THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

CITATION

Conte, M.H., and J.C. Weber. 2014. Particle flux in the deep Sargasso Sea: The 35-year Oceanic Flux Program time series. *Oceanography* 27(1):142–147, http://dx.doi.org/10.5670/oceanog.2014.17.

DOI

http://dx.doi.org/10.5670/oceanog.2014.17

Particle Flux in the Deep Sargasso Sea

The 35-Year Oceanic Flux Program Time Series

BY MAUREEN H. CONTE AND J.C. WEBER

An Oceanic Flux Program sediment trap comes aboard R/V *Atlantic Explorer* in November 2013. *Photo credit: J. Weber*

> "ALTHOUGH IT IS NOT YET CLEAR HOW A CHANGING OCEAN WILL AFFECT THE MANY PROCESSES THAT REGULATE PARTICLE FLUX GENERATION AND CYCLING WITHIN THE OCEAN INTERIOR, WHAT IS CLEAR IS THAT ANY LARGE-SCALE PERTURBATION IN PARTICLE FLUX WILL LIKELY HAVE GLOBAL REPERCUSSIONS."

ABSTRACT. The Oceanic Flux Program (OFP) sediment trap time series, the longest running time series of its kind, has continuously measured particle fluxes in the deep Sargasso Sea since 1978. OFP results provided the first direct observation of seasonality in the deep ocean, and they have documented the tight coupling between deep fluxes and upper ocean processes and the intensity of biological reprocessing of sinking flux in the ocean interior. The synergy among OFP and other research programs co-located at the Bermuda time-series site has provided unprecedented opportunities to study the linkages among ocean physics, biology, and chemistry; particle flux generation; and particle recycling in the ocean interior. The OFP time series is beginning to reveal how basin-scale climatic forcing, such as the North Atlantic Oscillation, affects the deep particle flux.

In March 1978, a sediment trap first descended through the Sargasso Sea southeast of Bermuda to settle at a depth of 3,200 m. An emerging technology, this trap's mission was to intercept the sinking shells of surface-dwelling foraminifera in an effort to better calibrate the temperature signal imprinted on shell oxygen isotopic composition. Little did Woods Hole Oceanographic Institution scientist Werner Deuser know at the time that his new study would evolve to become the Oceanic Flux Program (OFP), the longest running oceanographic time series of its kind (Figure 1).

One of the first OFP discoveries was the strong seasonality in the particle flux at 3,200 m depth (Deuser et al., 1981; Deuser, 1986). This discovery overturned the then widely held belief that the deep ocean was a remote, ever constant environment. In fact, the OFP showed that the deep ocean is closely connected with the surface via the rain of particles. We know now that the entire oceanic water column is strongly affected by variations in particle flux, which can be linked to the seasonality of primary production in the overlying surface waters, as well as to nonseasonal physical and biological processes that occur on time scales of days to decades (Conte et al., 1998, 2001, 2003).

Understanding oceanic particle flux is important, as this process regulates many aspects of ocean biogeochemistry and global element cycles (see review papers in Ittekkot et al., 1996). Excepting deep vent communities, the export of organic matter from the ocean's surface waters—including particle flux and a smaller contribution from vertically migrating zooplankton—ultimately provides the food source for all life below the euphotic zone. The overall fluxes and flux ratio of organic matter and carbonate shells produced by microscopic marine organisms control, in part, the ocean's ability to absorb excess carbon dioxide from the atmosphere. The depths at which nutrient and bioreactive elements incorporated into sinking organic debris undergo degradation and dissolution, coined the "length scale of remineralization," affect the redistribution of nutrients by ocean circulation and mixing, which, in turn, regulate geographic patterns of ocean productivity. Particle flux also efficiently transfers suspended materials, such as continentally derived clays advected by currents from ocean margins, to the deep ocean and eventually to the seafloor; zooplankton ingest these materials during nonselective feeding and repackage them into larger sinking particles such as fecal pellets and aggregates. Additionally, particulate pollutants, deposited from the atmosphere or transported by ocean currents, are also transferred via particle flux from surface waters to the deep ocean and eventually to the seafloor, where they contaminate deep ocean and benthic ecosystems. Particle flux also strongly controls the fate of dissolved and colloidal pollutants, such as the persistent organic compounds PCBs (polychlorinated biphenyls) and PAHs (polycyclic aromatic hydrocarbons) and organic complexes of elemental pollutants that adsorb onto particles that then may be ingested by zooplankton and enter the food chain.

