane Perry, Richard Sanders, Craig Lee, Eric D'Asaro, *Deep-Sea Research I* 58 (2011) 338–349 doi:10.1016/j.dsr.2011.01.006

We measured downward POC flux during a subpolar North Atlantic spring bloom at 100 m using thorium-234 ($_{234}$Th) disequilibria, and below 100 m using neutrally buoyant drifting sediment traps. The cruise followed a Lagrangian float, and a pronounced diatom bloom occurred in a 600 km^2 area around the float. Particle flux was low during the first three weeks of the bloom, between 10 and 30 mg POC m^{-2} d^{-1}. Then, nearly 20 days after the bloom had started, export as diagnosed from $_{234}$Th rose to 360–620 mg POC m^{-2} d^{-1}, co-incident with silicate depletion in the surface mixed layer. Sediment traps at 600 and 750 m depth collected 160 and 150 mg POC m^{-2} d^{-1}, with a settled volume of particles of 1000–1500 mL m^{-2} d^{-1}. This implies that 25–43% of the 100 m POC export sank below 750 m. The sinking particles were ungrazed diatom aggregates that contained transparent exopolymer particles (TEP). We can lead to substantial particle export that is transferred efficiently through the mesopelagic.

Underwater gliders observe aggregate flux event in high vertical and temporal resolution during the North Atlantic spring bloom, Briggs, Nathan, Mary Jane Perry, Ivona Cetinic, Craig Lee, Eric D'Asaro, Amanda Gray, Eric Rehm, *Deep-Sea Research Part I* 58 (2011) pp. 1031-1039, 10.1016/j.dsr.2011.07.007
An aggregate flux event was observed by four underwater gliders during the 2008 subpolar North Atlantic spring bloom experiment (NAB08). At the height of the diatom bloom, aggregates were observed as optical spikes in both particulate backscattering coefficient (bbp) and chlorophyll a fluorescence. Optical sensors on the ship and gliders were cross-calibrated through a series of simultaneous profiles, and bbp was converted to particulate organic carbon. The diatom aggregates sank as a discrete pulse, with an average sinking rate of ~75 m d^{-1}; 65% of aggregate backscattering and 90% of chlorophyll fluorescence content was lost between 100 m and 900 m. Mean aggregate organic carbon flux at 100 m in mid-May was estimated at 514 mg C m^{-2} d^{-1}, consistent with independent flux estimates. The use of optical spikes observed from gliders provides unprecedented coupled vertical and temporal resolution of aggregate flux events.

Optimizing models of the North Atlantic spring bloom using physical, chemical and bio-optical observations from a Lagrangian float, W. Bagniewski, K. Fennel, M. J. Perry, and E. A. D'Asaro,, *Biogeosciences Discuss.,* 7, 1–44, 2010 www.biogeosciences-discuss.net/7/1/2010/ doi:10.5194/bgd-7-1-2010
The North Atlantic spring bloom is one of the main events that lead to carbon export to the deep ocean and drive oceanic uptake of CO2 from the atmosphere. Here we use a suite of physical, bio-optical and chemical measurements made during the 2008 spring bloom to optimize and compare three different models of biological carbon export. The observations are from a Lagrangian float that operated south of Iceland from early April to late June, and were calibrated with ship-based measurements. The simplest model is representative of typical NPZD models used for the North Atlantic, while the most complex model explicitly includes diatoms and the formation of fast sinking diatom aggregates and cysts under silicate limitation. We carried out a variational optimization and error analysis for the biological parameters of all three models, and compared their ability to replicate the observations. The observations were sufficient to constrain most phytoplankton-related model parameters to accuracies of better than 15%. However, the lack of zooplankton observations leads to large uncertainties in model parameters for grazing. The simulated vertical carbon flux at 100m depth is similar between models and agrees well with available observations, but at 600m the simulated flux is larger by a factor of 2.5 to 4.5 for the model with diatom aggregation. While none of the models can be formally rejected based on their misfit with the available observations, the model that includes export by diatom aggregation has a statistically

significant better fit to the observations and more accurately represents the mechanisms and timing of carbon export based on observations not included in the optimization. Thus models that accurately simulate the upper 100m do not necessarily accurately simulate export to deeper depths.

