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# New Satellites Paint a Portrait of Plankton Spatial Variability

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*The newest generation of satellites reveals plankton variability changes in character from uniform to chaotic at different spatial scales, reviving a classic question in oceanography. How does plankton variability change at different spatial scales, and why?*

## New satellites, new insights

Satellite technologies can now collect images with resolution down to the scale of meters, presenting oceanographers data with unprecedented information about the fine-scale structure of plankton communities in the surface ocean. In August 2015, there was significant media attention after two of the world's most advanced satellites, Landsat 8 and Sentinel-2, published images of a cyanobacteria (algal) bloom in the Baltic sea (Fig. 1). For scale, the images conveniently have boats in them (you really have to squint, or just zoom in - a little game of Where's Waldo at sea).

While these images are beautiful in their own right, to an oceanographer they also illustrate the complexity of the biophysical interactions that drive plankton distributions. When we run computer models to simulate e.g., how plankton communities might respond to a changing climate, we can't replicate all of this variability, so we typically represent an X km × Y km square of ocean with a single value (e.g., plankton concentration), which we consider as the average for that box; one peek at an image like this demonstrates that it's difficult to justify this approach as doing full justice to the system it's simulating. Similarly, when we take samples out in the field, we often fill bottles with seawater and assume that sample represents a X km × Y km area around it. This image suggests that taking a measurement off one side of the boat might give you a

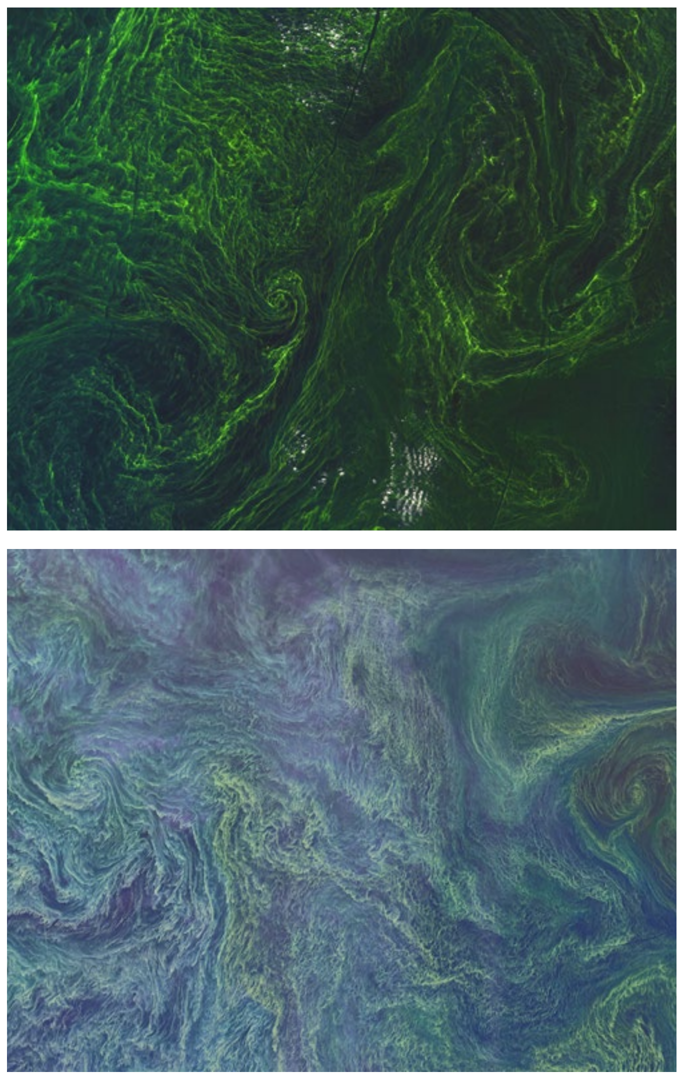


**Figure 1.** a) Sentinel-2 false color image of Baltic Sea cyanobacteria bloom, taken 7 Aug. 2015. b) Landsat 8 false color image of Baltic Sea cyanobacteria bloom, taken 11 Aug. 2015.

very different representation of that region than if you had taken it off the other side! These approaches are further complicated by studies indicating that the variability we see in these images persists at microscopic scales.

This is not meant to needlessly criticize these approaches; oceanography is a challenging science, and we do the best we can. Often, these approaches can yield wonderful insights. These images just draw attention to the fact that plankton spatial variability remains a fascinating and open problem in oceanography, which present-day technology puts us in good position to start addressing.

## Characterizing variability

One way we can characterize such variability is by using a power spectral density (PSD), which allows us to quantify how much variability is contained at each scale in an image. Computing the PSD for each of the above images is a straightforward exercise, thanks to modern computational capabilities. To draw an analogy, we can also compute the PSD for a painting by each of Rothko and Pollock (Figs. 2a. and 2b., respectively); we might take the former to represent 'homogeneity' and the latter to represent 'chaos' (as Pollock's paintings have been thought of for years). That is, imagine a satellite looks down on a plankton bloom and sees a rather gargantuan painting of each type; how do these paintings compare with observed blooms, in terms of spatial variability?

## Comparing power spectral densities

When we computed the PSDs (see Methods box) for these four images (Figs. 1a, b and 2a, b), we found remarkable consistency (almost identical PSDs) between the two satellite images (Figs. 1a and b), which were taken four days apart. This suggests that 1) the satellites are accurately and reproducibly capturing spatial bloom variability, and 2) bloom PSDs don't change significantly from day to day. The PSDs from the satellite images matched the Pollock spectrum at smaller spatial scales (i.e. high wavenumber) and the Rothko spectrum at larger spatial scales (i.e. low wavenumber) (Fig. 3) .This raises the question: why might this be happening? Also, at what scale does the 'Rothko-Pollock' transition occur and why?

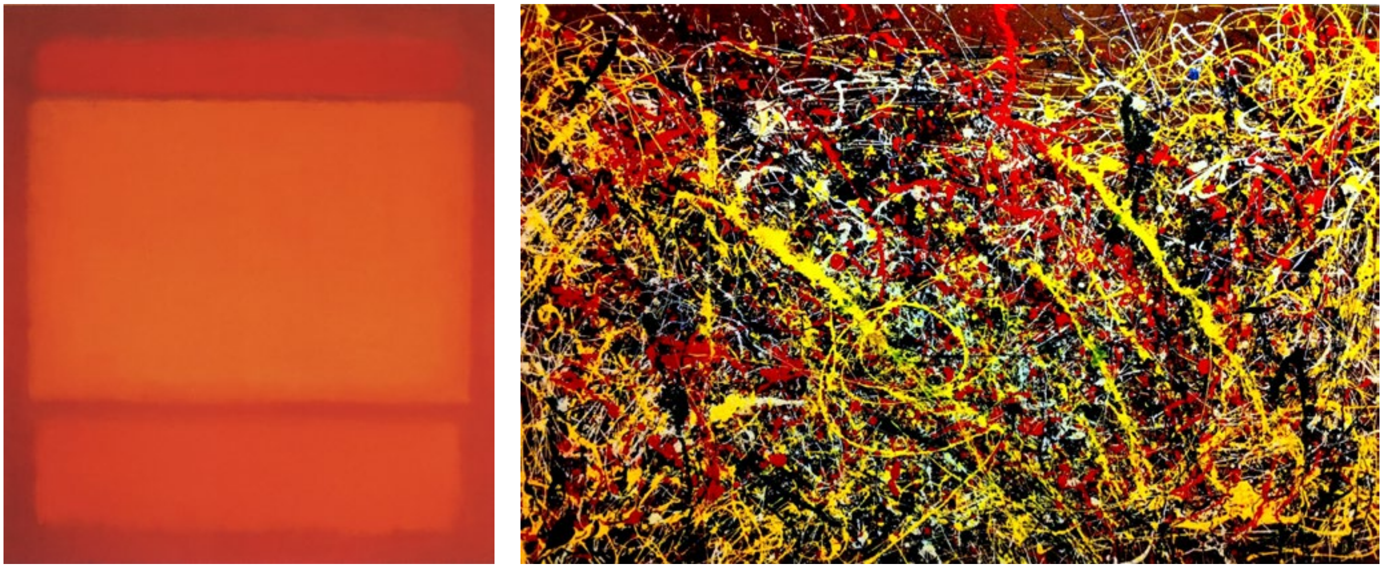
### Methods

The PSD has been computed for the red band of the RGB image of the Rothko painting, a black and white conversion of the Pollock painting, and for the green band of each of the satellite images. Computing the PSD for other configurations did not change the result. The wavenumber $k = 1$ in this case corresponds to a wavelength $\lambda \approx 50$ km. Wavenumbers have been rescaled to those of the Sentinel-2 image, and PSDs have been normalized to their L2 norm.