One of the central objectives of OFP research is to elucidate the processes that control particle flux generation and particle cycling within the ocean interior. This task is not straightforward. Particle flux is an aggregate of materials from diverse sources (Figure 2): organic and mineral remains of microscopic phytoplankton and animals, fecal pellets and amorphous aggregates produced by zooplankton, repackaged clay particles sourced from continental margins, minerals formed in situ as particles degrade, and other materials scavenged from the surrounding seawater.

Maureen H. Conte *(mconte@mbl.edu) is Associate Research Scientist, Bermuda Institute of Ocean Sciences, St. George's, Bermuda, and Adjunct Associate Scientist, Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, USA.* **J.C. Weber** *is Senior Research Assistant, Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA, USA.*

Only rarely do sinking particles formed in surface waters survive the trip to the abyssal seafloor. Rather, as particles sink, they are subjected to microbial remineralization, dissolution, consumption by deeper-dwelling zooplankton, particle disaggregation, and desorption/adsorption reactions. Materials associated with easily degradable organic materials or dissolvable minerals are released into the surrounding water, and new particles are formed as suspended materials are scavenged and repackaged by zooplankton grazers, particularly by nonselective gelatinous filter feeders that process copious quantities of seawater each day. The result is a continuing evolution in particle flux concentration and composition from the surface to the seafloor. Only a small fraction of the biogenic organic and mineral (i.e., biogenic silica, calcite, and aragonite) flux survives transit through the water column to become buried in deep ocean sediments. Globally, the fraction of surface production that is buried in deep ocean sediments is < 1% for organic carbon, ~ 3% for biogenic silica, and ~ 10% for carbonate (Nelson et al., 1995; Berelson et al., 2007). Even so, this residual material retains a wealth of information about past ocean conditions that can be used to reconstruct Earth's history.

As evidence for human-induced climate alteration mounts, questions arise on how anticipated changes in ocean physics, chemistry, and ecosystems might affect particle flux and, in turn, the environment of the ocean interior. The

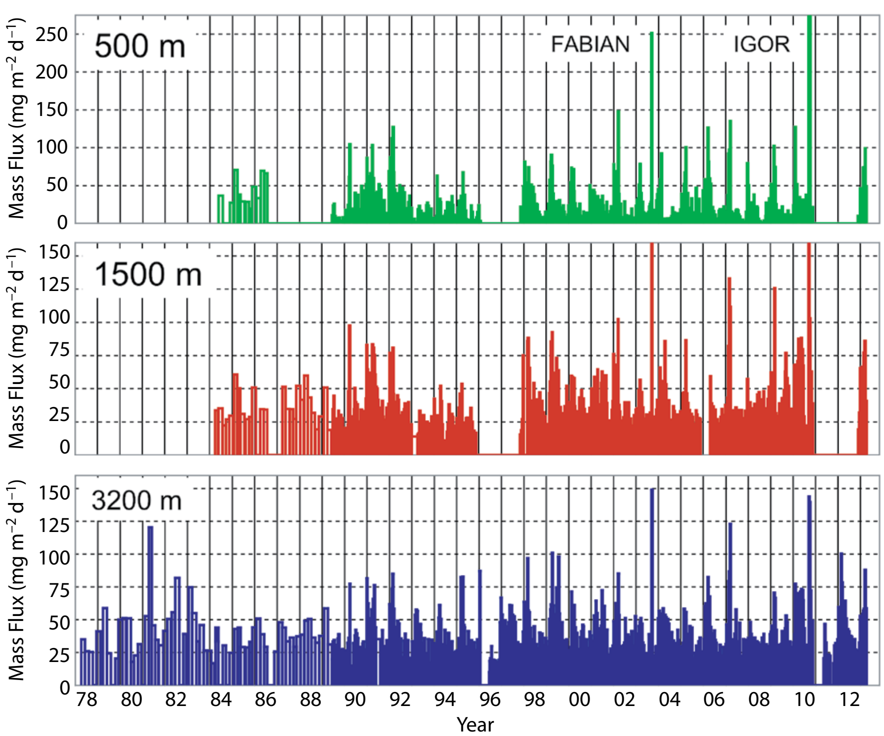

Figure 1. The 35-year Oceanic Flux Program record of mass flux in the northern Sargasso Sea. The extreme fluxes measured in September 2003 and 2010 are plumes of detrital carbonate sediments from the Bermuda platform that were advected offshore by Hurricanes Fabian (2003) and Igor (2010).

