

Final Report for Period: 07/2008 - 12/2008**Submitted on:** 03/26/2009**Principal Investigator:** McGillicuddy, Dennis J.**Award ID:** 0241310**Organization:** Woods Hole Ocean Inst**Submitted By:**

McGillicuddy, Dennis - Principal Investigator

Title:

Collaborative Research: Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea

Project Participants**Senior Personnel****Name:** McGillicuddy, Dennis**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Jenkins, William**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Buesseler, Ken**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Ledwell, James**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Davis, Cabell**Worked for more than 160 Hours:** No**Contribution to Project:****Post-doc****Graduate Student****Undergraduate Student****Technician, Programmer****Other Participant****Research Experience for Undergraduates****Organizational Partners****Bermuda Institute of Ocean Sciences (BIOS), Inc.****University of Miami Rosenstiel School of Marine&Atmospheric Sci**

University of California-Santa Barbara

Rutgers University

College of William & Mary Virginia Institute of Marine Science

Other Collaborators or Contacts

Blair Greenan, Bedford Institute of Oceanography

Activities and Findings

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

See attached Activities.pdf file.

Findings: (See PDF version submitted by PI at the end of the report)

See attached Findings.pdf file.

Training and Development:

Undergraduate students who have participated in the project include:

Sam Galle (UCSB)

Corinne Hartin (WHOI Summer Student Fellow)

Brian Pointer (WHOI Summer Student Fellow, Evergreen College)

Graduate students who have participated in the project include:

Andreas J. Andersson (BBSR @ Univ. Hawaii)

Naomi Levine (WHOI)

Qian Li (RSMAS)

Grace Henderson (VIMS)

Bethany Eden (VIMS)

Ilaria Nardello (University of Viterbo)

Mathew Horne (URI)

Donglai Gong (Rutgers)

Sara Bender (Rutgers)

Courtney Ewart (UCSB)

Damien Kunz (UCSB)

David Ciochetto (Dalhousie University)

Sherri Whittaker (Rutgers)

Louisa Bradtmiller (Lamont Doherty Earth Observatory)

Rebecca Walsh Dell (Cambridge University)

Pinghe Cai (Xiamen University)

Elisabet Verdeny (University of Barcelona)

Raphaelle Escoube (University of Paris)

Carolyn Walker (University of Otago)

Postdoctoral fellows who have participated in the project include:

Beatriz Mourino (WHOI)

Sarah Goldthwait (VIMS)

Thomas Bibby (Rutgers)

Diana Nemmergut (Rutgers)

Stephan Duller (Rutgers)

Carl Lamborg (WHOI)

International collaborators:

Pere Masque

Institut de Ciència i Tecnologia Ambientals - Departament de Física

Universitat Autònoma de Barcelona

The BATS technicians who have worked on the EDDIES project over the lifetime of the award have gained a significant level of new research skill and experience. During the summers of 2004 and 2005, several of the technicians participated in eight EDDIES cruises on board the R/V Oceanus and R/V Weatherbird II. New instrumentation (e.g., SAMI sensor) was deployed with training involved. Technicians gained new skills associated with the pre-cruise preparations, cruise participation, and post-cruise activities.

Outreach Activities:

The WHOI magazine called Oceanus published an article on the EDDIES project. The online version is available at

<http://www.whoi.edu/oceanus/viewArticle.do?id=10592>

We also have developed a project web site

http://science.whoi.edu/users/olga/eddies/EDDIES_Project.html

A high school teacher (Jim Dornicik) participated on Jim Ledwell's cruise OC415-2 as part of the NSF Armada Project; see

<http://www.armadaproject.org/rsrch-exp/2005-2006/dornicik.htm>.

An article on the zooplankton component of the EDDIES project appeared in the Virginia Institute of Marine Science (VIMS publication The Crest (Fall 2004, Vol 6, No. 2; <http://www.vims.edu/newsmedia/crest.html>) for which Steinberg and Goldthwait were both interviewed. We also use EDDIES samples in our participation in several career days at local high schools.

Steinberg regularly uses EDDIES results, and samples, in her Biological Oceanography and Zooplankton Ecology courses. Goldthwait gave a guest lecture on the zooplankton component of the EDDIES project to a 'Plankton Ecology' class at VIMS in Fall 2005. Steinberg participated in VIMS Marine Science Day by inviting K-12 students and their parents into her lab to learn about and look at zooplankton samples collected on various cruises.

Goldthwait was invited to participate in the Energy, Environment, and Society / Sustainable Futures speaker series sponsored by the Schatz Energy Research Center at Humboldt State University. In November of 2006, she gave a presentation to a mixed audience of scientists and the general public titled 'Plankton and CO₂: The Role of Marine Organisms in Global Climate', discussing EDDIES work.

In October 2006, Goldthwait set up an educational display focused on phytoplankton and zooplankton, using EDDIES samples, at the HSU Natural History Museum's Biodiversity Day. This special event was designed primarily for elementary and middle school children.

In June 2006, Goldthwait helped to organize a symposium for Oceanography alumni at Humboldt State University. This symposium featured both science and career talks spanning several disciplines. Goldthwait gave a broad overview of the EDDIES project to this general interest audience.