Spatial and temporal evolution of the Spring bloom and its communities

Although the overall rates of production and export found during NAB08 are similar to those previously observed, the space-time structure of this production and of the biological communities that support it were observed in unprecedented detail. This has resulted in new hypotheses explaining the physical and biological processes causing this structure.

The bloom is initiated by eddy restratification of the winter mixed layer

The spring bloom is initiated by the springtime increase in light due both to astronomical factors and to increased water column stratification. This stratification is not due to solar heating as has been traditionally believed. The NAB data (Fig. 1a) show stratification developing across the entire wintertime mixed layer, rather than near the surface as would be expected for solar heating. This behavior is predicted by a model of mixed layer eddy (MLE) restratification (Fig. 1b) developed by our collaborator Dr. Amala Mahadevan

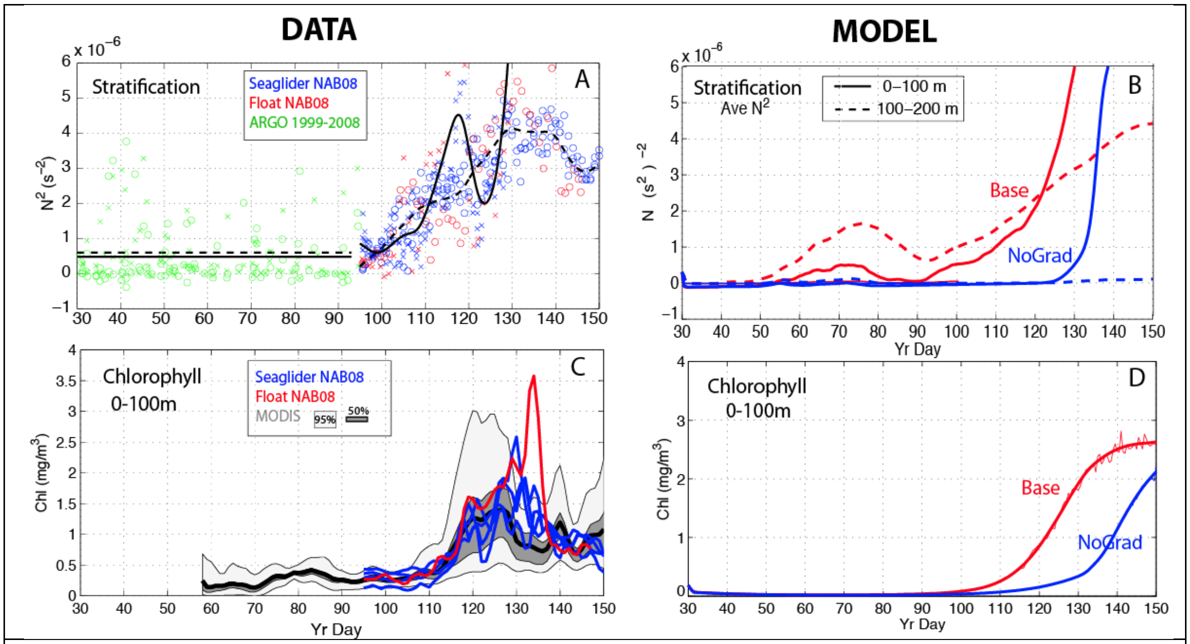


Figure 1. Comparison of data (A,C) and model (B,D) simulations of stratification and Chlorophyll.

now at WHOI. In this view, the lateral density gradients in the deep wintertime mixed layer are unstable to a baroclinic instability and continually act to restratify the mixed layer. In winter, surface cooling and westward winds minimize this effect, but in the Spring these competing processes relax and MLE restratification becomes increasingly important. Adding a light-limited phytoplankton model based Bagniewski et al, 2011, (Fig 1cd) shows that a model with MLE restratification (red) advances the onset of the bloom by about 20 days compared to one driven only by solar heating (blue). Since the MLE restratification is due to eddy processes, it intrinsically patchy and intermittent. Thus, also, is the early bloom intrinsically patching and intermittent.