OFP time series is ideally suited to provide valuable insights into how changing climate scenarios will affect the particle cycle. For over three decades, OFP traps have continuously recorded how the magnitude and composition of particle flux has varied in response to changes in upper ocean processes and meteorological forcing. These OFP observations have benefitted from the rich oceanographic context provided by the other Bermuda time series—Hydrostation S (1954 to present; Joyce and Robbins, 1996), the Bermuda Atlantic Time Series (BATS; 1989 to present; Steinberg et al., 2001; Lomas et al., 2013), and the Bermuda Testbed Mooring (1994–2007; Dickey et al., 2001)—and collaborative research. Together, the time-series programs, along with remote-sensing products, have permitted direct exploration of the interactions and linkages between deep particle flux and upper ocean physics, chemistry, and biology.

The OFP flux record for spring 2007 (Figure 1) provides a simple example of how changes in surface physical forcing propagate through ocean systems to affect the remineralization depth profiles of bioreactive elements and deepwater ecosystems. In 2007, as in several other years of particularly large spring fluxes, mesoscale cyclonic or mode water eddies were observed to pass through the area as the spring bloom was developing. The circulation of cyclonic eddies raises the pycnocline and increases the nutrient flux into the euphotic zone, which can induce or strengthen phytoplankton

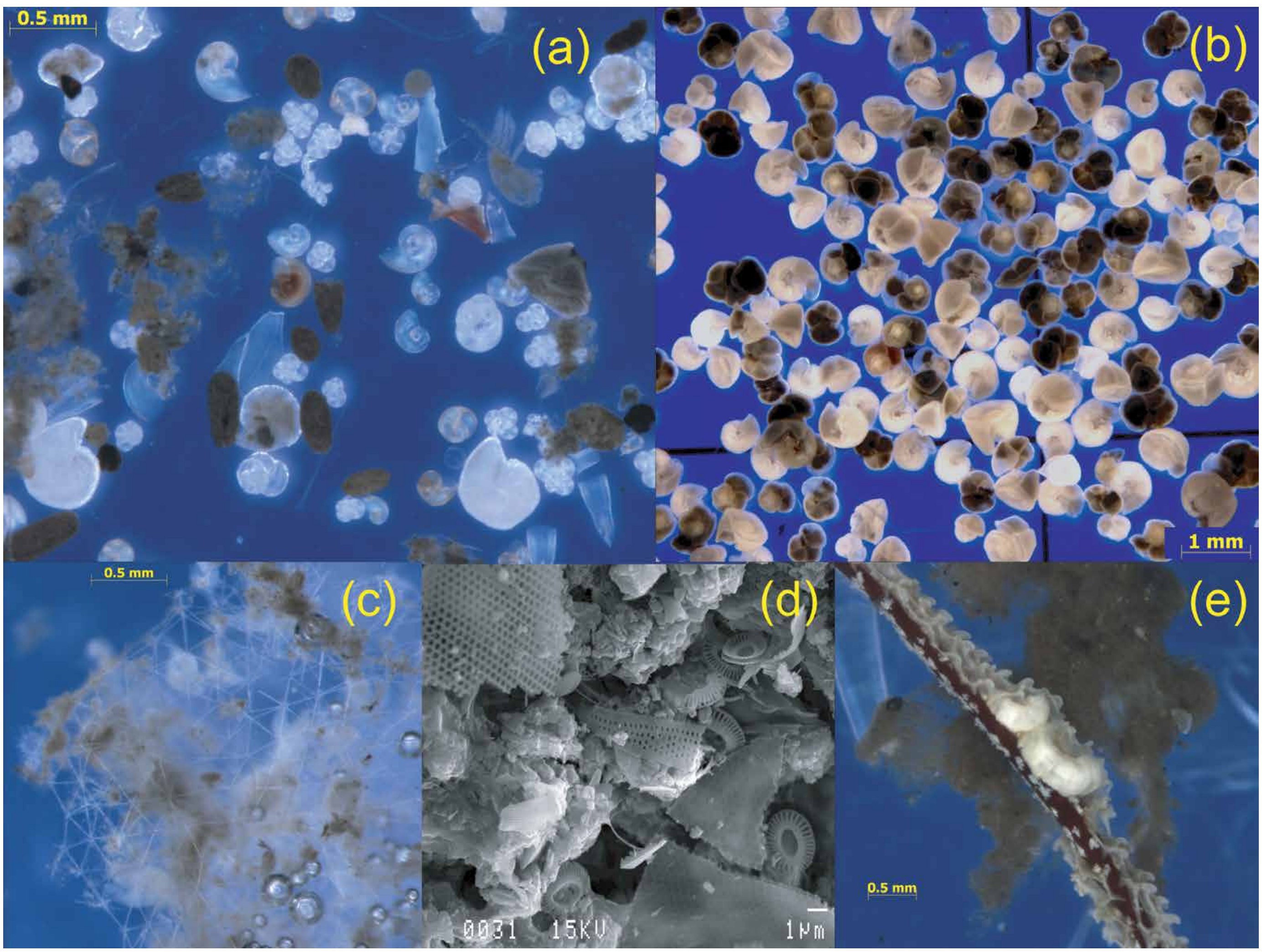

Figure 2. Components of deep ocean flux. (a) A typical assemblage of the larger 125–500 µm size fraction of the flux material, which includes shells of foraminifera, pteropods, and radiolarians, zooplankton fecal pellets, and amorphous aggregates (1,500 m depth, February 2013). (b) A post-bloom flux of shells of the foraminifera *Globorotalia truncatulinoides* (500 m depth, April 2007). (c) A discarded phaeodarian feeding net (1,500 m depth, August 2006). (d) A scanning electron micrograph of the < 125 µm size fraction, including fragmented remains of diatom and coccolithophore tests admixed with lithogenic clay platelets and organic debris (1,500 m depth, September 2003). (e) A fragment of *Sargassum* weed encrusted with biominerals resting on an amorphous aggregate (3,200 m depth, November 2009).