Students from BIOS's (formerly BBSR) microbial observatory summer course in Marine Microbial Ecology participated in biogeochemical cruises to hydrostation S in 2004, 2005 and 2006, where they learned basic oceanic sampling skills, collecting environmental samples to serve as a comparative data set for the eddies samples. The trips in 2004 and 2005 were designed in the context of the EDDIES program, as they occurred between the biogeochemical transects of the eddies aboard the R/V Weatherbird II during each field season.

Ewart presented lectures about the EDDIES project and microbial findings to undergraduates in two courses at UCSB: introductory biology and methods in aquatic biology.

Carlson presented a general lecture to incoming graduate students at UCSB, a component of which discussed mesoscale perturbations and biological response.

An undergraduate at UCSB has received training in basic marine microbiological methods and was involved in processing bacterial abundance

slides from higher resolution transects of the eddy performed aboard the R/V Oceanus.

Hansell has incorporated the findings of our research into lectures given to students at all levels and to the public. He has given lectures to senior citizens who return to the university for homecoming week, and discussed EDDIES results with those in the public generally interested in ocean sciences and climate change issues. He serves with scientific steering committees that have a role in directing future research priorities, and these priorities stem from EDDIES research findings.

Bates frequently gives talks to visiting schools and other groups on the research that is being conducted at BIOS and its relevance. This activity is geared to inform the local Bermuda populace of the important work that is being done at the BIOS. Recently, Bates has been interviewed several times for popular press articles on ocean acidification, and interviewed for several TV/film documentaries on CO₂ and climate change (including a Discovery Channel documentary and local TV channels).

The EDDIES project (and the complementary BATS project) have provided a central focus for outreach and development activities at BIOS including fund-raising for BIOS's new research vessel, R/V Atlantic Explorer.

Results have been presented at numerous seminars, both national and internationally. Presentations include:

McGillicuddy, D.J. Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea. AOPPE Departmental seminar, WHOI, September, 2006.

Ledwell, J.R. Upwelling in a mode water eddy in the Sargasso Sea. AOPPE Departmental seminar, WHOI, September, 2006.

McGillicuddy, D.J. Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea. National Oceanography Center, Southampton, UK, November, 2006.

Ledwell, J.R. A tracer measurement of nutrient flux in a mode water eddy. Departmental Seminar, Lamont Doherty Earth Observatory, March, 2007.

McGillicuddy, D.J. Oases in the Oceanic Desert: Turbulent Storms in the Sea and their Impact on Biological Productivity. Rosenstiel School of Marine and Atmospheric Science, April, 2008.

Ewart, C.S, Carlson, C.A, Meyers, M. Heterotrophic microbial processes and community structure inside a cyclonic eddy in the Sargasso Sea. EEMB annual research symposium, Santa Barbara, UCSB, January, 2005.

Ewart, C.S. Impact of a mesoscale feature on prokaryotic dynamics and community structure in the Sargasso Sea. IGPMS spring seminar series, Santa Barbara, UCSB, May, 2005.

Ewart, C.S. Heterotrophic microbial stocks and rates within two eddies in the Sargasso Sea. EEMB annual research symposium, Santa Barbara, UCSB, January, 2006.

Siegel, D, A, and S. Mitarai. Mixing and stirring in aquatic ecosystems: a micro scale review. Invited mini-review presentation, 2007 ASLO Winter Meeting, Santa Fe, NM, February, 2007.

Siegel, D.A. Ocean color from space. Invited presentation at the 2007 Ocean Carbon and Biogeochemistry meeting, Woods Hole MA, July, 2007.

Journal Publications

Mourino B., and McGillicuddy, D.J., "Mesoscale Variability in the Metabolic Balance of the Sargasso Sea", *Limnology & Oceanography*, p. 2675, vol. 51, (2006). Published,

Davis, C.S., and McGillicuddy, D.J., "Transatlantic Abundance of the N₂-Fixing Colonial Cyanobacterium *Trichodesmium*", *Science*, p. 1517, vol. 312, (2006). Published,