The bloom evolves as a series of short-lived patches of productivity

The evolution of the productivity of each patch is controlled by light, nutrients and probably grazing while its size and shape are controlled by lateral mixing of the water masses.

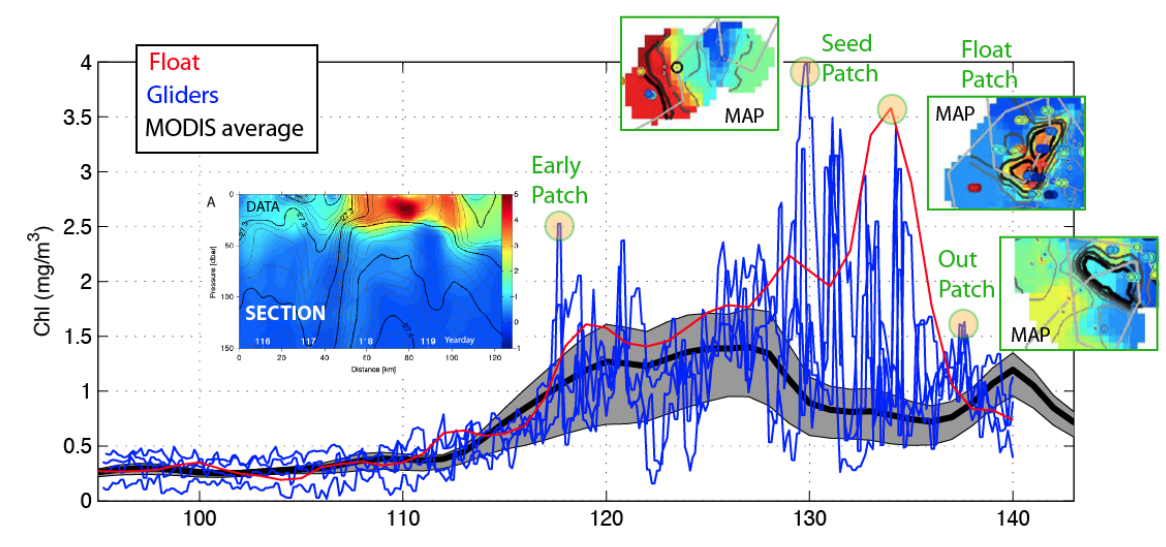


Fig. 2. Time series of chlorophyll from float (red), gliders (blue) and area averaged MODIS (gray). Mapped patches are marked, three with inset maps of chlorophyll (color), POC (contours) and silicate (colored dots). Each box is ~25x35 km. A section through the 'Early patch' is shown; 120 km long and to 150m depth.

The time histories of several patches was determined are now sketched. Fig. 3 shows time series of chlorophyll from floats, gliders and area averaged MODIS, with several of these patches labeled. The 'early patch' is the most prominent example of a patch caused by MLE; its high chlorophyll is associated with a shallow mixed layer and, thus higher light, in the upper ocean as seen in the insert section through this patch. During this time the float (red line) has a relatively low level of chlorophyll because it is in a saltier water mass with deeper mixed layers. The 'Seed patch' is in the same salty, high silicate water mass as the float, but blooms sooner, probably because it is on the edge of this water mass and thus has shallower mixed layers. Shortly afterwards, a small part of this water mass breaks away to form the 'float patch' which reaches its peak chlorophyll on day 133 as an ~15x20 km elliptical region of high chlorophyll circulating around a small anticyclonic eddy, seen in the insert map. Silicate rapidly becomes limiting in the float patch, its diatoms sink out and it disappears. Shortly afterwards, the surrounding water, which now has higher silicate, blooms to form the 'out patch.'