## Significance

If the distribution of plankton was purely that of Brownian (random) motion, we'd expect a flatter PSD (i.e. a line with slope = -2). Another null hypothesis is that the distribution of plankton might be set passively by advection of oceanic currents. In this case, we'd expect plankton distributions to have the same signature as temperature, which also has a PSD slope of -2. However, these spectra (Fig. 3) have slopes that are steeper than -2 (closer to -2.5 or -3), so clearly there's more afoot. The steeper slope of -3 at larger scales means that variability falls off

**Figure 2.** a) *Red Orange Orange on Red* by Mark Rothko, 1962. (rotated 90°). b) *Wild Beast* by Jackson Pollock, 1943.



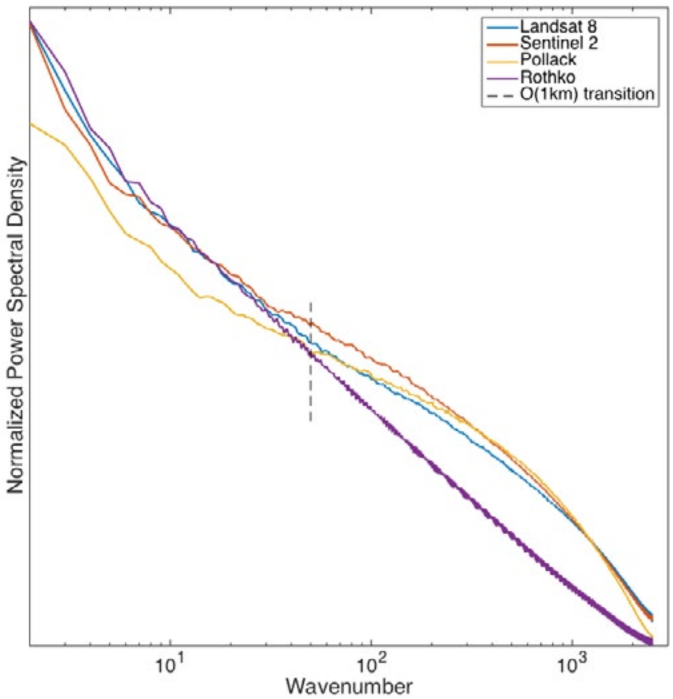



**Figure 3.** Power spectral densities (PSDs) of Figs. 1 and 2. The *X*-axis corresponds to wavenumber, which is the inverse of wavelength, so large wavenumbers reflect smaller spatial scales. This suggests that the blooms look like Pollock paintings on smaller scales and Rothko paintings on larger scales, with the transition occurring at a wavenumber that corresponds to a 1-km wavelength, represented by the black dotted line. The tailing for Pollock and the satellite images at the right end of the graph may have to do with how the images are processed, but the shoaling of the spectra at ~1-km wavelength remains distinct.

faster as we look at smaller scales, i.e. something about the plankton distribution is 'homogenizing' at larger scales. Then, the PSDs get shallower at wavelengths of ~1 km, indicating that something kicks in at sub-kilometer scales that introduces more variability.

One way to think about this transition, which has been hypothesized since the 1970s (1), is that different processes can dominate at different spatial scales. The specifics of the 70s manner of thinking aren't quite compatible with these data, but the general concept is plausible. Plankton grow in response to light and nutrient conditions, but also live in a turbulent environment. At large scales, growth occurs somewhat uniformly and is dominated by ambient light and nutrient conditions, whereas smaller-scale biophysical interactions can introduce an additional source of variability in plankton growth. Biophysical variability can occur in many ways, including small-scale horizontal motions that can stir plankton patches into filaments and small-scale vertical motions that can enhance growth locally by bringing up nutrients. In either case, these biophysical interactions are only observable at smaller scales.

Thus, at larger scales, the plankton will be distributed relatively homogeneously as uniform (light-/temperature-driven) growth wins out (à la Rothko), and at smaller scales, they will be distributed heterogenously as advective processes come into play (à la Pollock). The spatial scale at which this transition occurs is controversial and depends on many factors, though was originally hypothesized to be ~1 km, which here appears plausible. See the vertical line in Fig. 3, which corresponds to a 1-km wavelength and appears to agree well with the scale of the observed transition from Rothko-type to Pollock-type behavior.

Another thing to note is that these cyanobacterial mats (Fig. 1) are very thin and form just at the ocean surface – zoom in and you can see how the boat tracks cut through them. Thus, these patterns may be representative of a different set of physical processes occurring only in the uppermost layer of the ocean.

While two satellite images of the same bloom may not be enough to verify the growth vs. turbulence hypothesis, 'Rothko-type' versus 'Pollock-type' behavior may not be quantitative enough descriptions to satisfy any oceanographer, and the equally-complex third dimension isn't included in these pictures, there is still a clear message here. The spatial resolution available from the newest generation of satellites provides a novel opportunity to approach problems of scale in oceanography.

## Acknowledgments

It is a pleasure to thank Bror Jonsson, Mick Follows, Bryan Kaiser, and Amala Mahadevan for useful discussion of this topic.

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# *Mesodinium rubrum*: An Old Bug Meets New Technology

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Blooms of red water associated with the remarkable ciliate *Mesodinium rubrum* have been observed at least since Darwin's time (*1*). This ciliate retains the chloroplasts from ingested prey and is able to use them for photosynthesis (reviewed in *2*). Recent studies have shown that the plastids can reproduce within the ciliate and that nuclei from the original algal prey remain transcriptionally active (*3*). It is very likely that there are at least two different species of *Mesodinium* that perform this feat, the original *M. rubrum* and a recently described larger species, *M. major* (*4*). Both species have in common certain species of cryptophyte algae as their preferred food, and hence are colored deep red by their prey's phycoerythrin pigment and characteristic yellow fluorescence (Fig. 1). *Mesodinium* is believed to hold the ciliate swimming speed record, with short jumps of up to 1.2 cm $s^{-1}$, and can change its position vertically in the water column to access nutrients (*5*). Along with rapid growth, its impressive motility probably contributes to the large aggregations obvious to the naked eye, in which concentrations of >$10^6$ cells $l^{-1}$ have been observed (*6*) (Fig. 1). Even outside of bloom conditions, they are a regular component of estuarine and coastal plankton assemblages and can contribute significantly to primary productivity (*7*). However, as mixotrophs (organisms capable of both photosynthesis and ingestion), they are undersampled and underappreciated by phytoplankton and zooplankton ecologists alike.

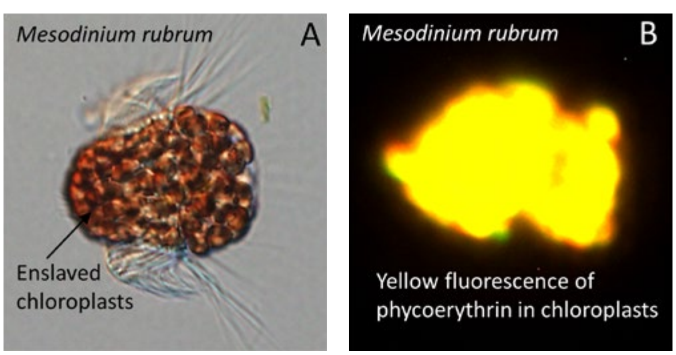


**Figure 1**. **A)** Micrograph of the ciliate *Mesodinium rubrum* with enslaved cryptophyte chloroplasts (courtesy of NOAA Phytoplankton Monitoring Network); **B)** Fluorescent microscopy shows characteristic yellow fluorescence (565-570 nm) of *Mesodinium rubrum* due to high amounts of phycoerythrin pigment. Figure modified from (**8**).

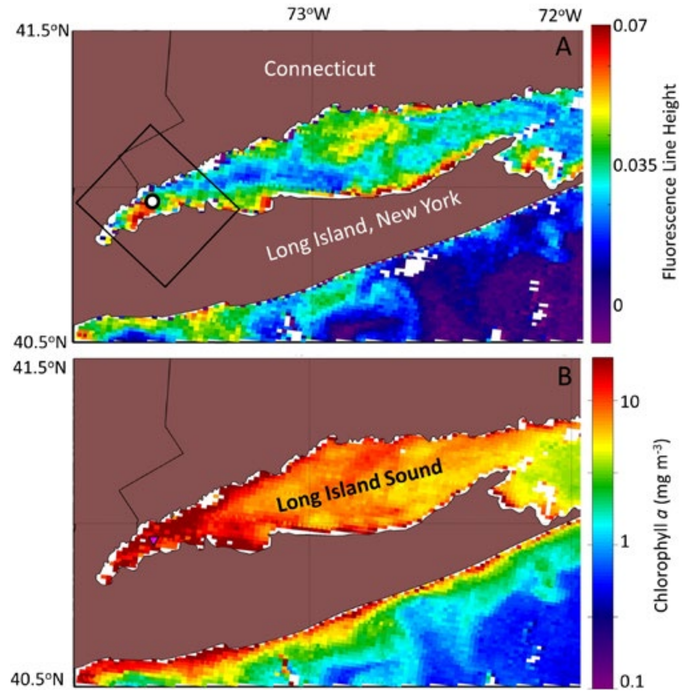


**Figure 2**. **A)** The 1-km resolution image of western Long Island Sound from the MODIS Terra sensor shows an elevated chlorophyll **a** fluorescence patch in Western Long Island Sound on 23 September 2012 with the field sampling station identified with a white circle. The black square outlines the swath of the coincident HICO image. **B)** The standard Chlorophyll *a* product from the MODIS sensor is not accurate in the optically complex Long Island Sound (**9**) and incorrectly shows the entire Long Island Sound having high bloom-like phytoplankton concentration. Figure modified from (**8**).