- McGillicuddy, D.J., et. al., "Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms", *Science*, p. 1021, vol. 316, (2007). Published,
- Buesseler, K.O., Lamborg, C., Cai, P., Escoube, R., Johnson, R., Pike, S., Masque, P., McGillicuddy, D.J., Verdeny, E., "Particle Fluxes Associated with Mesoscale Eddies in the Sargasso Sea", *Deep-Sea Research II*, p. 1426, vol. 55, (2008). Published,
- Ewart, C.S., Meyers, M.K., Wallner, E., McGillicuddy, D.J., Carlson, C.A., "Microbial Dynamics in Cyclonic and Anticyclonic Mode-Water Eddies in the Northwestern Sargasso Sea", *Deep-Sea Research II*, p. 1334, vol. 55, (2008). Published,
- Andrews, J.E., Hartin, C., Buesseler, K.O., "7Be Analyses in Seawater by Low Background Gamma-Spectroscopy", *Journal of Radioanalytical and Nuclear Chemistry*, p. 253, vol. 277, (2008). Published,
- Benitez-Nelson, C.R. and McGillicuddy, D.J., "Mesoscale Physical-Biological-Biogeochemical Linkages in the Open Ocean: An Introduction to the Results of the E-Flux and EDDIES Programs", *Deep-Sea Research II*, p. 1133, vol. 55, (2008). Published,
- Jenkins, W.J., McGillicuddy, D.J., Lott III, D.E., "The Distributions of, and Relationship Between ^3He and Nitrate in Eddies", *Deep-Sea Research II*, p. 1389, vol. 55, (2008). Published,
- Ledwell, J.R., McGillicuddy, D.J., Anderson, L.A., "Nutrient Flux into an Intense Deep Chlorophyll Layer in a Mode-water Eddy", *Deep-Sea Research II*, p. 1139, vol. 55, (2008). Published,
- McGillicuddy, D.J., Ledwell, J.R., Anderson, L.A., "Response to Comment on "Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Bloom"", *Science*, p. , vol. 320, (2008). Published, doi:10.1126/science.1148974
- Bibby, T.S., Gorbunov, M.Y., Wyman, K.W., Falkowski, P.G., "Photosynthetic community responses to upwelling in mesoscale eddies in the subtropical North Atlantic and Pacific Oceans", *Deep-Sea Research Part II: Topical Studies in Oceanography*, p. 1310, vol. 55, (2008). Published,
- Goldthwait, S.A. and Steinberg, D.K., "Elevated biomass of mesozooplankton and enhanced fecal pellet flux in cyclonic and mode-water eddies in the Sargasso Sea", *Deep-Sea Research Part II: Topical Studies in Oceanography*, p. 1360, vol. 55, (2008). Published,
- Greenan, B.J.W., "Shear and Richardson number in a mode-water eddy", *Deep-Sea Research Part II: Topical Studies in Oceanography*, p. 1161, vol. 55, (2008). Published,
- Li, Q.P., Hansell, D.A., McGillicuddy, D.J., Bates, N.R., Johnson, R.J., "Tracer-based assessment of the origin and biogeochemical transformation of a cyclonic eddy in the Sargasso Sea", *Journal of Geophysical Research*, p. 10006, vol. 113, (2008). Published, doi:10.1029/2008JC004840
- Carlson, C.A., del Giorgio, P., Herdl, G., "Microbes and the dissipation of energy and respiration: From cells to ecosystems", *Oceanography*, p. 89, vol. 20, (2007). Published,
- Li, Q.P., Zhang, J.-Z., Millero, F.J., Hansell, D.A., "Continuous colorimetric determination of trace ammonium in seawater with a long-path liquid waveguide capillary cell", *Marine Chemistry*, p. 73, vol. 96, (2005). Published,
- Li, Q.P. and Hansell, D.A., "Intercomparison and coupling of MAGIC and LWCC techniques for trace analysis of phosphate in seawater", *Analytical Chimica Acta*, p. 68, vol. 611, (2008). Published,
- Li, Q.P., Hansell, D.A., Zhang, J.-Z., "Underway monitoring of nanomolar nitrate plus nitrite and phosphate in oligotrophic seawater", *Limnology and Oceanography: Methods*, p. 319, vol. 6, (2008). Published,
- Buesseler, K.O. and Boyd, P.W., "Shedding light on processes that control particle export and flux attenuation in the twilight zone of the open ocean", *Limnology and Oceanography*, p. , vol. , (2008). Accepted,

Eden, B.R., Steinberg, D.K., Goldthwait, S.A., McGillicuddy, D.J., "Zooplankton Community Structure in a Cyclonic and Mode-water Eddy in the Sargasso Sea", *Deep-Sea Research I*, p. , vol. , (2008). Submitted,

Li, Q.P., Bibby, T.S., Hansell, D.A., Falkowski, P.G., "Nutrient and light interactions within an intense deep-chlorophyll-maximum in a warm-core eddy", *Journal of Marine Systems*, p. , vol. , (2008). Submitted,

Books or Other One-time Publications

Eden, B.R., Steinberg, D.K., Goldthwait, S.A., McGillicuddy, D.J., "The Effect of Mesoscale Eddies on Zooplankton Community Structure in the Sargasso Sea", (2007). Abstract, Published

Bibliography: ASLO 2007 Aquatic Sciences Meeting, Sante Fe, NM, Abstract Number 196

Anderson, L.A., McGillicuddy, D.J., Ledwell, J.R., "Plankton Bloom in a Mode-Water Eddy Caused by Eddy-Wind Interactions", (2008). Abstract, Published

Bibliography: Ocean Sciences 2008, Orlando, FL, Conference Abstract Book, p. 14.

Marsay, C.M., Sedwick, P.N., Johnson, R.J., Lohan, M.C., McGillicuddy, D.J., Church, T.M., "Pronounced Temporal and Mesoscale Variability of Dissolved Iron in the Sargasso Sea (BATS Region)", (2008). Abstract, Published

Bibliography: Ocean Sciences 2008, Orlando, FL, Conference Abstract Book, p. 286.