Each of these patches grow and die in 5-10 days. However, their areal average, seen by the MODIS band in Fig. 2, shows a more slowly evolving pattern. Thus the pattern of evolution seen by an individual plankton is different from that of the overall bloom. Furthermore, the variety of patches at any given time allows a variety of biological communities to coexist and thus increase the diversity of the bloom. It appears that the evolution of the patches is more closely tied to the actual biological processes than is that of overall bloom,

Export is dominated by the patches

Shipboard sampling and the optical community index (see below) indicate that the patches of high productivity were dominated by diatoms. Budgets (Alkire et al, 2011, above) indicate that this diatom-dominated community exports about 70% of its net community production, while the picoplankton community that succeeds it has little net export. This implies that the pattern of export is also patchy and linked to the processes controlling the patch structure.

Evolution of the phytoplankton community

The shipboard sampling during NAB08 utilized flow cytometry and imaging-in-flow technology to determine the plankton community composition, abundance and biomass over the course of the spring bloom (both within and out of the "float patch" as described

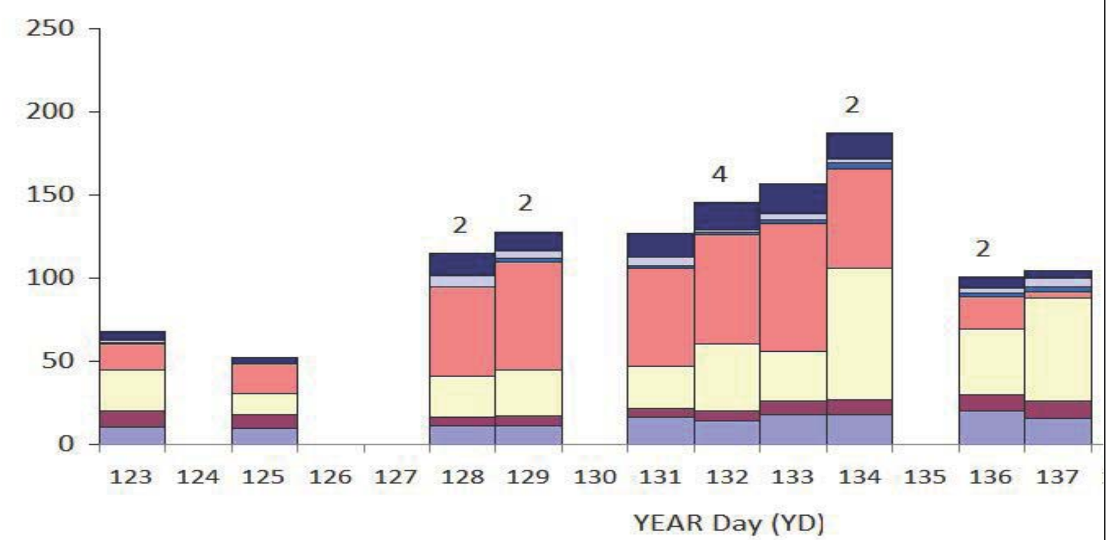


Fig. 3. Phytoplankton community composition and total plankton biomass (µg C/L) at the surface (3-10 m) as determined by flow and imaging cytometry during the NAB 2008 ship survey. Initially, carbon biomass is low (pre-bloom - YD 123-126) and gradually, the diatom biomass increases (YD 128-134). At the biomass maximum (YD 133), diatoms dominate and the bloom declines. Pico-eukaryotes, heterotrophs and bacteria increase as a proportion of the total biomass as the diatoms decrease and sink out of the water column. Numbers above bars indicate number of samples averaged.