Red water has been reported in Long Island Sound on occasion by other observers. While *Mesodinium* was present in >80% of all samples examined in >10 years of monthly plankton monitoring data, no sample ever exceeded 2.6 x $10^4$ cells $l^{-1}$. In Fall 2012, Univ. Connecticut personnel servicing a moored array observed and sampled red water in western Long Island Sound (40.9° N 73.6° W). Microscopy and DNA sequencing confirmed that the bloom was due to *Mesodinium* (100% identical by small subunit rDNA to the larger *M. major*), and we subsequently reported on our efforts to document the bloom using satellite imagery (*8*). Here, we summarize those results and discuss the promise of new sensors for quantifying blooms of specific plankton groups by their pigment signatures, especially when coarsely resolved monitoring samples are inadequate.

Ocean color satellites provide a means to assess such red tides, but the standard chlorophyll products are inaccurate in the optically complex waters of Long Island Sound, which contain river runoff with colored dissolved organic matter (cDOM) and suspended sediments (*9, 10*) (Fig 2). Imagery from the MODIS sensor of fluorescence line height (Fig. 2A) indicated the presence of an unspecified bloom in Western Long Island Sound coincident with the bloom, but the spatial resolution (1-km pixels) did not allow us to gauge the bloom extent adequately, and the spectral bands of that sensor are not sufficient to discriminate the type of bloom.

Serendipitously, an image was available for the western Sound from the novel Hyperspectral Imager for the Coastal Ocean (HICO) instrument aboard the International Space Station. This sensor contains >100 channels in the visible and near infrared regions of the spectrum and hence has the capability to resolve multiple peaks and valleys due to fluorescence and absorbance of the chlorophylls and accessory pigments found in various phytoplankton groups. It also has the higher spatial resolution (110-m pixels) needed to quantify the extent of the bloom and variation in ciliate abundance within it. Because the red water we observed appeared (microscopically) to be almost exclusively due to *Mesodinium*, the HICO reflectance spectrum was an almost pure example of the *in situ* optical signature of this unique organism (i.e. an "end-member" in remote sensing terminology).

In addition to phycoerythrin, the cryptophyte chloroplasts that the ciliate retains contain chlorophyll-a, chlorophyll-c2, phycocyanin, and the carotenoid alloxanthin. The reflectance spectrum measured with the HICO sensor revealed features related to the fluorescence and absorption associated with these pigments that can be used as a spectral "fingerprint" of this specific organism (Fig. 3A). With reflectance measured across the full visible spectrum, small dips in the spectrum can be revealed with a $4^{th}$ derivative analysis and related to the associated pigments (*11*) (Fig. 3B). In addition to absorbing green light, phycoerythrin also fluoresces yellow light (*12*) (Fig. 1B) and a peak in reflectance was observed at ~565 nm associated with this feature. This unique fluorescence feature allowed us to map the surface distribution of *Mesodinium* in Long Island Sound. Traditional ocean color satellites do not measure reflectance of light at this waveband, but yellow fluorescence (band depth at 565 nm) could be detected from the hyperspectral measurements of HICO and related to the relative amount of *Mesodinium* up to the measured $10^6$ cells $L^{-1}$ with distinctly red colored water (Fig. 4).

The fine-scale distribution of the HICO imagery reveals that *Mesodinium* was found in small 100-m patches along the sea surface rather than distributed throughout a single multi-kilometer patch as suggested by the 1-km MODIS imagery (Fig 2A). Such high spatial resolution from aircraft has been used to assess concentration mechanisms of blooms, including internal waves (*13*) and Langmuir circulation (*14*). Further research is underway to assess the observed patterns with hydrographic and air-sea processes local to this region. Understanding the spatial distribution may also lead to a better understanding of the environmental factors that lead to these episodic

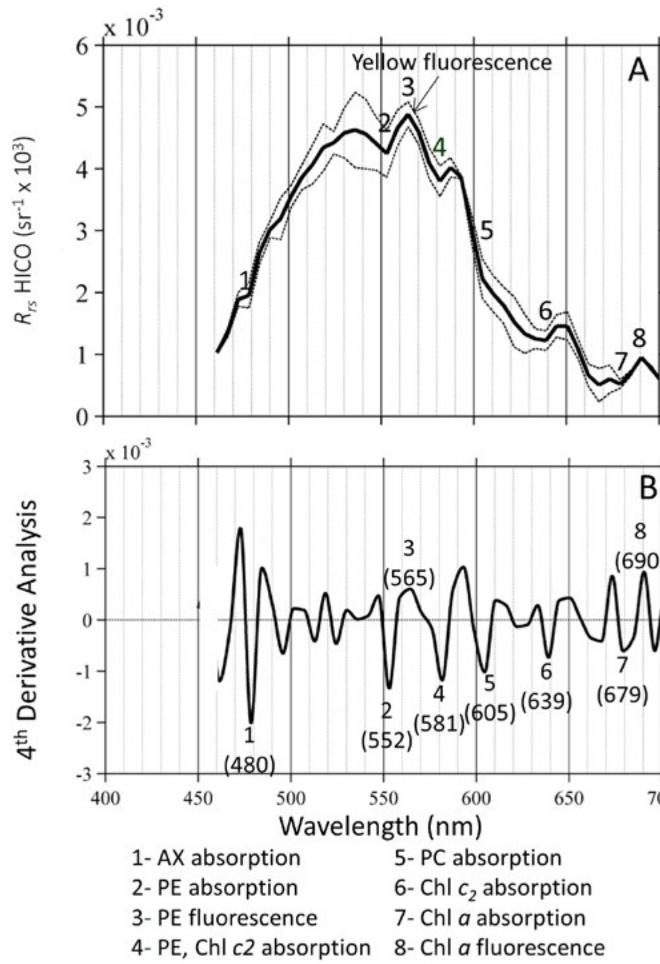


**Figure 3**. **A)** The spectral information available from the hyperspectral HICO sensor shows many peaks and dips related to the pigment absorption and fluorescence features from phycoerythrin (PE), phycocyanin (PC), alloxanthin (AX), chlorophyll *a* and *c2* contained within the enslaved cryptophytes in the ciliate *Mesodinium rubrum*. **B)** A 4th derivative of the spectrum in panel A amplifies the subtle changes in the spectrum such that values above 0 relate to peaks in reflectance from fluorescence or a local minimum in absorption and those falling below 0 related to dips in reflectance from pigment absorption. Figure modified from (**8**).

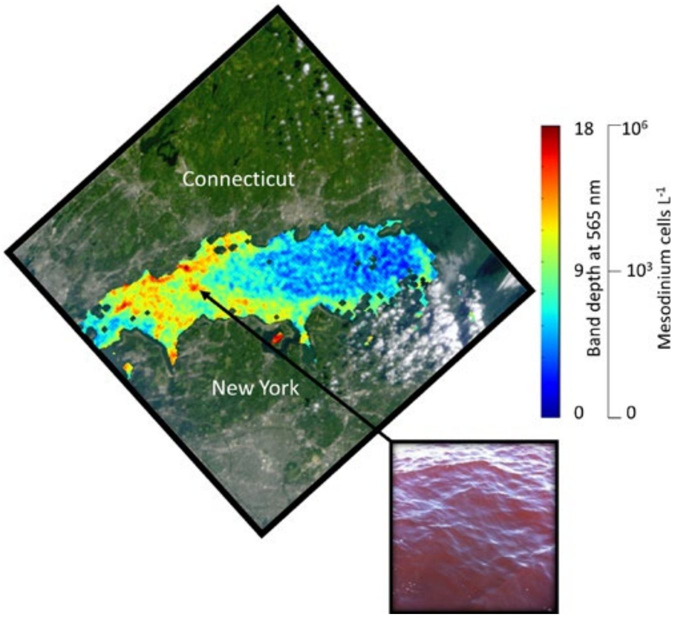


**Figure 4**. Hyperspectral HICO imagery at 110 m resolution from the International Space Station reveals characteristic yellow fluorescence due to phycoerythrin pigment within the enslaved chloroplasts of the ciliate *Mesodinium rubrum*. Dense, patchy near-surface blooms of this motile and actively photosynthesizing mixotrophic marine protist (>1x$10^6$ cells $L^{-1}$) periodically dominate primary productivity in the region and produce extremely red water as shown in photograph (credit Kay Howard-Strobel). Figure modified from (**8**).

blooms of *Mesodinium*. Generally, *Mesodinium* is more abundant in lower salinity estuarine water, but the causes of bloom initiation and demise are not well known (*15*).