Neely, K., Bates, N.R., Johnson, R.J., McGillicuddy, D.J., "The Influence of Mesoscale Eddies on Inorganic Carbon Cycling and Air-Sea CO₂ Gas Exchange in the North Atlantic Ocean", (2008). Abstract, Published

Bibliography: Ocean Sciences 2008, Orlando, FL, Conference Abstract Book, p.327

Benitez-Nelson, C.R. and McGillicuddy, D.J., "Eddies and Fronts: Mesoscale Physical-Biological-Biogeochemical Linkages in the Open Ocean", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS16D

Ewart, C.S., Carlson, C.A., Meyers, M., Wallner, E., "Impact of Eddies on Heterotrophic Microbial Processes in the Sargasso Sea Eos Trans", (2006). Abstract, Published

Bibliography: AGU, 87(36), Ocean Sci. Meet. Suppl., Abstract OS16D-10

Goldthwait, S., Steinberg, D.K., McGillicuddy, D.J., "Elevated Biomass of Mesozooplankton and Enhanced Fecal Pellet Flux in Cold-Core and Mode-Water Eddies in the Sargasso Sea", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS14H-05

Greenan, B.J. and Ledwell, J.R., "Fine Structure Measurements in a Mode Water Eddy", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS13H-06

Goldthwait, S.A., McGillicuddy, D.J., Davis, C., "VPR visualization of a mode-water eddy diatom bloom", (2006). Abstract, Published

Bibliography: Abstract, Published Bibliography: American Geophysical Union Fall Meeting, San Francisco, CA.-Program Abstracts

Jenkins, W.J. and McGillicuddy, D.J., "Vertical Nutrient Transport in Cyclonic and Anticyclonic Eddies in the Sargasso Sea as Evidenced from ³He Distributions", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS14H-01

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS14H-01

Johnson, R.J., Bates, N.R., McGillicuddy, D.J., Anderson, A., Bell, S., Buck, N., Lethaby, P.J., Lochhead, V.L., Lomas, D., Neely, K., Roadman, M.J., Pequignet, M.J., Pluvinage, S., "Mesoscale Eddy Variability in the Sargasso Sea and its Impact on Upper Ocean Biogeochemistry", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS13H-03

Ledwell, J.R., McGillicuddy, D.J., Anderson, L., Girton, J.B., Greenan, B., "Diapycnal Fluxes at the Base of the Euphotic Zone in a Mode-water Eddy", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS13H-04

Li, Q., McGillicuddy, D.J., Hansell, D.A., Bates, N.R., Jenkins, W.J., Johnson, R., "Biogeochemical Impacts of a Cyclonic Eddy in the Sargasso Sea", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS14H-02

McGillicuddy, D.J., Bates, N., Bibby, T., Buesseler, K., Carlson, C., Davis, C.S., Falkowski, P., Goldthwait, S., Hansell, D.A., Jenkins, W., Johnson, R., Ledwell, J., Li, Q., Siegel, D., Steinberg, D., "Impacts of Eddies and Mixing on Plankton Community Structure and Biogeochemical Cycling in the Sargasso Sea", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS13H-02

Menzies, D.W., Court, D.B., Nelson, N.B., Siegel, D.A., "Observations of Light Climate and the Ocean Color of EDDIES in the Sargasso Sea", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS16D-11

Mourino-Carballido, B. and McGillicuddy, D.J., "Investigating the Role of Mesoscale Eddies in the Metabolic Balance of Subtropical Regions", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS16D-08.

Nardello, I. and McGillicuddy, D.J., "Impact of Mesoscale Eddy Activity in the Sargasso Sea on the Summertime Distribution of Phytoplankton", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS16D-09

Neely, K., Bates, N.R., Johnson, R.J., McGillicuddy, D.J., "The Influence of Mesoscale Eddies on Inorganic Carbon Cycling and Air-Sea CO₂ Gas Exchange in the North Atlantic Ocean", (2008). Abstract, Published

Bibliography: Ocean Sciences 2008, Orlando, FL, Conference Abstract Book, p. 327

Pointer, B., Pike, S., Lamborg, C., Andrews, J., Verdeny, E., Cai, P., Henderson, P., McGillicuddy, D.J. and Buesseler, K., "Particle Export During EDDIES", (2006). Abstract, Published

Bibliography: Ocean Sciences 2006, Honolulu, Hawaii, Abstract# OS14H-06

Roadman, M.J., Bates, N.R., Johnson, R.J., McGillicuddy, D.J., Anderson, A., Bell, S., Buck, N., Lethaby, P., Lomas, D., Neely, K., Pequignot, C., Pluvinage, S., Lochhead, V., "Overview of EDDIES Transect cruises in the Sargasso Sea", (2006). Abstract, Published

Bibliography: Ocean Sciences, Honolulu, Hawaii, Abstract# OS16D-07

Web/Internet Site

URL(s):

http://science.whoi.edu/users/mcgillic/eddies_test/EDDIES_Project.html

Description:

Other Specific Products

Product Type:

Data or databases

Product Description:

EDDIES PI Steinberg maintains an extensive database (in microsoft Access) containing size fractionated zooplankton biomass and major taxonomic composition data for discrete depth intervals from 0-700m for EDDIES cruises in summer 2004 and 2005.

Sharing Information:

Zooplankton biomass data are currently being prepared for transfer into the Ocean Carbon and Biogeochemistry database.

http://ocb.whoi.edu/data_collection.html

<http://ocb.whoi.edu/eddies.html>

Product Type:

Physical collection (samples, etc.)

Product Description:

EDDIES PI Steinberg maintains archived, buffered formaldehyde-preserved samples of all zooplankton tows from both study sites (in discrete depth intervals from 0-700m).

