OCEANOGRAPHY

"Breaking" news for the ocean's carbon budget

Fragmentation of particle aggregates helps regulate carbon sequestration in the ocean

By **Aditya R. Nayak**[1,2] *and* **Michael S. Twardowski**[1,2]

Oceans play a critical role in Earth's carbon cycle. Quantifying essential processes in carbon cycling and extending these to future predictions remain great scientific challenges. Nearly 30% of anthropogenic carbon is absorbed from the atmosphere into the ocean, where sempiternal, ubiquitous populations of microscopic particles transport carbon into the isolated deep sea (*1*). This complex pathway is driven by various biophysical and chemical interactions, including phytoplankton productivity, zooplankton grazing, oceanic mixing and turbulence, advection, and the sinking of particles and aggregates (*2*) (see the figure). On page 791 of this issue, Briggs *et al.* (*3*) quantitatively describe the key role of particle fragmentation in carbon storage by the ocean, potentially accounting for half of the particle flux that fails to sink into the deep ocean.

Of 10 to 12 billion metric tons of carbon absorbed at the ocean's surface, estimates suggest that only about 10 to 30% makes its way to 1000-m depth, a point of transition between the mesopelagic and abyssal regions (*4*, *5*). What happens to the remaining carbon in the mesopelagic has puzzled the scientific community for decades. Traditionally, sediment traps, both moored and drifting, collect sinking particles at a certain depth over a period of days to months. However, limited spatial and temporal coverage, hydrodynamic effects that alter collection efficiency, and pooling of collected particles within traps hamper broad-ranging interpretation of results. Moreover, elucidating sinking rates of individual particles of different sizes and densities has been a difficult problem. Advances in optical instrumentation and autonomous robotic platforms show promise for characterizing particle concentrations, size distributions, bulk densities, and sinking rates over large regions of Earth's oceans (*6*), making carbon flux estimates a potentially more tractable problem. Briggs *et al.* leveraged a network of 25 Biogeochemical-Argo floats distributed over two different oceanic regions and equipped with optical scattering and chlorophyll fluorescence sensors to explore this problem.

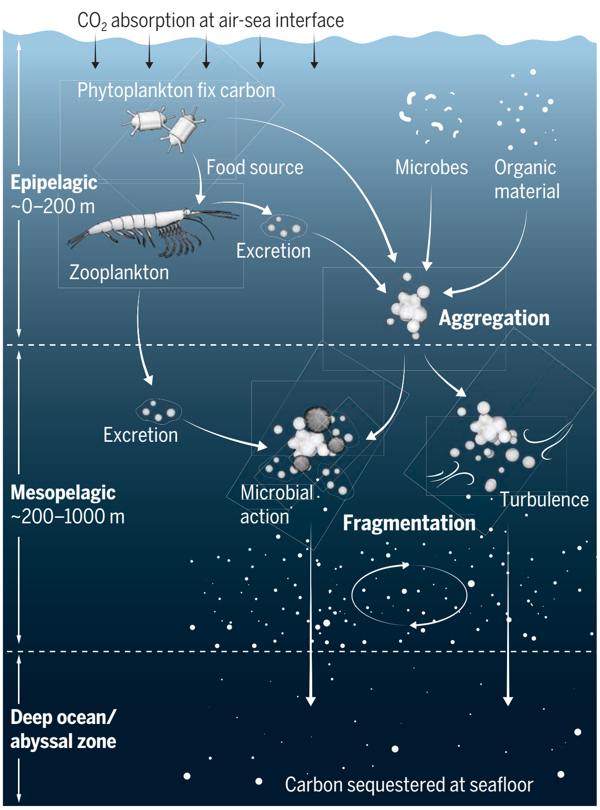
Since the emergence of practical beam transmissometers in the 1970s for measuring light attenuation through water, a wide range of optical sensors have been developed and commercialized. Approaches for measuring particle optical properties include spectral and angular scattering, silhouette and reflection imaging, holographic imaging, diffractometry, flow cytometry, and fluorescence (*6*, *7*). Some of these sensors have been integrated on autonomous ocean platforms in the last 20 years. Coincident with these emerging technologies have been efforts to develop algorithms to interpret data in terms of particle biogeochemical properties. The study by Briggs *et al.* is in many ways a culmination of these efforts.

The composition of sinking particles differs vastly in shape and size: Single-celled and colonial phytoplankton, zooplankton, marine snow, fecal pellets, organic detritus, and large aggregates can vary in size from 0.2 μm to several centimeters (*1*). Particle sinking rates are higher for larger and denser particles (*8*). Quantification of sinking rates plays an important role in understanding carbon flux budgets. Typically, large phytoplankton blooms form in the Atlantic and Southern Oceans during spring and summer. When nutrients are depleted, blooms die out, forming rapidly sinking large aggregates (*9*). Briggs *et al.* isolated such "pulses" of large sinking particle fluxes for analysis and found that small and large particle-size classes increase concomitantly. Particle aggregation is a common occurrence in the water column, driven by various processes, including Brownian motion, shear coagulation, gravitational settling, and differential sedimentation (*10*). Assuming the absence of fragmentation, smaller particles would aggregate to form larger particles, leading to a decrease in their concentrations. Hence, increased small-particle concentrations support the claim that large-particle fragmentation is indeed occurring. This helps to explain carbon flux loss in the mesopelagic.