Though now defunct, the HICO sensor should serve as a model for remote sensing in the coastal zone. With its high spectral and spatial resolution, images from HICO could be used to assess coastal processes, as highlighted here, but only at infrequent intervals. While possible with airborne technology, no existing or planned satellite sensor can sample at high spectral, spatial, and temporal resolution for adequate monitoring of the coastal zone. Providing near-daily coverage for much of the globe, the next generation NASA ocean color sensor, Pre-Aerosol, Cloud and ocean Ecosystems (PACE), is slated to have the unique hyperspectral capabilities to allow for better discrimination of marine blooms and habitats, but with a larger km-scale resolution. International sensors with new capabilities will also help to fill this gap (*16*). With new hyperspectral technology in space, autonomous and routine differentiation of phyto- and mixotrophic plankton blooms in surface waters may be possible and could provide an important tool for resource managers. Improved monitoring of bloom-forming plankton will also lead to more refined estimates of coastal primary productivity and mechanisms for their episodic growth and decline. If future sensors or sensor constellations combine high repeat sampling with the hyperspectral capabilities and high spatial resolution of HICO, we will be able to understand not only the composition and extent of blooms, but also the sub-mesoscale processes that drive their persistence and spatial structure.

## Acknowledgments

We thank Kay Howard-Strobel, Senjie Lin, and the NOAA Phytoplankton Monitoring Network for images of the bloom and of *Mesodinium*. Dajun Qiu verified the genetic identity of the ciliate. Adam Chlus and Bo-Cai Gao contributed to the image processing. We also thank the HICO Science Team and NASA Ocean Biology Distributed Active Archive Center for providing satellite imagery.

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# IMBER – Synthesis and the Way Forward

*By Eileen E. Hofmann, IMBER Past-Chair (Old Dominion University, Norfolk, VA) and Carol Robinson, IMBER Chair (University of East Anglia, Norwich, UK)*

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project grew from a desire by the international marine science community to address the challenges of understanding the interactions and relationships between biogeochemical cycles and food webs across multiple space-time scales, and to quantify and predict marine system responses to natural and anthropogenic forcings. IMBER was initiated in 2005 as a joint project of the International Geosphere-Biosphere Programme (IGBP) and the Scientific Committee on Oceanic Research (SCOR) with the central goal *to provide a comprehensive understanding of, and accurate predictive capacity for, ocean responses to accelerating global change and the consequent effects on the Earth system and human society.* IMBER has its origins in previous IGBP-SCOR projects, the Joint Global Ocean Flux Study (JGOFS) and the Global Ocean Ecosystem Dynamics (GLOBEC) project, which highlighted knowledge gaps and limitations in the global research capacity for integrated approaches across multiple scales and key processes that were needed to understand global change effects on marine ecosystems.

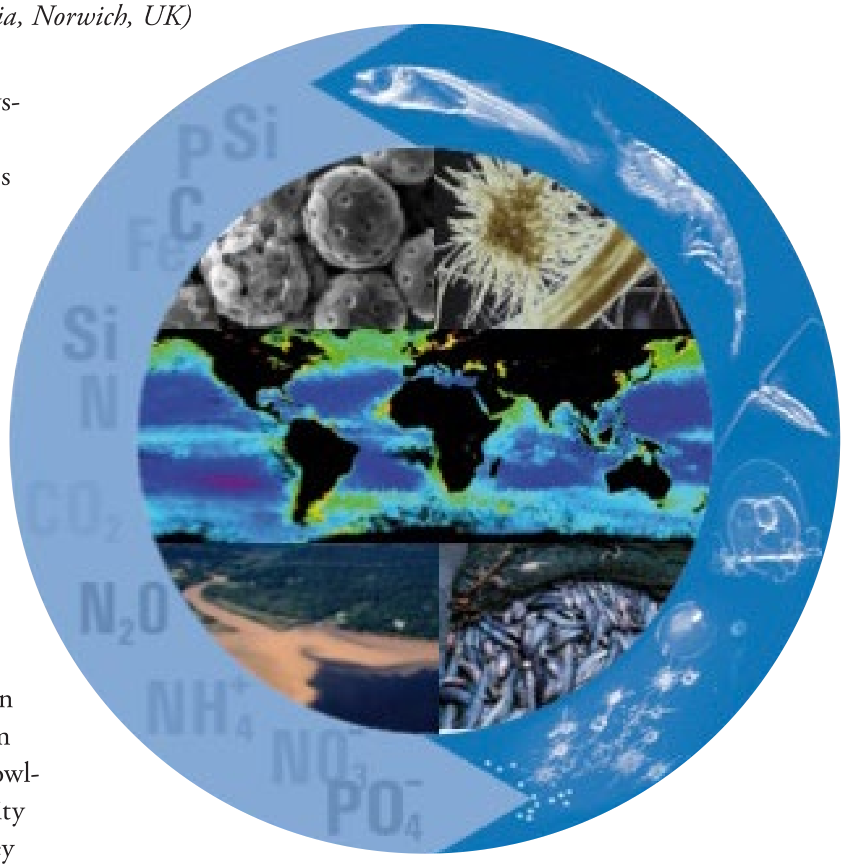


**Figure 1.** Schematic of interacting science themes that guided the first decade of IMBER research (2005-2015), illustrating the linkages between food webs and biogeochemical cycles (Theme 1 key interactions, outer circle), marine organisms (such as calcifying and nitrogen-fixing phytoplankton) that respond to global change (Theme 2 sensitivity to global change, upper panel), a global chlorophyll distribution (Theme 3 feedbacks to the Earth system, middle panel), and human-marine interactions including fisheries (Theme 4 responses of societies, bottom panel).

During the past ten years (2005-2015), the IMBER goal has been pursued through science activities under four overarching and interlinked themes that consider key interactions in marine ecosystems, sensitivity to global change, feedbacks to the Earth system, and responses of society (Fig. 1). IMBER has addressed these themes through international coordination, networking and capacity building activities, regional programs, working groups, national contributions, endorsed projects, and integrative, project-wide activities (Fig. 2). In-depth regional and topical analyses and comprehensive comparisons of diverse marine ecosystems have provided new understanding about the potential effects of global environmental change on biogeochemical cycling, food web dynamics, and impacts and linkages to human systems at multiple scales. The focus of a global community of natural and social scientists on a specific research agenda facilitated these important advances (see (*1*) for an overview).

The IMBER project is now undergoing a transition in parallel with changes and transitions in the global environmental research community. The IGBP ended operations in late 2015, following the ending of other international science coordination bodies, the International Human Dimension Programme, DIVERSITAS and the Earth System Science Partnership. These multiple organizations were replaced with a single overarching program, Future Earth, a 10-year international research initiative focused on providing the knowledge and support to accelerate transformations to a sustainable world. The science plan and implementation strategy (SPIS) that guided IMBER for the past 10 years is ending, which provides the opportunity to reconsider IMBER's vision and goal in light of its accomplishments and research needs and directions for the future.

