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Autonomous Data Describe North Atlantic Spring Bloom

PAGES 465–466

Each spring, increasing sunlight and associated changes in the ocean structure trigger rapid growth of phytoplankton across most of the North Atlantic Ocean north of 30°N. The bloom, one of the largest in the world, is a major sink for atmospheric carbon dioxide and a prototype for similar blooms around the world. Models of the ocean carbon cycle, a necessary component of climate models, need to accurately reproduce the biological, chemical, and physical processes occurring during these blooms. However, a paucity of detailed observations severely limits efforts to evaluate such models.

The development of autonomous oceanographic platforms and compact, low-power sensors capable of measuring many important biological and chemical quantities opens up the potential for gathering much more data. To this end, researchers deployed autonomous floats and gliders south of Iceland for 85 days in 2008 to measure the initiation, peak, and demise of the North Atlantic spring bloom. A cruise at the peak of the bloom provided more detailed measurements and calibrated the autonomous sensors. These data, now publicly available, provide a new, continuous view of the bloom's evolution and were used to test and improve models of the bloom.

The Need to Improve Biogeochemical Ocean Models

Biogeochemical ocean models have evolved rapidly over the past 2 decades because of better understanding and numerical representation of ocean biogeochemical processes, improved capabilities in circulation modeling, and rapid increases in computational power. These models are now routinely coupled to circulation models of ever finer spatial resolution and have become increasingly sophisticated in terms of the range of essential nutrients (e.g., nitrogen, phosphorous, silicon, and iron) and biogeochemical processes (e.g., nitrogen fixation and photoacclimation) that are represented. These models often include multiple phytoplankton and zooplankton groups with different functional traits and ecosystem roles, and some describe the dynamics of inorganic carbon species and dissolved oxygen. However, the availability of observations needed to evaluate these increasingly detailed models has not improved at the same pace, arguably the biggest impediment to improving biogeochemical predictions.

Biogeochemical observations typically used in quantitative model assessments include (1) chlorophyll products from satellites, which have obvious limitations in terms of spatial coverage (i.e., surface only and compromised by clouds) and represent only indirect proxies of phytoplankton biomass; (2) observations from ocean time series sites, which are located primarily in the subtropics and are sampled, at most, at biweekly or monthly intervals; and (3) other ship-based data sets, which offer limited spatial and temporal coverage.

The recent maturation of autonomous platforms and biogeochemical sensors has opened up enormous potential for overcoming some of these limitations by offering unprecedented temporal and spatial resolution for a continuously expanding suite of observable variables including nitrate, oxygen, spectral absorption, and chlorophyll fluorescence [e.g., *Johnson et al.*, 2009]. It is expected that the increased data availability will help scientists assess whether current models of phytoplankton accurately reflect actual dynamics or whether models need to be rejected, overhauled, or fine-tuned. Because ocean nutrient cycling is a key component of global climate models, ensuring the accuracy of their biogeochemical components will thus increase the accuracy of future climate predictions.

Measuring the 2008 Bloom

During spring 2008 a system that included a heavily instrumented Lagrangian float, four long-endurance Seagliders, and a wide range of ship-based measurements characterized patch-scale evolution of the spring phytoplankton bloom in the Icelandic Basin of the subpolar North Atlantic (Figure 1). The site was chosen because its spring bloom leads to one of the largest known biological carbon export events and because its pronounced mesoscale variability makes it challenging to interpret ship-based measurements from this region.

The Seagliders and float were deployed in early April, well before the start of the spring bloom, and some remained operational until late June. The float drifted passively in the mixed layer, except for a daily dive to 230-meter depth, and hence its path can be interpreted as the trajectory of a patch of water. Float-borne sensors (see Table S1 in the online supplement to this brief report (http://www.agu.org/journals/eo/v092/i050/2011EO500002/2011EO500002_suppl.pdf)) characterized the biochemical evolution of this patch from prebloom conditions through onset and decline of the diatom spring bloom. Four sensor-equipped Seagliders (see Table S1) followed the float while taking vertical profiles to up to 1000-meter depth to characterize spatial variability surrounding the float patch. In addition to these autonomous observations, ship-based sampling occurred during three short cruises and a more extended process cruise at the height of the bloom. The ship-based observations were used for quality control and calibration of float and glider observations; a series of calibration reports detail all analytical procedures and practices. The combined autonomous and ship-based data set (see Table S1) and calibration reports are now available to the scientific community through the Biological and Chemical Oceanography Data Management Office at http://osprey.bcodmo.org/project.cfm?flag=view&id=102&sortby=project.