previously). The phytoplankton community and biomass within the float patch was dominated by chains of diatoms (i.e. *Chaetoceros, Pseudo-nitzschia, Thalassionema*). As the bloom progressed the community shifted to a mix of large mixotrophic ciliates, dinoflagellates, heterotrophs and phototrophic nanoplankton (picoeukaryotes). The surface community succession coincided with a flux of carbon (diatoms sinking) and *Chaetoceros* resting stages to subsurface depths. The carbon biomass of phototrophic and heterotrophic pico-, nano- and microplankton was determined and compared to the particulate organic carbon shipboard measurements. The total plankton biomass increased over the course of the diatom bloom until YD 133 and then decreased to a post-bloom community from YD 136-141 (Figure 3).

Interpretation of optical signals

Optical indices and proxies

An optical community index (chlorophyll a fluorescence and particulate backscattering ratio – ChlF/b_{bp}), differed across community types, reflecting the change in community composition and/or phytoplankton physiological status. ChlF/b_{bp} was high when community was dominated with diatoms, as confirmed by HPLC pigment and Flow CAM analysis (Fig. 4).

The co-variability of particulate backscattering (b_{bp}) and attenuation coefficients (c_p) with particulate organic carbon (POC) provides a basis for estimating POC from autonomous platforms *in-situ* measurements, and on larger spatial and temporal scales that surpass the limitation of traditional (expensive) discrete water sampling and chemical analysis

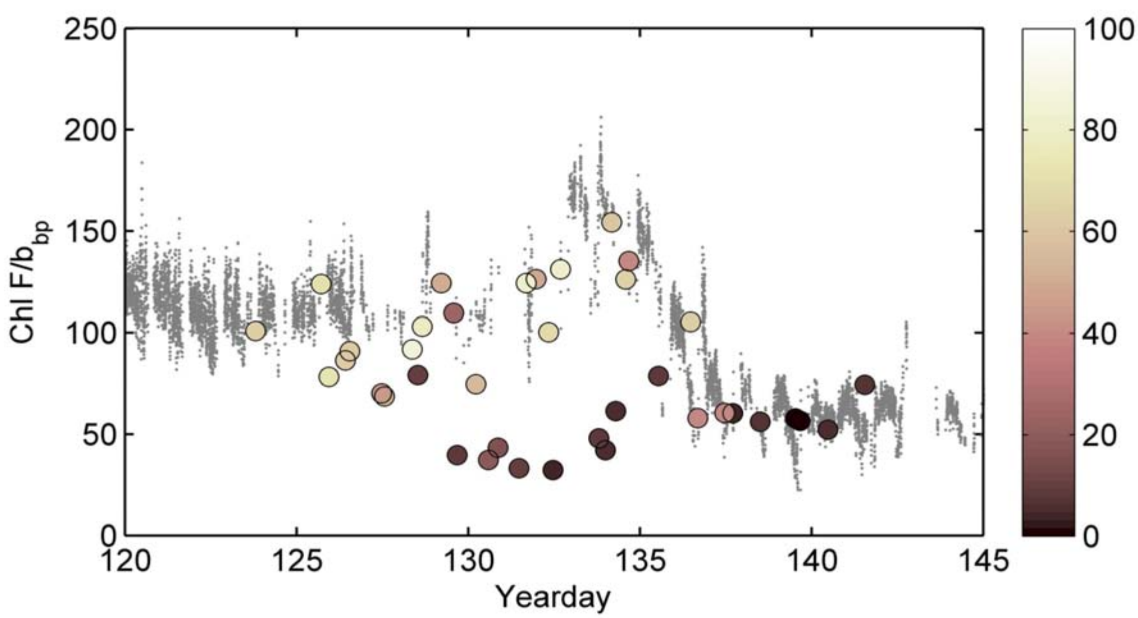


Fig. 4. Optical community proxy (ChlF/b_{bp}) changed over time, as observed in the float patch (gray dots in background). Color bar for ship data (round circles) is relative % diatom concentration as carbon.