Sharing Information:

The availability of these samples will be noted on the Ocean Carbon and Biogeochemistry web site.

http://ocb.whoi.edu/data_collection.html

<http://ocb.whoi.edu/eddies.html>

Contributions

Contributions within Discipline:

The data collected as part of the EDDIES research program will contribute significantly to the field of oceanography. This contribution is in the form of better understanding of the impact of mesoscale eddies on the biogeochemical dynamics of carbon and nitrogen, and the ecology of the North Atlantic subtropical gyre.

Contributions to Other Disciplines:

Our measurements advance understanding of the complex interactions between physics and biology in eddies, to elucidate the role mesoscale features play in structuring plankton communities and influencing biogeochemical cycling. This type of knowledge is an essential component of the larger field of earth system science, as we begin to understand coupled physical-biogeochemical processes on a global scale.

Contributions to Human Resource Development:

Several of the themes emerging from EDDIES findings were woven into course materials for a graduate course in the MIT/WHOI Joint Program co-taught by Drs. McGillicuddy, Solow, and Sosik entitled 'Topics in Quantitative Marine Science (7.430): Linking Models and Observations in Marine Planktonic Ecosystems.' The course emphasized the use of models in hypothesis driven research. We surveyed the continuum of complexity in modeling approaches, ranging from simple NPZ models in zero-dimensional physical frameworks to complex ecosystem formulations coupled to three-dimensional circulation models. We explored various levels of sophistication in connecting models with observations, from qualitative comparisons to statistical techniques involving parameter estimation and model selection. The goals included providing students with 1) hands-on experience with simple models and 2) enough familiarity with more complex models and techniques for critical reading of literature and facilitation of collaborative interactions with modeling experts from a range of disciplines.

The information and data generated as part of the EDDIES project was integrated into undergraduate courses taught at the BIOS as part of the Duke University-BIOS Beaufort to Bermuda course in Biological Oceanography. Bates also incorporated research findings from the EDDIES project into lectures for the second SOLAS summer school in Corsica in September 2005, and into a summer course on chemical oceanography to be conducted at BIOS in summer 2008.

We have provided research experience for females at several different levels: undergraduate students(1), graduate students(11), and postdocs (3).

Contributions to Resources for Research and Education:

Information about this project has been publicly disseminated via newspaper and online articles, publicly available websites, and through visits to K-12 student classrooms. Our data have also been integrated into the teaching framework of graduate and undergraduate level courses relating to plankton ecology.

EDDIES data have been ingested into the Ocean Carbon Biogeochemistry Data System:

<http://ocb.whoi.edu/>

EDDIES bio-optical data have also been submitted to NASA's SeaBASS data system:

<http://seabass.gsfc.nasa.gov/>

Contributions Beyond Science and Engineering:

None to report.

Categories for which nothing is reported:

Research and Education

Our primary activity during the final year was analysis and synthesis of the EDDIES field work. A key aspect of this synthesis effort was comparative analysis with the E-FLUX program. The results of this were recently published in a special issue of *Deep-Sea Research II* volume 55 (issues 10-13) entitled *Mesoscale Physical-Biological-Biogeochemical Linkages in the Open Ocean: Results from the E-FLUX and EDDIES Programs*, edited by Claudia Benitez-Nelson and D. J. McGillicuddy. This volume of 26 papers draws on the results of both programs to synthesize new findings on eddy-driven biogeochemical processes:

E-FLUX: <http://www.soest.hawaii.edu/oceanography/eddy/eddy.html>

EDDIES: http://science.whoi.edu/users/olga/eddies/EDDIES_Project.html

These two studies targeted different types of eddies in different regions: E-FLUX focused on wind-driven eddies in the lee of Hawaii, whereas EDDIES focused on mid-ocean cyclones and mode-water eddies (MWEs). Our objective was to produce a volume that will contain cutting-edge research papers from both programs, as well as providing a basis for comparative analysis. Authors were encouraged to compare and contrast their results with other findings from both within and between projects, and a web site was set up to facilitate exchange of manuscripts as they were being drafted:

http://science.whoi.edu/users/mcgillic/DSRII/E-FLUX_EDDIES_DSRII.htm

Findings

The EDDIES program sampled ten different eddies in varying degrees of detail in the Sargasso Sea off Bermuda (McGillicuddy et al., 2007), whereas the E-Flux program was comprised of three cruises in the lee of the Hawaiian Islands that sampled two cold-core cyclonic eddies of different ages (Benitez-Nelson et al., 2007). The joint EDDIES/E-FLUX synthesis effort focused on the question of why are the biological and biogeochemical responses within the sampled eddies so different and complex (Benitez-Nelson and McGillicuddy, 2008). It is likely due to a combination of variations in the magnitude, timing, and duration of nutrient input caused by differences in eddy formation, intensity, age, and movement as shown in this volume and previously (Bibby et al., 2008; Brown et al., 2008; McGillicuddy et al., 1999; Nencioli et al., 2008; Olaizola et al., 1993; Rii et al., 2008; Sweeney et al., 2003). For example, Hawaiian lee cyclones (and anticyclones) appear to be wind-driven, formed by a combination of strong northeasterly winds and island topography (Chavanne et al., 2002; Lumpkin, 1998; Patzert, 1969), whereas mid-ocean eddies in the Sargasso Sea are formed by instability processes that feed on the larger scale flow (Robinson, 1983). Once formed, cyclones and MWEs may also respond differently to eddy-wind interactions. A spatially uniform wind forcing over an eddy gives rise to mesoscale variations in surface stress because the wind blows in the same direction on one flank of the eddy and opposes it on the other. This effect causes upwelling in the interiors of anticyclones (Dewar and Flierl, 1987; Martin and Richards, 2001), which reinforces eddy-induced upwelling in MWEs (Ledwell et al., 2008; McGillicuddy et al., 2007). In contrast, this same type of eddy-wind interaction tends to depress the isopycnal uplift associated with cyclones (McGillicuddy et al., 2007).