IMBER began the process of developing a new SPIS with its 2014 Open Science Conference (OSC). The OSC

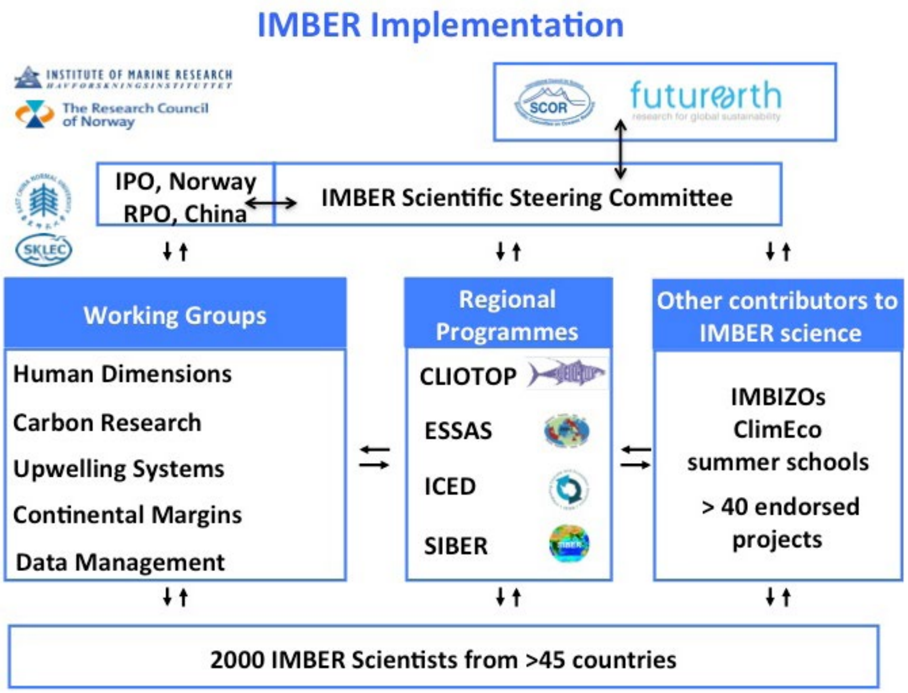


**Figure 2.** IMBER Project organization and implementation. Coordination of IMBER activities is through the International Project Office (IPO), the Regional Project Office (RPO) and the Scientific Steering Committee. IMBER science is implemented through working groups, regional programs, project-wide activities (IMBIZOs, ClimEco summer schools), and endorsed projects; all supported by an international community of scientists. The Carbon, Upwelling and Continental Margins working groups are jointly sponsored with the Surface Ocean-Lower Atmosphere Study (SOLAS), the Climate and Ocean: Variability, Predictability and Change (CLIVAR) project, and the Future Earth Coasts project, respectively. The regional programs are: CLimate Impacts on Oceanic Top Predators (CLIOTOP), Ecosystem Studies of Subarctic and Arctic Seas (ESSAS), Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean, and Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER).

provided an opportunity for the marine science community to present key findings of IMBER-relevant research and promote integrated syntheses of IMBER research. It also gave a planned opportunity to solicit and discuss approaches for updating the IMBER research agenda to guide future research into marine biogeochemistry, ecosystem structure and functioning, the human dimensions of global marine change, and interactions between each of these. The outputs from the OSC, subsequent community-wide consultations, and inputs from partner organizations and national programs resulted in the development of a new IMBER SPIS to guide the next decade of research, and to provide the basis for IMBER to transition to becoming a core project of Future Earth and to continue as a research focus for SCOR.

The new IMBER SPIS recognizes that the evolution of marine ecosystems (including biogeochemical cycles and human systems) is linked to natural and anthropogenic drivers and stressors. This broadened the IMBER vision to focus on *ocean sustainability under global change for the benefit of society*. This vision is supported by a research goal for the next decade to: *Understand, quantify and compare historic and present structure and functioning of linked ocean and human systems to predict their future structure and functioning and develop options for securing or transitioning towards ocean sustainability.*

The integrated research agenda for the next decade supports this new vision and goal, and is based on three grand challenges that focus on climate variability, global change and human drivers and stressors, and innovation challenges that focus on new areas for IMBER where research is needed and where it is believed that major achievements can be made within 3-5 years (Fig. 3). The first grand challenge considers the state and variability of marine ecosystems, the impacts of natural variability and anthropogenic global change, and interactions across time and space scales. This is further developed in the second grand challenge, which focuses on predictions and projections of ocean-human systems at multiple scales, including improving ecosystem models for scenario testing and evaluation, and considerations of biodiversity maintenance and direct anthropogenic drivers such as fishing. The final grand challenge focuses on improving and achieving sustainable governance and recognizes the need to improve the science-policy-society interface and develop new linkages between marine and human systems. This challenge includes "communicating relevant information and knowledge needed by society to secure sustainable, productive and healthy oceans." Implementation of the grand challenges in a 3- to 5-year time horizon is provided by the innovation challenges that consider metabolic diversity and evolution, global ocean observational and modeling networks, ecological feedbacks in the Earth system, and social science data for ocean management, decision-making and policy development.

With its new SPIS, IMBER will maintain its strong commitment to basic, curiosity-driven science and expand into new areas of problem-driven, policy-relevant interdisciplinary research. The IMBER project is now evaluating its working group and regional program structure with a view towards better alignment with the new SPIS. As IMBER moves forward into a new decade of research, the project will maintain the legacy of IGBP, continue to contribute to the objectives of SCOR which focus on promoting international cooperation in planning and conducting oceanographic research, and solving methodological and conceptual problems that hinder research, and transition to a core project of Future Earth to contribute to their vision of supporting research which enables transformation to global sustainability and equitability. The IMBER SPIS is undergoing final review by SCOR and Future Earth and will be jointly published by both organizations in 2016.

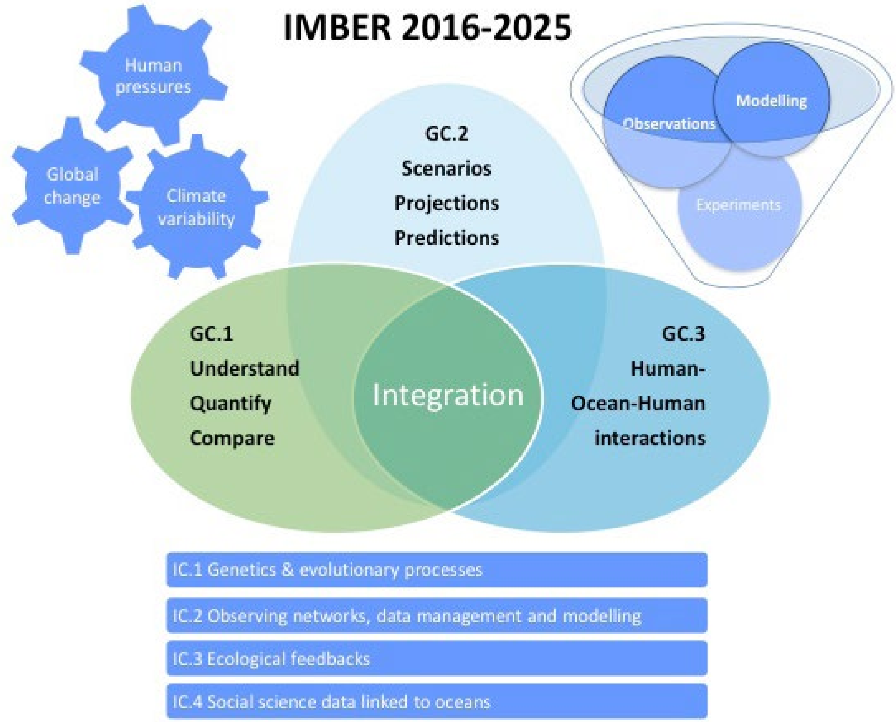


**Figure 3.** Integrative structure of IMBER Grand Challenges (GC) and Innovative Challenges (IC). Marine ecosystems are responding to major pressures (upper left) that operate at a range of scales. Understanding, quantifying and predicting responses of marine ecosystems to these pressures requires integrated observational, experimental and modeling programs (upper right).

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# Marine and Human Systems: Addressing Multiple Scales and Multiple Stressors

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The Integrated Marine Biogeochemistry and Ecosystem Research Project (IMBER) is developed around four research themes, which include: Key interactions in marine ecosystems; sensitivity to global change; feedbacks to the Earth system; and responses of society. When IMBER was initiated in 2005, the responses of society theme represented a new direction for global environmental change programs because it explicitly acknowledged the role of humans as both drivers and recipients of change in marine ecosystems. IMBER project-wide activities, regional programs and working groups have advanced the science associated with each research theme. However, the strength of these activities has been in the identification of theoretical and methodological overlap among the themes, facilitating integration of ideas and synthesis of research outcomes, and highlighting new research directions.


Fig. 1. Schematic of human-ocean interactions and the four workshop topics that were the focus of IMBIZO IV.

The biennial IMBIZO (Zulu word for a gathering) is an important IMBER-wide activity for assessing current understanding of theoretical and empirical research at the local, regional and global scale, and pointing to future research needs. IMBIZO IV, held in October 2015 in Trieste, Italy, addressed linkages between marine ecosystems and human systems (Fig. 1). In particular, emphasis was on current systems understanding and approaches to predict the effects of multiple stressors, at multiple scales, on marine ecosystems and dependent human populations. A novel aspect of this IMBIZO was the focus on exposing the need for human systems to respond to changes and for governance systems to adequately guide these responses.