I methods. Using an extensive dataset collected during NAB08 we show a non-linear dependency of POC/b_{bp} on particulate composition and a sharp decrease in POC/b_{bp} below the mixed layer. POC/b_{bp} did not vary with phytoplankton community composition within the mixed layer; in contrast, POC/c_p was lower for diatoms than for cells without vacuoles. These results are important for the broader community, and for remote sensing studies of POC.

nversion of optical radiances

This thesis work, by Eric Rehm, focuses on inverting data from the two hyperspectral radiometers on the Lagrangian float to compute hyperspectral optical properties (IOPs) of seawater using iterative numerical algorithms.   The first of three papers describes a simple analytical algorithm which provides an approximate inversion.

Inherent optical property estimation in deep waters, Eric Rehm and Norman J. McCormick, *Optics Express*, *submitted*

We develop two analytic algorithms for determining two inherent optical properties (IOPs) from radiometric measurements in vertically homogeneous waters. The first algorithm is for estimation of the ratio of the backscattering to absorption coefficients from measurements of only the vertically upward radiance and the downward planar irradiance at any depth not too close to the surface. The second algorithm enables estimation of the absorption coefficient from measurement of the diffuse attenuation

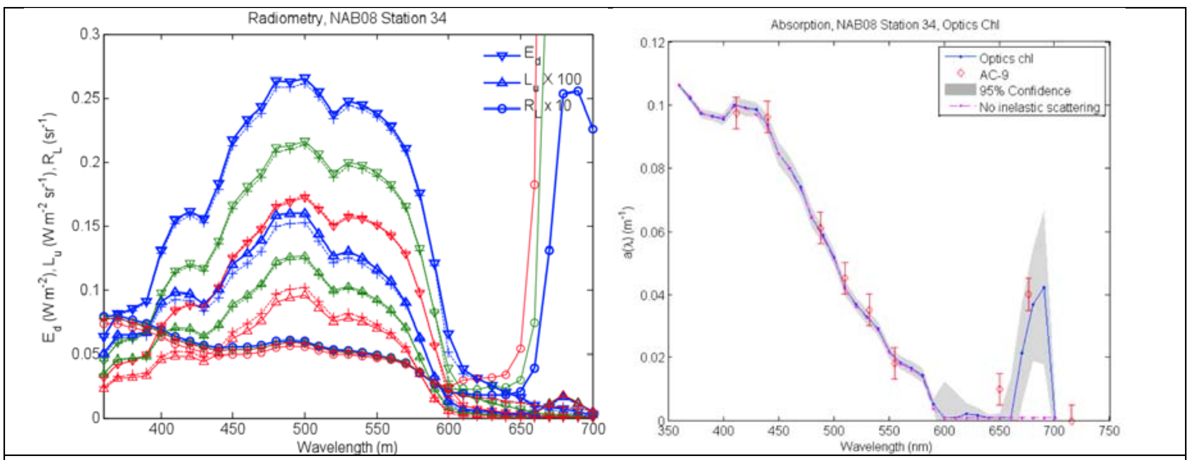


Fig. 5 Spectral absorption estimated from NAB08 radiometric measurements. Hyperspectral measurements of downward and upward radiation (left) from the Lagrangian float were inverted to compute hyperspectral absorption (right) at at Station 34 (blue) using non-linear least-squares inversions of the radiative transfer equation (Ecolight modeling program). Gray regions indicate the 95% confidence interval in absorption based first-order analysis using the Jacobian (sensitivity) matrix around the final inversion point, assuming 5% radiometric uncertainty. Spectral absorption measurements are in good agreement with direct measurement of absorption by a WET Labs AC-9 (red circles) and their associated uncertainty (+/- 0.05 m). Note that measurements beyond 550 nm require correct modeling of chlorophyll fluorescence and Raman scattering; both can be modeled by Ecolight.