Despite the many differences among the eddies sampled by the two programs, it is clear that cyclones in both the Atlantic and Pacific can result in substantial nutrient injection. Cyclones *Opal* and C1 were both relatively strong features, with eddy-induced nitrate injections estimated to be 0.2 mol m^{-2} (Mahaffey et al., 2008) and 1.4 mol m^{-2} (Jenkins et al., 2008), respectively. Interestingly, of all the cyclones that have been sampled intensively in the lee of Hawaii (Table 1, Benitez-Nelson and McGillicuddy, 2008) and in the Sargasso Sea (Table S1, (McGillicuddy et al., 2007), only Cyclone *Opal* contained an extraordinary diatom bloom. Others contained more modest enhancements of diatoms (a factor of two or less), whereas some did not appear to perturb phytoplankton community structure at all.

Why was Cyclone *Opal* unique in this regard? Cyclone *Opal* was characterized by very large isopycnal displacements of over 100 m at the eddy core relative to surrounding waters and was less than 6 weeks in age (Dickey et al., 2008; Nencioli et al., 2008). The only other Hawaiian cyclone studied to date to have similarly large displacements in isopycnal surfaces was Cyclone *Haulani*, a month older (Vaillancourt et al., 2003), yet no increase in diatom biomass was observed. However, Vaillancourt et al. (2003) report a relative minimum in Si:N within *Haulani*'s core, consistent with a prior diatom bloom. Thus, older Cyclone *Haulani* may have already peaked in diatom biomass prior to sampling. That being said, eddy age may not be the only issue. As Rii et al. (2008) and Brown et al. (2008) point out, the absolute magnitude and rate of nutrient injection, e.g. due to wind intensity and/or eddy movement (Nencioli et al., 2008), at any point within an eddy's life cycle may influence the composition of the biological community. For example, Cyclone *Noah*, at 2.5 months of age, was relatively weak and

provided no evidence that a substantial diatom bloom had ever occurred. The same is true for young (1 month) and weak Cyclone *Mikalele*, whereas Cyclone *Loretta* was older (6 months) yet still strong enough that it accommodated a two-fold enhancement in diatoms (Seki et al., 2001).

Why hasn't a diatom bloom similar to that found in *Opal* ever been observed in a Sargasso Sea cyclone? The answer may in part be due to sampling. The E-Flux experimental design took advantage of predictability in the formation region for wind-driven cyclones, and sampling of a young and strong cyclone revealed the presence of diatoms in large numbers. However, that response was ephemeral, as diatom abundance decreased by 50% during the 9 days the E-Flux team was on site (Brown et al., 2008; Rii et al., 2008). In contrast, formation of cyclones in the Sargasso Sea is unpredictable by virtue of the geophysical turbulence processes that create them. These features are detectable by satellite altimetry (and more weakly in ocean color; Siegel et al., 2008), but sampling thus far may have been biased toward mature cyclones with stronger expressions in satellite observations. As a result, if diatom blooms have occurred in the initial formation and intensification phases of Sargasso Sea cyclones, they could have been missed (McGillicuddy et al., 2007; Bibby et al., 2008).

In contrast to cyclones in the Sargasso Sea and in the lee of Hawaii, Sargasso Sea MWEs have a tendency to contain significant numbers of diatoms, regardless of eddy age (McGillicuddy et al., 2007; McNeil et al., 1999; Sweeney et al., 2003). Sustainance of longer-lasting diatom blooms inside MWEs may be due to upwelling driven by eddy-wind interactions described above as well as enhanced mixing caused by trapping of near-inertial motions (Kunze, 1985). Evidence of both mechanisms was revealed in the tracer release experiment in MWE A4 (Ledwell et al., 2008), and fine-structure measurements in the core of that feature are consistent with enhanced mixing (Greenan, 2008). Although the nutrient flux of $0.6 \text{ mmol N m}^{-2} \text{ d}^{-1}$ inferred from the tracer release experiment in MWE A4 is not particularly large (Ledwell et al., 2008), the character of the $^3\text{He-NO}_3$ relationship suggests steady upwelling (Jenkins et al., 2008). Thus, we hypothesize that it is the persistence of the nutrient flux that leads to the extraordinary biological response in MWE A4.