blooms (McGillicuddy et al., 1998). In spring 2007, satellite and in situ BATS data documented the progression of a strong phytoplankton bloom as the cyclonic eddy passed through the site (Shatova et al., 2012). Coincident with eddy passage was an abrupt increase in fluxes of phytodetritus debris, amorphous aggregates, and fecal pellets of zooplankton and gelatinous filter feeders. The flux also contained shells of the foraminifera *Globorotalia truncatulinoides*, a species that dwells between 200 and 500 m depth (Figure 2c; Fang et al., 2010; Shatova et al., 2012). Thus, the large phytoplankton bloom induced by eddy-driven nutrient upwelling appeared to have increased the export of fresh organic material into mesopelagic waters, stimulating animal grazing and reproduction that, in turn, increased particle flux generation at depth. Chemical analyses of the flux material collected during this and other such short-lived episodic flux "events" indicate that this type of transient forcing is particularly important for increasing the penetration depth of labile organic materials and associated elements (Conte et al., 1998, 2003, and recent work of author Conte).

Physical forcing by synoptic-scale weather systems also affects nutrient supply and phytoplankton production in the euphotic zone by influencing surface water stability and mixing. Particularly in spring and fall, passage of weather systems results in variable periods of positive and negative ocean heat flux and fluctuations in mechanical forcing of the upper ocean via wind stress. Because water column stability is low, it can lead to alternation between warm, stable periods of weak surface stratification and cold, windy periods when the stratification is eroded and the mixed layer deepens. The deepening results in a transient resupply of nutrients to the euphotic zone that can support phytoplankton production during the next calm period, which is then followed by downmixing of phytoplankton products and increased particle flux (Koeve et al., 2002). Episodic flux peaks are common at the OFP site in early winter when the mixed layer is deepening and surface water stratification is variable (Conte et al., 2001).

In the northern Sargasso Sea, a major driver of weather is the North Atlantic Oscillation (NAO), a measure of the pressure differential between the Iceland Low and the Azores High (Hurrell and van Loon, 1997). When the NAO is in its low phase (low pressure differential), storm systems are less intense but track farther south across the Atlantic, resulting in colder winter air temperatures and increased winter storminess in the subtropical North Atlantic. Modeling studies indicate that in the Bermuda region, nitrate flux into surface waters is enhanced when the NAO is in its low phase, (Oschlies, 2001) which, in turn, should support higher primary production in these years.