coefficient at three depths or the upward radiance at two depths far from the surface and after use of the first algorithm. Multiplication of the two estimates leads to an estimate for the backscattering coefficient. The algorithms are shown to potentially provide good starting conditions for iteratively determining the absorption and backscattering coefficients of a wide variety of waters; the uncertainty in the estimates defines a subspace for IOPs that may reduce ambiguity in such iterative solutions. Because of the ease of estimating the backscattering to absorption ratio from in-water measurements, this IOP deserves further

Ongoing work shows that more complex numerical algorithms can accurately invert the hyperspectral data to compute spectra of absorption as shown in Fig. 5. Such spectra can be used in manner similar to HPLC pigment data to obtained detailed information on planktonic processes, but using data from autonomous platforms.

Activities during the last year (Oct. 2010 through September 2011) have focused on further analysis, synthesis and archiving of data collected during the 2008 field year and, in particular, on publishing these results.

Continuing coordination among NAB participants:

1) The NAB PIs communicate frequently via emails and by tele and/or video conferences.
2) A data workshop was held in August 2011, including PIs, students and postdocs, and other collaborators.
3) Graduate student supervision is highly interactive; Perry and D'Asaro have been on the committees for all four students supported by the Collaborative Research grant; Lee is on two committees. All three PIs are involved in discussions with and in mentoring the two NAB postdocs – Dr. Ivona Cetinic (at U. Maine) and Dr. Matthew Alkire (at U. Washington). Please see additional details of education and mentoring under the "Training and Development" section.

Data analysis, synthesis and archiving activities:

Calibration and quality control of the large and diverse NAB data set has been a major emphasis of our work. During the past year, the QA/QC NAB data has been submitted the BCO-DMO data base including data four cruises and five autonomous platforms along with a series of data providing details of calibration, cross calibration, analytical methodology, data analysis, quality assurance and control procedures for the NAB bottle samples, shipboard measurements and autonomous sensors. The data is available at http://osprey.bcodmo.org/project.cfm?flag=viewd&id=102&sortby=project .

Cyndy Chandler of BCO-DMO has used the NAB submission as an example of a carefully considered and well documented data sets. For example, in her talk at the OCB meeting in July 2011 she commented that the NAB sets are noteworthy because of the rigorous quality assurance procedures that we applied and because the data sets are accompanied by very complete documentation. For these reasons the data sets will be of high value to the broader oceanographic community.

Major educational activities:

Educational endeavors included mentoring of the four graduate students and two postdocs. Two students (Gray, Bagniewski) have now graduated with Masters', one (Rehm) is expected to graduate with a Ph.D. One postdoc (Alkire) now has a permanent position at APL, but continues to work NAB. The NAB PIs and collaborators worked with marine educator Annette deCharon and her group at COSEE Ocean Systems to develop and present five webinars along with a concept map and classroom exercise material associated with each webinar. These are available at http://cosee.umaine.edu/programs/webinars/nab/ . Data from this program has been incorporated data into graduate and undergraduate classes at the University of Washington and University of Maine.

Dissemination of findings:

Lee gave an invited talk at the summer OCB workshop on the lessons for autonomous ocean sampling learned from NAB08 in a special session organized by Ken Johnson and Perry – on 'Toward the Implementation of a Global Autonomous Biogeochemical Observing System'

Perry and Briggs each gave talks at the international in Alaska in late September 2010.

Perry et al. – 'The carbon to chlorophyll ratio in the ocean: do changes in the ratio reflect changing physiology, community structure, or both?'

Briggs et al. – Using spikes in optical measurement to track an aggregate flux event from autonomous platforms.

Perry presented seminars on NAB findings at the University of Southern California in March 2011 and at the University of Connecticut, Avery Point, also in March 2011.

Nicole Poulton from Bigelow Laboratory gave a seminar to the general public entitled, "Sea Truth - Chasing the North Atlantic Bloom" as part of Bigelow Laboratory's Café Scientifique Summer Lecture Series describing the 2008 North Atlantic Bloom experiment.