IMBIZO IV was developed around four workshops (Fig. 1) that addressed i) marine ecosystem-based governance, ii) upwelling systems as models for interdisciplinary global change studies, iii) integrated modeling to support marine socio-ecological systems under global change, and iv) regime shifts and their socio-ecological implications. Although each workshop had distinct objectives, all addressed aspects of climate, ecosystems and societies with a view towards integrating and synthesizing current understanding and highlighting approaches for developing innovative societal responses to changing marine ecosystems. The workshops were supplemented with plenary presentations that provided overviews of the state of understanding and research needs and joint sessions and debates that allowed cross-workshop interactions (Fig. 2).

Within the context of each workshop, questions were addressed that considered the challenges of multiple stressors, pressures, and drivers, existing knowledge gaps, and the type of expertise needed to move forward. Some workshops also evaluated the need for paradigm shifts to adequately address particular research questions. The overall goal of each workshop was to determine how integration of the diverse array of knowledge and different research outcomes for marine systems could be done to provide useful advice for policy and management.

The results of the individual workshops are being summarized in a variety of ways including white papers, synthesis papers, short communications, and special issues.  However, the workshop results have common components with perhaps the clearest message being the need for continued conversations and exchange of information between scientists from different disciplinary backgrounds. To enable this dialogue to take place collaboratively and ultimately to develop workable solutions will mean that a common understanding of language will need to be developed and that jargon be avoided. Facilitating cross-disciplinary communication by domain experts will also help crucially important communication to management authorities and decision makers.

Aside from the need for good communication between scientists that straddle the physical, ecological and human domains, the different workshops considered the linkages and interactions between the driving forces (pressures-state-impacts-responses, DPSIR) and how these are understood and represented. For most marine systems, the system state, how much of what is present and where, can be described with differing degrees of certainty depending on location and factors such as monitoring intensity and accessibility.  The connectivity and linkages between marine system components and driving forces are known from a theoretical perspective and for many systems these have been described quantitatively using different modeling approaches. However, there is considerable empirical uncertainty about how marine systems might respond to continued and cumulative anthropogenic stresses and how

Figure 2. Debates held at IMBIZO IV engaged the audience to take a position on four questions that addressed the importance of natural versus social sciences to inform marine governance and control of managers and stakeholders on scientific research. Clockwise from top: Ratana Chuenpagdee and Stuart Corney debated opposing viewpoints, Eric Galbraith (debate moderator) and Einar Svendsen (debator), debate audience, and discussion group. Photo credit: V. Villanger.

in turn, this may feed back to the human domain and affect, for instance, future food security.

Marine systems may not be generalizable, sometimes cannot be simply scaled up, or may not respond linearly to anthropogenic stressors. Regime shifts may occur that are not easily (or not at all) reversible, thus requiring adaptation by resource users. The governance system is crucially important in this context as it provides links to management, policy and regulatory systems that influence use of and access to marine resources. Governance institutions are ultimately responsible for the sustainable management of marine resources and any necessary reduction in the pressure exerted on the resources. These governance systems in essence close the loop between the natural and human systems. Natural, socio-economic, and governance systems need to be central to continued research efforts and inform all levels of decision making to ensure informed steps are taken.

Global environmental change is happening and will continue to affect ecosystems and alter the ecosystem services provided to humanity. The need for timely detection and attribution of these changes remains, especially where change is irreversible. Human systems and society at large are both creators of the many stressors that drive change in marine ecosystems as well as recipients of these changes. Human systems can drive positive changes through good governance aimed at reducing vulnerability, and enhancing adaptive capacity and resilience. It is clear that many knowledge gaps remain, in particular the way in which multiple drivers and stressors interact. Much work also remains to be done in further detailing and modeling the crucial dependencies between human and ocean systems. All of these uncertainties place limitations on the predictability of governance outcomes and risk unintended consequences and maladaptation if not addressed adequately. Outcomes from IMBIZO IV will provide guidance for these important research efforts for the next decade of IMBER research.

IMBER gratefully acknowledges the support provided by the OCB Program for IMBIZO IV and its ongoing support of IMBER activities.

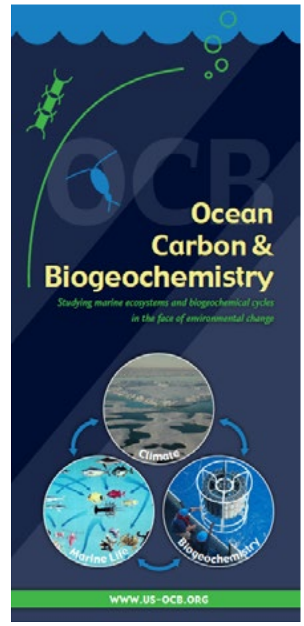
# Upcoming OCB Events

July 25-28, 2016: OCB Summer Workshop (Woods Hole, MA)

August 1-4, 2016: Joint GEOTRACES-OCB Workshop on Internal cycling of trace elements in the ocean (Lamont-Doherty Earth Observatory, Palisades, NY)

# About OCB

- OCB mission statement
- New informational brochure about OCB




# OCB Leadership Changes

OCB welcomes the newest members of its Scientific Steering Committee (SSC): Anton Post (URI), Laurie Juranek (OSU), Dennis McGillicuddy (WHOI), and Andrew Barton (early career representative, Princeton/NOAA GFDL). The new SSC chair is Matt Church (Univ. Hawaii) and vice chair is Bethany Jenkins (URI). We would like to thank outgoing members Carol Arnosti (UNC), Craig Carlson (UCSB), Hugh Ducklow (LDEO), Eileen Hofmann (ODU), and Todd Martz (SIO) for their dedicated service, particularly Craig Carlson, who served as vice-chair (2012-2013) and chair (2014-2015) of the SSC.

To find out what the OCB SSC is up to, access the monthly SSC minutes on our website (2015 SSC minutes, 2016 SSC minutes).

# Recent Activities

## Workshop report: How Biology Influences Ocean Carbon Export: Beyond the Biological "Pump"

*February 19-20, 2016 (New Orleans, LA)*
*Heather Benway (WHOI/OCB), Adrian Burd (Univ. Georgia)*


The biological pump is a key component of the marine carbon cycle and is driven by a complex combination of physical, chemical, and biological processes. Our ability to make accurate, quantitative predictions about the biological pump is hampered by our incomplete understanding of these drivers, and how they will change in a changing climate. As a result, many models still use semi-empirical relationships for the attenuation of particle flux with depth.

Potential interest from NSF Ocean Sciences, stimulated by the possibility of the NASA EXport Processes in the

Ocean from RemoTe Sensing (EXPORTS) Program in the near future, has created the opportunity to address major gaps in our knowledge and understanding of the biological processes driving and controlling the biological pump and flux attenuation in the ocean.

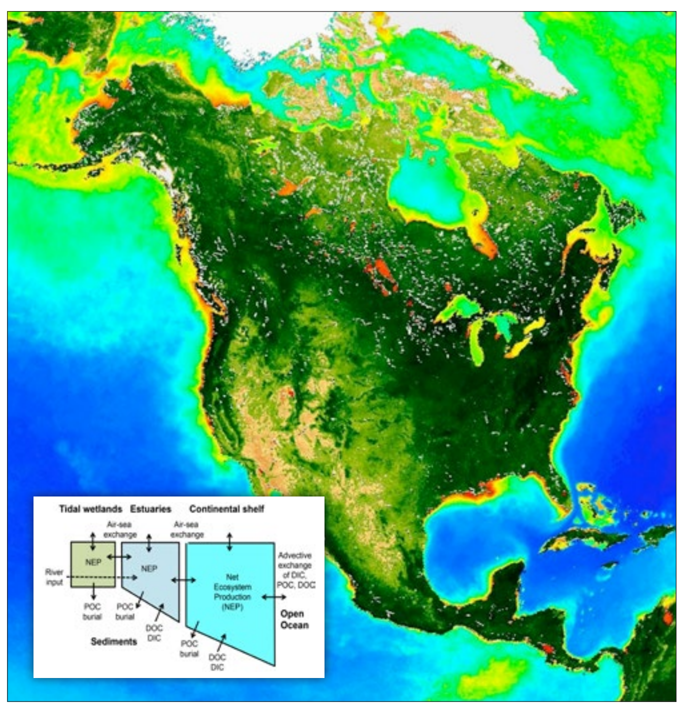
On February 19-20, 2016, a workshop was held in New Orleans, LA just prior to the 2016 Ocean Sciences meeting to foster discussions around new perspectives and identify critical gaps in our understanding of key biological processes involved in ocean carbon export. The workshop, which was funded by NSF and coordinated by the Ocean Carbon and Biogeochemistry (OCB) Project Office, convened 39 participants, including researchers working in key areas related to biological pump function, as well as NSF and NASA program managers. The workshop opened with a plenary session that included talks on biological pump research initiatives, an overview of the biological pump, new instrumentation, new biological processes, aggregation and marine snow, and quantifying export. These talks helped set the stage for the real work that took place thereafter by providing an overview of our current understanding, as well as identifying potential new questions and opportunities. The remainder of the workshop was spent in a series of smaller group discussions. Throughout these small group activities, a consensus-building exercise called the KJ Technique was employed. The KJ activities ultimately helped distill key research priorities in each of five focus areas:

- Particle formation in the upper ocean and processes that drive export
- Mesopelagic flux attenuation and the biological processes that drive it
- Particles: Characteristics, bioreactivity, export, stoichiometry, episodic export events
- Microbial and viral processes and newly revealed biological pathways
- Food web, community structure, and trophic interactions

### Your input is needed!

The primary outcome of this workshop will be a White Paper that identifies those critical gaps in our understanding whose study will lead to significant advances in the field. While workshop participation was limited in order to be effective, input from the broader community is critical in this process. We encourage all who are interested to provide feedback when the draft is released for public comment (Summer 2016) via the OCB website and email list. The final report, which will be used to coordinate NSF and NASA EXPORTS planning activities, will be delivered to NSF in early Fall 2016.