The OFP record provides tantalizing evidence that this influence of the NAO on biogeochemical cycles extends to the deep ocean as well. In years when the wintertime NAO is in its low phase, the flux of particulate nitrogen at 3,200 m depth is higher than in years when the NAO is in its high phase (Figure 3). The observed inverse relationship between the NAO phase and the deep particle flux agrees with predictions that increased nutrient influx into surface waters due to NAO forcing will increase primary production and, in turn, particle flux generation. The weak but statistically significant correlation underscores the fact that multidecadal time series such as the OFP are needed to extract the influence of the

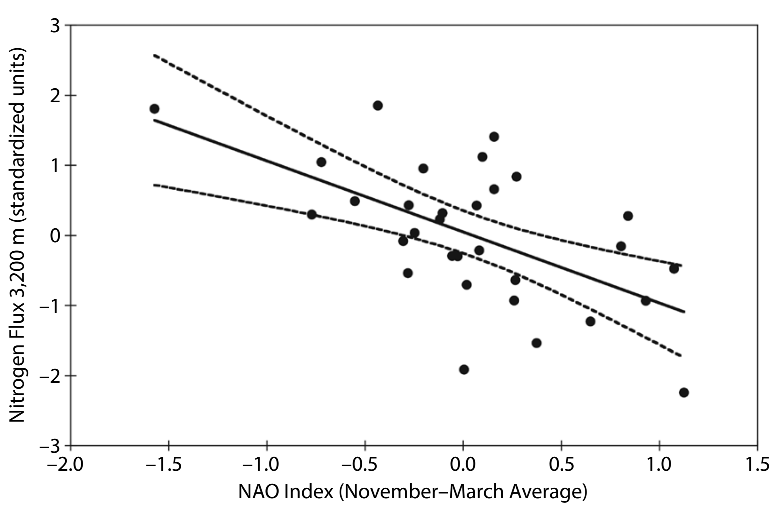

Figure 3. The influence of the North Atlantic Oscillation (NAO) on deep particle flux. The figure plots the annual (July to July) particulate nitrogen flux at 3,200 m depth (Z-standardized values) versus the winter NAO index (November to March). The trend line and 95% confidence interval are shown. The regression ($r^2 = 0.34$) is significant at the < 0.001 level.

more subtle yet underlying climatic drivers of ocean biogeochemistry.

As the OFP time series heads into the future, its data and samples will continue to reveal new evidence of the sensitivity of the deep ocean to changes in upper-ocean physics and biology. Mesoscale physical variability and decadal climate patterns that affect nutrient availability and phytoplankton production in the surface ocean are now known to have a dramatic effect on particle flux generation and, in turn, on life in the relative calm of the deep (Smith et al., 2008). Less well understood is how altered ecosystem structure, as predicted in the face of ocean acidification and increasing surface stratification, might impact particle flux. Although it is not yet clear how a changing ocean will affect the many processes that regulate particle flux generation and cycling within the ocean interior, what is clear is that any large-scale perturbation in particle flux will likely have global repercussions.

ACKNOWLEDGEMENTS

We gratefully acknowledge the National Science Foundation's continuous financial support of the Oceanic Flux Program time series for the past 35 years, most recently by NSF grants OCE 1234294 and OCE 0927098. We also acknowledge all the past and present scientists, ship personnel, and students who have contributed to the OFP's success.

REFERENCES

Berelson, W.M., W.M. Balch, R. Najjar, R.A. Feely, C. Sabine, and K. Lee. 2007. Relating estimates of $CaCO_3$ production, export, and dissolution in the water column to measurements of $CaCO_3$ rain into sediment traps and dissolution on the sea floor: A revised global carbonate budget. *Global Biogeochemical Cycles* 21, GB1024, http://dx.doi.org/10.1029/2006GB002803.

Conte, M.H., T.D. Dickey, J.C. Weber, R.J. Johnson, and A.H. Knap. 2003. Transient physical forcing of pulsed export of bioreactive organic material to the deep Sargasso Sea. *Deep Sea Research Part I* 50:1,157–1,187, http://dx.doi.org/10.1016/S0967-0637(03)00141-9.

Conte, M.H., N. Ralph, and E.H. Ross. 2001. Seasonal and interannual variability in deep ocean particle fluxes at the Oceanic Flux Program (OFP)/Bermuda Atlantic Time-Series (BATS) site in the western Sargasso Sea near Bermuda. *Deep Sea Research Part II* 48:1,471–1,506, http://dx.doi.org/10.1016/S0967-0645(00)00150-8.

Conte, M.H., J.C. Weber, and N. Ralph. 1998. Episodic particle flux in the deep Sargasso Sea: an organic geochemical assessment. *Deep Sea Research Part I* 45:1,819–1,841, http://dx.doi.org/10.1016/S0967-0637(98)00046-6.

Deuser, W.G. 1986. Seasonal and interannual variations in deep-water particle fluxes in the Sargasso Sea and their relation to surface hydrography. *Deep Sea Research* 33:225–246, http://dx.doi.org/10.1016/0198-0149(86)90120-2.