Given the strong biological responses of large phytoplankton in Cyclone *Opal* and MWE A4 it is surprising that neither feature showed any *direct* evidence of enhanced overall particulate carbon export either by sediment traps or by ^{234}Th : ^{238}U and ^{210}Pb : ^{210}Po disequilibria during the field campaigns (Buesseler et al., 2008; Maiti et al., 2008; Rii et al., 2008; Verdeny et al., 2008). Rather, enhanced export was only observed in particulate silica, with a small increase in zooplankton fecal pellet production. Silica export was three to four times higher than ambient waters in both Cyclone *Opal* (Maiti et al., 2008; Rii et al., 2008; Verdeny et al., 2008) and MWE A4 (Buesseler et al., 2008), suggesting that eddies may play a role in the removal of silicate from surface waters. Enhanced silicate removal would thus drive these already oligotrophic systems towards silica stress and minimize the potential for diatom growth in future upwelling events (Benitez-Nelson et al., 2007; Rii et al., 2008). Additionally, enhanced zooplankton fecal pellet flux was observed in Cyclone C1 and MWE A4. Although increased fecal pellet POC flux did not enhance overall particulate C flux, eddies appear to affect higher trophic level community structure which in turn influences the composition and quantity of sinking particles (Goldthwait and Steinberg, 2008).

Although significant enhancement of particulate carbon flux was not observed in either E-Flux or EDDIES field programs, it is possible that the export events were somehow missed. Both C1 and A4 contained mesopelagic oxygen anomalies that, if interpreted as the geochemical signature of prior export events, amount to 1-3 times annual new production for the region (McGillicuddy et al., 2007), even after accounting for cyclone C1's potential distant water origin (Li et al., Submitted). Why no similar evidence of a large export event has been observed in any of the Hawaiian lee eddies is unknown. According to the "leaky bottom" model proposed by Nencioli et al. (2008), Cyclone *Opal* may have left a trail of its biological and biogeochemical signature in its wake as it translated, similar to the conceptual model introduced by (Olaizola et al., 1993). This is consistent with the generally shallow penetration of Hawaiian lee eddies and would not allow for a coherent oxygen deficit to form at depth. The same might be true for Cyclone *Noah*, although this eddy remained spatially stable and there is no evidence to suggest that the wake hypothesized in the leaky bottom model occurred (Kuwahara et al., 2008).

The biomass produced by eddy-induced blooms may also have fates other than particle export. Observations within Cyclone *Opal* indicate that rapid microzooplankton grazing by large (> 50 μm) ciliates and dinoflagellates released suspended and dissolved organic matter (Landry et al., 2008b) rather than producing fecal pellets. This finding is consistent with mass balance estimates of nutrients and inorganic and organic carbon, which suggests that most of the new production within Cyclone *Opal* accumulated as dissolved organic matter (Chen et al., 2008). In contrast, Li et al. (submitted) found no evidence of dissolved organic matter accumulation within the euphotic zone in cyclone C1.

It is important to note here that zooplankton may play a role in organic matter transport beyond fecal pellet production. Both Goldthwait and Steinberg (2008) and Landry et al. (2008b) found an increase in mesozooplankton biomass and grazing within MWE A4 and Cyclone *Opal*, respectively, which resulted in migrant mediated active export fluxes that were 43 and 50% of that measured within corresponding sediment trap deployments. Within Cyclone *Opal*, active transport may reconcile ^{15}N based nitrogen mass balance estimates (Landry et al., 2008b). However, active transport is still not sufficient to explain the magnitude of the oxygen deficits observed at depth in cyclone C1 or MWE A4 (Goldthwait and Steinberg, 2008).

The mechanisms that control export of material out of the euphotic zone thus remain enigmatic. In neither the Pacific nor the Atlantic are the observed particle fluxes sufficient to balance geochemical estimates of new production (e.g. Jenkins, 1982; Schulenberger and Reid, 1981). One hypothesis underlying both the E-Flux and EDDIES programs was that episodic pulses of organic matter might be undersampled in existing databases, perhaps explaining the imbalances in mass budgets computed from time-series observations (e.g. Michaels et al., 1994). Although the deep oxygen anomalies present in C1 and A4 are suggestive of significant export events, the fact remains that neither E-Flux nor EDDIES were able to directly measure substantially enhanced particulate carbon fluxes associated with mesoscale eddies. While sampling may still be an issue, it is clear that the rarer such export events are, the more extraordinary the particle fluxes will have to be in order to dominate the mean flux.