The Briggs *et al.* study opens several new avenues of research. For example, the authors treated all particles in the 100- to 2000-μm range as "large." This coarse binning can lead to incomplete characterization of particle aggregation and/or fragmentation processes within that size range. In situ imaging instrumentation is now advanced enough to be used in particle flux characterization studies (*11*) and can help investigate these processes in the future. Other emerging techniques, such as remote imaging with range-

Biological carbon pump

A schematic of the processes involved in the "biological pump" that sequesters carbon to the deep ocean, with a focus on particle aggregation, fragmentation, and associated mechanisms.



GRAPHIC: N. DESAI/*SCIENCE*

[1]Department of Ocean and Mechanical Engineering, Florida Atlantic University, Boca Raton, FL, USA. [2]Harbor Branch Oceanographic Institute, Florida Atlantic University, Fort Pierce, FL, USA. Email: anayak@fau.edu

gated, scanning light detection and ranging (LIDAR) and holographic imaging to refine particle-size distributions and sinking rates, are also promising (*12*). Intriguingly, Briggs *et al.* found varying particle fragmentation rates between the Atlantic and Southern oceans. Characterizing fragmentation mechanisms might provide some clarity, as limited field studies have shown that several factors, including microbial action, oceanic turbulence, and zooplankton grazing, can be substantial contributors (*13*, *14*). Elucidating these complex small-scale interactions holds the key to addressing bigger problems.

Better understanding the intricate mechanisms involved in oceanic carbon export will improve global climate studies. Ongoing research initiatives implementing in situ optical particle-size measurements to quantify global carbon export include the U.S.-led EXport Processes in the Ocean from RemoTe Sensing (EXPORTS), and Europe-led programs such as Robots Explore plankton-driven Fluxes in the marine twIlight zoNE (REFINE), Gauging ocean Organic Carbon fluxes using Autonomous Robotic Technologies (GOCART), and CarbOcean. However, a major gap remains in providing the observational data required by models to accurately estimate global export. Of the 3858 Argo floats currently deployed throughout Earth's oceans, less than 5% are equipped with sensors that can resolve biogeochemical properties of particles. Briggs *et al.* demonstrate the value to be gained with an increased focus and investment in leading-edge optical technologies for ocean exploration. ■

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ACKNOWLEDGMENTS

A.R.N. is supported by National Science Foundation grant OCE-1657332 and Florida Atlantic University (FAU) internal funds. A.R.N. and M.S.T. are supported by NOAA Office of Ocean Exploration and Research under awards NA09OAR4320073 and NA14OAR4320260 to the Cooperative Institute for Ocean Exploration, Research and Technology (CIOERT) at FAU Harbor Branch Oceanographic Institute (HBOI) and the HBOI Foundation.

10.1126/science.aba7109

Increasing aridity will affect structural and functional attributes of global drylands, such as the Namib Desert in Namibia.

PHOTO: TIAGO_FERNANDEZ/ISTOCK.COM

ECOLOGY

Crossing thresholds on the way to ecosystem shifts

Meshing evidence from multiple datasets unveils Earth's mechanisms for adapting to environmental changes

By **Marina Hirota**[1,2] *and* **Rafael Oliveira**[2]

As the Earth system moves through continuous changes, scientists have attempted to predict pathways the planet will follow by unraveling trajectories of individual ecosystems and their interactions and by identifying the thresholds beyond which irreversible changes might occur (*1*). For example, increases in global aridity are known to affect terrestrial ecosystems, but it remains unknown whether modifications in global aridity will cause gradual or abrupt systemic or idiosyncratic transitions. Now, on page 787 of this issue, Berdugo *et al.* (*2*) analyze large datasets of observational and empirical evidence from studies of drylands. The authors show that changes occur in a sequential series of nonlinear thresholds beyond which dryland vegetation can vanish, leaving bare soil to prevail.

[1]Department of Physics, Federal University of Santa Catarina, Florianópolis, Brazil. [2]Department of Plant Biology, University of Campinas, Campinas, Brazil. Email: marinahirota@gmail.com; rafaelso@unicamp.br

New monitoring technologies have increased the availability of empirical measurements from the field and observations from remote sensors. Analyses of these massive amounts of data have unveiled some of the underpinnings of vegetation's response to drivers such as climate, nutrient availability, water-table depth, and others. Berdugo *et al.*'s sequential thresholds encompass patterns of cascading shifts in multiple ecosystem variables (e.g., productivity, soil carbon, and plant cover). This approach illuminates how ecosystems might respond to changes in future climatic regimes.

Three key issues remain unsolved to inspire future studies. The highly variable data analyzed by Berdugo *et al.* indicate that aridity is not the only driving factor affecting their adjusted nonlinear statistical models. Certain soil properties—determined mostly by the parent material, and not aridity, or the underlying geology of a landscape (*3*)—drive shifts in key vegetation properties (*4*). For example, in some of the

Science

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Science **367** (6479), 738-739.
DOI: 10.1126/science.aba7109

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.