As an illustration of the usefulness of these observations, their use in constraining

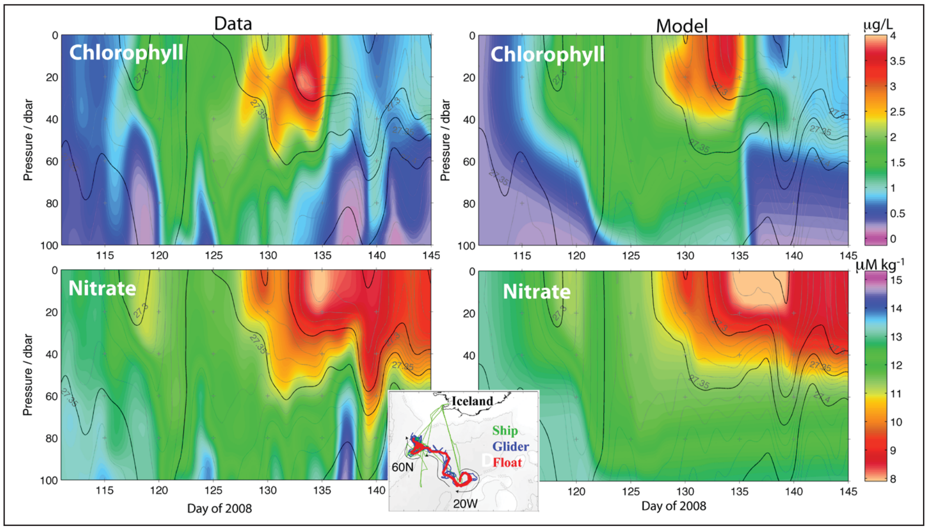

Fig. 1. Colors show (left) float-based and (right) model-simulated concentrations (using a model with diatom aggregation from Bagniewski et al. *[2011]) of (top) chlorophyll and (bottom) nitrate during 38 days starting on 17 April 2008. Contours show potential density. Data and model are gridded using Gaussian averaging over 10 meters vertically and over 0.4 day and 0.8 day temporally for the model and data, respectively. Experimental location and tracks of floats, gliders, and ship are seen in the inset. The spring bloom is seen as the rapid increase of chlorophyll peaking at about day 135 and rapidly disappearing thereafter. The concurrent decrease in nitrate shows the consumption of this nutrient by phytoplankton. The success of the model in reproducing the patterns in these and other variables shows the suitability of these observations for enhancing model studies of the spring bloom.*

and comparing three biological models that describe the bloom and associated vertical carbon export [*Bagniewski et al.*, 2011] are summarized below. The models differ in biological complexity, with the simplest corresponding to typical nutrient/phytoplankton/zooplankton/detritus–type models used in large-scale North Atlantic biogeochemical simulations, while the most complex model explicitly includes diatoms and the formation of fast sinking diatom aggregates under silicate limitation. Spatial model configuration is one-dimensional (vertical) and designed to mimic conditions in the float patch (Figure 1). Model parameters, describing, for example, the exact dependence of phytoplankton growth rate on light and nutrients, were constrained through variational assimilation of float observations. In contrast to previous assimilation studies, the temporal resolution and diversity of the observations allowed for the majority of biological parameters to be constrained well [*Bagniewski et al.*, 2011]. Each model version, when run with the optimized parameters, reproduced the observations well.

Although all optimized models describe the observed evolution of surface variables well (no model could be formally rejected), they differ markedly in their efficiency of vertical carbon export. For example, much higher fluxes occur at 600-meter depth in the model with diatom aggregation; this model also fits the observations best and represents the mechanisms and timing of carbon export inferred from unassimilated observations more accurately. This implies that modeled carbon export, a key output of biological models, is sensitive to the fine details of the model.

A Promising Approach

The study demonstrates the potential of autonomous observations for biogeochemical modeling but also emphasizes remaining gaps in observational capabilities and limits in current modeling approaches. For example, no zooplankton sensors are available at present, and models tend to rely on surface observations, which may not be sufficient to determine the efficiency of vertical carbon export.

More widespread use of autonomous platforms equipped with interdisciplinary sensor suites will lead to significant advances in biogeochemical modeling, especially if open data policies and common data formats are adopted. Targeted use, such as in this experiment [*Bagniewski et al.*, 2011], is one viable sampling strategy. A distributed deployment of assets similar to the Argo array (3000 profiling floats distributed throughout the world's oceans that currently supply information primarily on temperature and salinity) is another [*Johnson et al.*, 2009; *Claustre et al.*, 2010]. Availability of these new data streams will undoubtedly spur the development of new methods for combining observations and models as well as new modeling approaches.

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