References

- Benitez-Nelson, C.R. et al., 2007. Mesoscale eddies drive increased silica export in the subtropical Pacific Ocean. *Science*, 316(5827): 1017-1021.
- Benitez-Nelson, C.R. and McGillicuddy, D.J., 2008. Mesoscale physical-biological-biogeochemical linkages in the open ocean: An introduction to the results of the E-Flux and EDDIES programs. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1133-1138.
- Bennett, A.F., 1976. Open boundary conditions for dispersive waves. *Journal of Atmospheric Science*, 33: 176-182.
- Bibby, T.S., Gorbunov, M.Y., Wyman, K.W. and Falkowski, P.G., 2008. Photosynthetic community responses to upwelling in mesoscale eddies in the subtropical North Atlantic and Pacific Oceans. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1310-1320.
- Brown, S.L. et al., 2008. Diatoms in the desert: Plankton community response to a mesoscale eddy in the subtropical North Pacific. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1321-1333.
- Buesseler, K.O. et al., 2008. Particle fluxes associated with mesoscale eddies in the Sargasso Sea. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1426-1444.
- Chavanne, C., Flament, P., Lumpkin, R., Dousset, B. and Bentamy, A., 2002. Scatterometer observations of wind variations by oceanic islands: Implications for wind driven ocean circulation. *Canadian Journal of Remote Sensing*, 28: 466-474.
- Chen, F. et al., 2008. The carbon dioxide system and net community production within a cyclonic eddy in the lee of Hawaii. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1412-1425.
- Dewar, W.K. and Flierl, G.R., 1987. Some effects of wind on rings. *Journal of Physical Oceanography*, 17: 1653-1667.
- Dickey, T.D. et al., 2008. Physical and bio-optical observations of oceanic cyclones west of the island of Hawai'i. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1195-1217.
- Goldthwait, S.A. and Steinberg, D.K., 2008. Elevated biomass of mesozooplankton and enhanced fecal pellet flux in cyclonic and mode-water eddies in the Sargasso Sea. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1360-1377.
- Greenan, B.J.W., 2008. Shear and Richardson number in a mode-water eddy. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1161-1178.
- Jenkins, W.J., McGillicuddy, D.J. and Lott, D.E., 2008. The distributions of, and relationship between, ^3He and nitrate in eddies. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1389-1397.
- Kunze, E., 1985. Near-inertial wave propagation in geostrophic shear. *Journal of Physical Oceanography*, 15: 544-656.
- Ledwell, J.R., McGillicuddy, D.J. and Anderson, L.A., 2008. Nutrient flux into an intense deep chlorophyll layer in a mode-water eddy. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1139-1160.
- Li, Q.P., Hansell, D.A., McGillicuddy, D.J., Bates, N.R. and Johnson, R.J., Submitted. Biogeochemical impacts of a cyclonic eddy in the Sargasso Sea. *Deep-Sea Research I*.
- Lumpkin, C.F., 1998. Eddies and currents in the Hawaii islands, University of Hawaii, Honolulu.

- Mahaffey, C., Benitez-Nelson, C.R., Bidigare, R.R., Rii, Y. and Karl, D.M., 2008. Nitrogen dynamics within a wind-driven eddy. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1398-1411.
- Maiti, K., Benitez-Nelson, C.R., Rii, Y. and Bidigare, R., 2008. The influence of a mature cyclonic eddy on particle export in the lee of Hawaii. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1445-1460.
- Martin, A.P. and Richards, K.J., 2001. Mechanisms for vertical nutrient transport within a North Atlantic mesoscale eddy. *Deep-Sea Research II*, 48: 757-773.
- McGillicuddy, D.J. et al., 2007. Eddy/wind interactions stimulate extraordinary mid-ocean plankton blooms. *Science*, 316(5827): 1021-1026.
- McGillicuddy, D.J. et al., 1999. Mesoscale Variations of Biogeochemical Properties in the Sargasso Sea. *Journal of Geophysical Research*, 104: 13,381-13,394.
- McGillicuddy, D.J., Ledwell, J.R. and Anderson, L.A., 2008. Response to Comment on "Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Bloom". *Science*, 448c: doi:10.1126/science.1148974.
- McNeil, J.D. et al., 1999. New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda. *Journal of Geophysical Research*, 104: 15537-15548.
- Nencioli, F., Kuwahara, V.S., Dickey, T.D., Rii, Y.M. and Bidigare, R.R., 2008. Physical dynamics and biological implications of a mesoscale eddy in the lee of Hawai'i: Cyclone Opal observations during E-Flux III. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1252-1274.
- Olaizola, M., Ziemann, D.A., Bienfang, P.K., Walsh, W.A. and Conquest, L.D., 1993. Eddy-induced oscillations of the pycnocline affect the floristic composition and depth distribution of phytoplankton in the subtropical Pacific. *Marine Biology*, V116(4): 533-542.
- Patzert, W., 1969. Eddies in Hawaiian Islands Report No. HIG-69-8, University of Hawaii, Hawaii Institute of Geophysics.
- Rii, Y.M. et al., 2008. The transient oasis: Nutrient-phytoplankton dynamics and particle export in Hawaiian lee cyclones. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1275-1290.
- Robinson, A.R., 1983. Eddies in Marine Science. Springer - Verlag, New York.
- Seki, M.P. et al., 2001. Biological enhancement at cyclonic eddies tracked with GOES thermal imagery in Hawaiian waters. *Geophysical Research Letters*, 28(8): 1583-1586.
- Sweeney, E.N., McGillicuddy, D.J. and Buesseler, K.O., 2003. Biogeochemical impacts due to mesoscale eddy activity in the Sargasso Sea as measured at the Bermuda Atlantic Time Series (BATS) site. *Deep-Sea Research II*, 50: 3017-3039.
- Vaillancourt, R., Marra, J., Seki, M., Parsons, M. and Bidigare, R., 2003. Impact of a cyclonic eddy on phytoplankton community structure and photosynthetic competency in the subtropical North Pacific Ocean. *Deep-Sea Research I*, 50: 829-847.
- Verdeny, E. et al., 2008. Particle export within cyclonic Hawaiian lee eddies derived from ²¹⁰Pb-²¹⁰Po disequilibrium. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 55(10-13): 1461-1472.