Deuser, W.G., E.H. Ross, and R.F. Anderson. 1981. Seasonality in the supply of sediment to the deep Sargasso Sea and implications for the rapid transfer of matter to the deep ocean. *Deep Sea Research Part A* 28:495–505, http://dx.doi.org/10.1016/0198-0149(81)90140-0.

Dickey, T., S. Zedler, D. Frye, H. Jannasch, D. Manov, D. Sigurdson, J. D. McNeil, L. Dobeck, X. Yu, T. Gilboy, and others. 2001. Physical and biogeochemical variability from hours to years at the Bermuda Testbed Mooring site: June 1994–March 1998. *Deep Sea Research Part II* 48:2,105–2,140, http://dx.doi.org/10.1016/S0967-0645(00)00173-9.

Fang, J., M.H. Conte, and J.C. Weber. 2010. Influence of physical forcing on seasonality of biological components and deep ocean particulate flux in the Sargasso Sea. *Eos, Transactions American Geophysical Union* 91(26), Ocean Sciences Meeting Supplement, Abstract BO24B-02.

Hurrell, J.W., and H. van Loon. 1997. Decadal variations in climate associated with the North Atlantic oscillation. *Climate Change* 36:301–326, http://dx.doi.org/10.1023/A:1005314315270.

Ittekkot, V., P. Schafer, S. Honjo, and P. Depetris. 1996. *Particle Flux in the Ocean*. John Wiley, and Sons, New York, NY, 396 pp.

Joyce, T.M., and P. Robbins. 1996. The long-term hydrographic record at Bermuda. *Journal of Climate* 9:3,121–3,131, http://dx.doi.org/10.1175/1520-0442(1996)009<3121:TLTHRA>2.0.CO;2.

Koeve, W., F. Pollehne, A. Oschlies, and B. Zeitzschel. 2002. Storm-induced convective export of organic matter during spring in the northeast Atlantic Ocean. *Deep Sea Research Part I* 49:1,431–1,444, http://dx.doi.org/10.1016/S0967-0637(02)00022-5.

Lomas, M.W., N.R. Bates, R.J. Johnson, A.H. Knap, D.K. Steinberg, and C.A. Carlson. 2013. Two decades and counting: 24 years of sustained open ocean biogeochemical measurements in the Sargasso Sea. *Deep Sea Research Part II* 93:16–32, http://dx.doi.org/10.1016/j.dsr2.2013.01.008.

McGillicuddy, D.J., A.R. Robinson, D.A. Siegel, H.W. Jannasch R. Johnson, T.D. Dickey, J. McNeil A.F. Michaels, and A.H. Knap. 1998. Influence of mesoscale eddies on new production in the Sargasso Sea. *Nature* 394:263–265, http://dx.doi.org/10.1038/28367.

Nelson, D.M., P. Treguer, M.A. Brzezinski, A. Leynaert, and B. Queguiner. 1995. Production and dissolution of biogenic silica in the ocean: Revised global estimates, comparisons with regional data and relationship to biogenic sedimentation. *Global Biogeochemical Cycles* 9:359–372, http://dx.doi.org/10.1029/95GB01070.

Oschlies, A. 2001. NAO-induced long-term changes in nutrient supply to the surface waters of the North Atlantic. *Geophysical Research Letters* 28:1,751–1,754, http://dx.doi.org/10.1029/2000GL012328.

Shatova, O., D. Koweek, M.H. Conte, and J.C. Weber. 2012. Contribution of zooplankton fecal pellets to deep ocean particle flux in the Sargasso Sea assessed using quantitative image analysis. *Journal of Plankton Research* 34:905–921, http://dx.doi.org/10.1093/plankt/fbs053.

Smith, C.R., F.C. DeLeo, A.F. Bernardino, A.K. Sweetman, and P.M. Arbizu. 2008. Abyssal food limitation, ecosystem structure and climate change. *Trends in Ecology and Evolution* 23:518–528, http://dx.doi.org/10.1016/j.tree.2008.05.002.

Steinberg, D.K., C.A. Carlson, N.R. Bates, R.J. Johnson, A.F. Michaels, and A.H. Knap. 2001. Overview of the US JGOFS Bermuda Atlantic Time-Series Study (BATS): A decade-scale look at ocean biology and biogeochemistry. *Deep Sea Research Part II* 48:1,405–1,448, http://dx.doi.org/10.1016/S0967-0645(00)00148-X.