## New science plan published for carbon cycle research in North American coastal waters




A few months ago, OCB sought community input on a draft science plan for carbon cycle research in North American coastal waters. We are pleased to share with you the final version of this science plan, which is the culminating activity of a series of workshops and research activities that have been conducted over the past several years as a partner activity between OCB and the North American Carbon Program (NACP) to synthesize existing data and improve quantitative assessments of the North American carbon budget. These activities were made possible with funding from the NASA Ocean Biology and Biogeochemistry Program and NSF Chemical Oceanography. This document will be used by researchers and federal agencies in future planning efforts. You can download the science plan here.

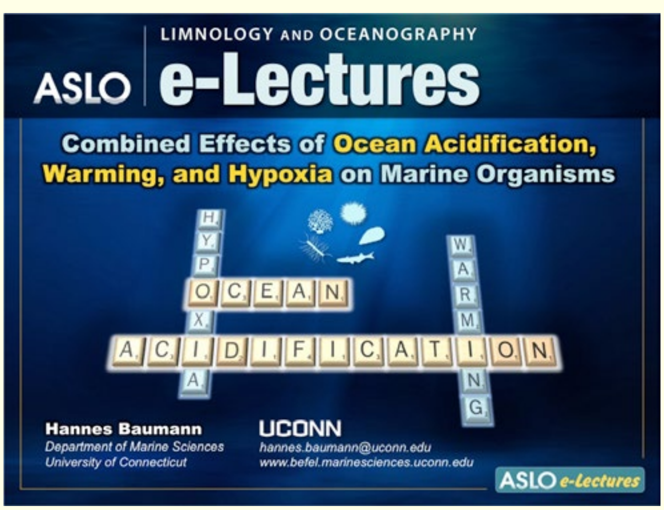
**Suggested Citation**: Benway, H., Alin, S., Boyer, E., Cai, W.-J., Coble, P., Cross, J., Friedrichs, M., Goñi, M., Griffith, P., Herrmann, M., Lohrenz, S., Mathis,

J., McKinley, G., Najjar, R., Pilskaln, C., Siedlecki, S., Smith, R. (2016). A Science Plan for Carbon Cycle Research in North American Coastal Waters. Report of the Coastal CARbon Synthesis (CCARS) community workshop, August 19-21, 2014, Ocean Carbon and Biogeochemistry Program and North American Carbon Program, 84 pp., DOI 10.1575/1912/7777.

# Community Announcements

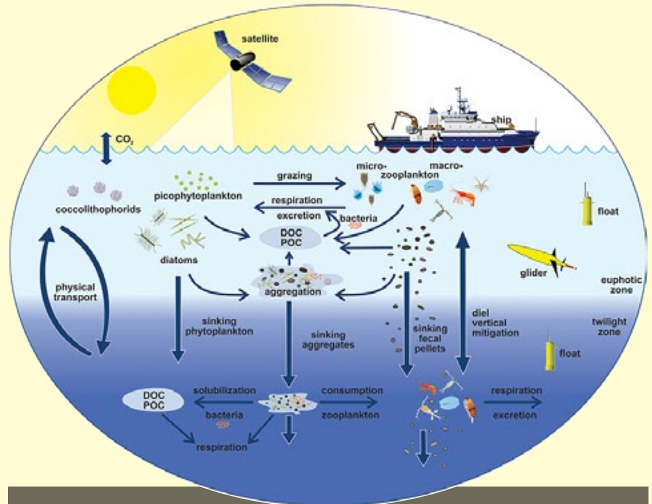
## Outreach and networking

- *Eos* opinion piece on the need to strengthen carbon cycle science in support of policy
- **New OCB slide deck** *Temporal and Spatial Perspectives on the Fate of Anthropogenic Carbon: A Carbon Cycle Slide Deck for Broad Audiences* - also download accompanying explanatory notes (doi:10.1575/1912/7670)
- New open access L&O e-lecture "Combined Effects of Ocean Acidification, Warming, and Hypoxia on Marine Organisms"
- Meet the new US SOLAS Representative Rachel Stanley
- 2016 POGO-SCOR Visiting Fellowships programme deadline April 15
- New Latin American Ocean Acidification (LAOCA) Network


## For Your Reading Pleasure

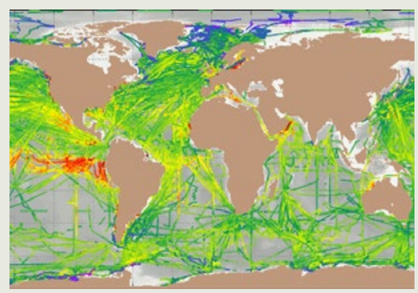
- IOCCP Position Paper on Global Ocean Biogeochemistry Data Management
- North American Coastal Carbon Science Plan
- U.S.-Canada Joint Statement on Climate, Energy, and Arctic Leadership
- SOLAS article Scientific synthesis and contribution to Earth system science
- Report from international workshop Bridging the Gap Between Ocean acidification Impacts and Economic Valuation
- Tribute to IGBP in Science
- NASA EXPORTS paper in *Frontiers in Marine Science*
- Future Earth Highlights of 2015
- Marine Chemistry Special Issue *Cycles of metals and carbon in the oceans – A tribute to the work stimulated by Hein de Baar*



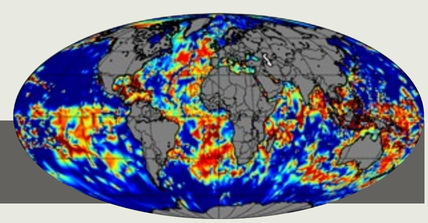

NASA EXPORTS paper published in Frontiers of Marine Science

## Science

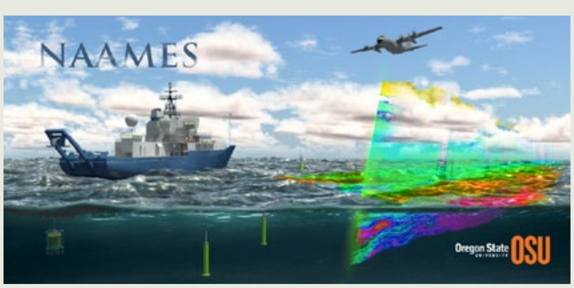
- New Global Synthesis Product of Seafloor Surficial Carbonate
- Internally Consistent Dataset of δ$^{13}$C-DIC Data in the North Atlantic Ocean
- Call for CTD and CFC watchstanders on GO-SHIP P18 Line
- EPA 1990-2014 GHG Inventory
- NAAMES: North Atlantic Aerosols and Marine Ecosystems Study
- Global Carbon Budget 2015
- GLobal Ocean Data Analysis Project version 2, GLODAPv2
- New Blue Carbon maps and reports released by the Commission for Environmental Cooperation
- Surface Ocean $CO_2$ Observations (SOCAT) v. 3
- Short survey to inform 3rd Global Ocean Acidification Observing Network (GOA-ON) workshop (responses due April 11)



Surface Ocean CO2 Observations (SOCAT) v. 3



Seabed Surficial Carbonate: interpolated grid




The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) is a five year investigation to resolve key processes controlling ocean system function, their influences on atmospheric aerosols and clouds and their implications for climate.


# Ocean Time-Series News

## Report from 2016 Ocean Sciences Town Hall Meeting

## *The Future of Biogeochemical Ocean Time-series (New Orleans, LA)*

### Introduction and Purpose

Monitoring ocean change requires a sustained, globally distributed network of observatories that integrates shipboard, autonomous, and remote sensing platforms. Data intercomparability within such a network is facilitated by universally established guidelines and methodological approaches, a commitment to data sharing, and improved coordination and communication across sites and programs. This town hall meeting was organized by the US Ocean Carbon and Biogeochemistry (OCB) Program's Ocean Time-series Committee (OTC). There were ~90-100 people in attendance at the Town Hall Meeting. The focus of the town hall was to highlight previous and ongoing scientific, observing, and capacity-building coordination efforts across ocean time-series and gather feedback from the community on next steps.

### Town Hall Presentations

The town hall opened with a brief overview of the OTC and its charge by Susanne Neuer (OTC chair) and the overall importance of ocean time-series in monitoring ocean change. Following this overview, brief presentations were given on recent best practices activities to support the international time-series community. Heather Benway (OCB/WHOI) gave a brief summary of a shipboard biogeochemical time-series methods workshop that OCB and the International Ocean Carbon Coordination Project (IOCCP) co-organized in Bermuda in November 2012 to convene representatives from global marine biogeochemical time-series sites to review current methodologies being used at the sites. Laura Lorenzoni (Univ. South Florida) then provided a summary of a recent IOCCP best practices training workshop on autonomous biogeochemical sensors held in Kristineberg, Sweden. The following presentation by Laura Lorenzoni (Univ. South Florida) provided an overview of methodologies, scientific insights and products of the International Group for Marine Ecological Time Series (IGMETS), a scientific initiative that seeks to integrate a suite of in situ biogeochemical variables from time-series stations, together with satellite-derived information, to look at holistic changes within different ocean regions and explore connections at a global level. Richard Lampitt (National Oceanography Centre, Southampton, UK) then spoke about OceanSITES, an international observing network consisting of long-term, open-ocean reference stations measuring dozens of variables and monitoring the full depth of the ocean from air-sea interactions down to the seafloor, including observations of meteorology, physical oceanography, transport of water, biogeochemistry, and parameters relevant to the carbon cycle, ocean acidification, the ecosystem, and geophysics. Finally, Mike Lomas (Bigelow Laboratory) gave a presentation on the Nippon Foundation – POGO Alumni Network for Oceans (NANO), a capacity building initiative that supports an international network of ocean scientists with a shared vision of "Integrated Observations of a Changing Ocean" who are dedicated to educating the next generation of ocean scientists and communicating the results of their work to the general public to raise awareness and maximize societal benefit.

### Community Discussion

Immediately following the presentations, there was a community Q&A and discussion to identify key priorities and next steps. Attendees discussed approaches, activities, products, and coordination efforts to support an international time-series network. Overall, participants stressed that we must continue to let the scientific question(s) at hand guide our coordination efforts across time-series. To maximize use and visibility of time-series data sets, participants stressed the need to maximize data access and incentivize data sharing via publication options and provision of citation guidelines. Participants identified several mechanisms to strengthen the current time-series network, including:

- forging collaborations across different international groups/time-series (e.g., sharing students and postdocs)
- exploring international partnerships to establish new time-series in poorly sampled regions of the world's oceans
- developing a portal of education and public outreach materials to support teaching and outreach across the time-series network
- improving communication and providing much needed coordination across discipline-specific (e.g., physics/climate, biogeochemistry, biology, geology, etc.) observing assets to leverage and enhance existing networks when and where possible

In the coming weeks, the OCB OTC will be meeting to discuss important next steps in light of the feedback received at the town hall meeting. For more information about the international time-series network, please visit http://www.whoi.edu/website/TS-network/ or join our time-series email list.

# Calendar

*Please note that we maintain an up-to-date calendar on the OCB website.*

| 2016 | |
|---|---|
| April 17-22 | 2016 EGU Meeting (Vienna, Austria) |
| April 28-29 | Ocean Acidification research in China: an international workshop (Shanghai, China) |
| May 3-6 | 4th Oceans in a High CO2 World Meeting (Hobart, Tasmania Australia) |
| May 8-10 | 3rd GOA-ON Science Workshop (Hobart, Tasmania Australia) |
| May 23-27 | 48h International Liege colloquium on Ocean Dynamics Submesoscale Processes: Mechanisms, implications and new frontiers (Liège, Belgium) |
| May 23-25 | 2016 Paleo AMOC Workshop Connecting Paleo and Modern Oceanographic Data to Understand AMOC over Decades to Centuries (Boulder, CO) |
| June 1-2 | Chesapeake Modeling Symposium "Advancing transparency and communication through community modeling" (Williamsburg, VA) |
| June 5-10 | ASLO 2016 Summer Meeting (Santa Fe, NM) |
| June 8-10 | Training course on Marine Radiochemistry (Xiamen, China) |
| June 12-17 | Gordon Research Conference: Biologically driven ocean carbon pumps (Hong Kong, China) |
| June 13-24 | Summer course (Bergen Summer Research School) 2016: The ocean, climate and society (Bergen, Norway) |
| June 19-24 | 13th International Coral Reef Symposium (Honolulu, Hawai'i) |
| June 26 | Exploring GEOTRACES data with Ocean Data View (Yokohama, Japan) |
| June 26-July 1 | Goldschmidt 2016 (Yokohama, Japan) |
| July 4-22 | BIOS Modern Observational Oceanography course (BIOS, Bermuda) |
| July 5-7 | Antarctic Science Conference (Norwich, UK) |
| July 16-17 | Ocean Global Change Biology Gordon Research Seminar (Waterville Valley, NH) |
| July 17-22 | Ocean Global Change Biology Gordon Research Conference (Waterville Valley, NH) |
| July 24-29** | Gordon Research Conference *Unifying ecology across scales* (Biddeford, ME) |
| July 25-28* | 2016 OCB Summer Workshop (Woods Hole, MA) |
| August 1-4* | Joint OCB/GEOTRACES workshop: Internal Cycling of Trace Elements in the Ocean (Palisades, NY) |
| August 10-11** | Forecasting ENSO Impacts on Marine Ecosystems (San Diego, CA) |
| August 10-17** | IMBER ClimECO5 Summer School (Natal, Brazil) |
| August 31-September 4 | 1st Altimetry for Regional and Coastal Ocean Models Workshop (Pilot ARCOM Workshop) (Lisbon, Portugal) |
| September 6-9 | 2nd International workshop on Air-Sea Gas Flux Climatology (Brest, France) |
| *OCB-led activity **OCB co-sponsorship or travel support | |

| 2016 | |
|---|---|
| September 6-8 | Colour and Light in the Ocean from Earth Observation (CLEO) workshop: Relevance and Applications Products from Space and Perspectives from Models (Frascati, Italy) |
| September 18-25 | CLIVAR Open Science Conference: Charting the course for future climate and ocean research (Qingdao, China) |
| September 19-23 | ICES Annual Science Conference (Riga, Latvia) |
| September 26-30 | International Global Atmospheric Chemistry (IGAC) Project 2016 Science Conference (Breckenridge, CO) |
| October 9-14 | Dissertations Symposium in Chemical Oceanography (DISCO) XXV meeting (Honolulu, HI) ´ |
| October 11-13 | IMDIS 2016 - the International Conference on Marine Data and Information Systems (Gdansk, Poland) |
| October 14-16 | COME ABOARD! Chemical Oceanography MEeting: A BOttom-up Approach to Research Directions (Honolulu, HI) |
| October 23-28** | Ocean Optics 2016 (Victoria, BC Canada) |
| October 23-29 | Eco-DAS XII (Honolulu, HI) |
| October 26-27 | SOLAS Science and Society (Brussels, Belgium) |
| December 12-16 | Fall AGU Meeting (San Francisco, CA) |
| *OCB-led activity **OCB co-sponsorship or travel support | |

| 2017 | |
|---|---|
| August 13-18 | Goldschmidt 2017 (Paris, France) |
| August 20-25 | 10th International Carbon Dioxide Conference (Interlaken, Switzerland) |
| *OCB-led activity **OCB co-sponsorship or travel support | |

# Upcoming Funding Opportunities

*For more information, please visit OCB's funding opportunities web page. The OCB calendar also lists upcoming deadlines.*

- NSF Research Coordination Networks (RCN)
- NSF North Atlantic-Arctic Dear Colleague Letter
- NOAA SBIR Phase I Solicitation for Fiscal Year 2016
- Full list of upcoming NSF proposal deadlines
- NSF Oceanographic Facilities and Equipment Support
- NASA ROSES 2016 solicitation

| | |
|---|---|
| April 17 | SCOR Working Group Proposal Deadline |
| May 16 | NSF Antarctic Research proposal deadline |
| August 2 | NSF full proposal deadline for new LTER site |
| August 15 | NSF Chemical Oceanography, and Biological Oceanography and Physical Oceanography and Marine Geology & Geophysics proposal deadlines |
| August 18 | NSF Arctic Research Opportunities proposal deadline |
| October 18 | NSF Arctic Research Opportunities |

## OCB News

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