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A stormy ocean voyage yields insights on the global carbon cycle

In the midst of the COVID pandemic, scientists embarked on an ambitious research expedition to the North Atlantic to investigate the inner workings of the ocean's carbon cycle. A series of storms hammered the three vessels, among the most advanced research ships in the world, while bureaucratic mayhem threatened to scrub the voyage entirely.

Despite these challenges, the multinational, interdisciplinary team and able crew were wildly productive. A resulting study, led by UC Santa Barbara's David Siegel, published in the journal Global Biogeochemical Cycles, reveals important insights for our understanding of Earth's climate. The paper details how the ocean's biological pump, a critical component of the planet's carbon cycle, transports organic matter from the surface to depths. It also presents some of the first findings to go beyond merely observing the sinking carbon pump and actually predicts fluxes of carbon into the deep sea.

Marine snow and the ocean carbon cycle

Photosynthetic plankton, called phytoplankton, convert inorganic carbon (like CO_2) into organic compounds. This forms the basis of the ocean food web. In fact, phytoplankton fix between 55 to 60 billion metric tons of carbon annually. Roughly 15% of that biologically fixed carbon is exported from the ocean' surface layers into its interior via the ocean's biological carbon pump largely by sinking particles. This carbon is then sequestered from the atmosphere for months to millennia.

Much of the sinking carbon is carried by tiny organic particles known as marine snow. Oceanographers Alice Alldredge (UCSB) and Mary Silver (UC Santa Cruz) began exploring the importance of marine snow, fluffy particles of detritus larger than 0.5 millimeters that drift down from the upper ocean. “It’s incredibly porous,” said Siegel, a distinguished professor in UCSB’s Department of Geography, “so it looks like snow as it drifts down from the surface.”

Alldredge and Silver conducted the seminal work on marine snow in the 1980s, observing how it forms, how it breaks up and how quickly it sinks. It turns out, marine snow sinks relatively quickly: up to 100 meters each day. In contrast, an individual phytoplankton may sink only 1 meter per day. And the deeper carbon goes into the ocean, the longer it’s sequestered.

But until now, scientists didn’t have a firm grasp of how ocean dynamics and interactions with living organisms affect marine snow. “We knew quite a bit about marine snow — the dust bunnies of the ocean — especially about their composition,” said co-author Uta Passow, a professor at Memorial University of Newfoundland. “But we knew very little about their real behavior in the ocean.”

Fluxes, like sinking and degradation rates, are difficult to measure directly in the field, so most knowledge about these comes from laboratory experiments. Siegel, Passow and their colleagues sought to build upon Alldredge and Silver’s work, taking advantage of modern technology to fill in the gaps in our current models of the planet’s carbon cycle.

Proposing a mission

NASA has a long history of using satellites to measure photosynthetic activity in the ocean. “The fate of that primary production energy is what drives the biological component of the carbon cycle, the ocean’s biological carbon pump,” Siegel said. So in 2012, he and his colleagues presented a proposal to NASA to conduct an expedition to link these satellite measurements to the fate of this carbon.

What emerged was the Export Processes in the Ocean from RemoTe Sensing (EXPORTS) field campaign, an effort to understand how the ocean's carbon cycle works — specifically how organic matter from the surface is transported to the deep ocean and what happens to it.

The marine component of the carbon cycle is a complex affair involving three pathways, which scientists call “pumps” due to their role in pumping carbon around the ocean. Vertical currents can carry organic carbon in the seawater to depth, driving the so-called mixing pump. Sealife itself forms the second carbon pump: the migrant pump. Every night an untold number of creatures travel upward to the ocean’s surface to feed, resulting in the largest migration on the planet. Their return trip brings carbon from the sunlit zone to the ocean’s depths. Finally, some organic material coagulates and sinks downward in the water column. This sinking pump is the focus of the current paper.

Coordinating during a pandemic

The EXPORTS North Pacific expedition took place in the fall of 2018, and was incredibly productive, but the emergence of COVID-19 nearly scuttled the North Atlantic campaign. The pandemic froze the intended launch date during the spring of 2020. After a hiatus, ships set sail in late April 2021, right as the first vaccine was rolling out in the U.S. This meant all the scientists based in America managed to receive their shots before sailing.

Image

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The EXPORTS mission chartered three ships R/V Sarmiento de Gamboa (foreground), RRS Discovery (middle), and RRS James Cook (background).

Organizing the expedition in the middle of the pandemic was a feat of logistical wizardry. The project drew on grants that were supposed to have ended. Meanwhile, the lead organizers coordinated safety plans between some 40 institutions across more than five countries. Ships needed commissioning after a long time at port; crews and researchers needed vaccinations and quarantine accommodations; and frequent antigen testing tracked the health of the team. Not a single instance of COVID-19 occurred on any of the three ships.

“It’s a friggin’ miracle that we pulled this off,” Siegel said.

The successful effort earned the NASA project office an Administrator’s Group Achievement Award in 2022 “for perseverance, creative thinking, and optimism in the face of adversity, enabling the successful completion of the EXPORTS project.”

Shaking the snow globe

Four major storms battered the team over the course of the research cruise, with wind speeds in excess of 50 knots and, at times, surface waves higher than 20 feet.

The authors found that each storm acted like a blender, shredding the marine snow into smaller pieces. Since finer particles sink much slower than larger ones, this reduced the flux of marine snow into the deep ocean. However, the team noticed a pulse of marine snow leaving the surface ocean just a couple days after each storm abated.

The researchers discovered that, by churning the upper ocean, storms increased the depth of the ocean’s mixed layer — the upper layer of the ocean where turbulence homogenizes the water. When calm conditions returned, the mixed layer became shallower. This left a large quantity of shredded particles beneath the reestablished mixed layer. These particles could then reaggregate into marine snow below the influence of surface turbulence that would otherwise delay their descent into the deep sea. These are the first field observations the team knows of that illustrate this coupling between the ocean turbulence, particle aggregation and disaggregation, and sinking particle fluxes.

The field data on the effects of turbulence on the size of marine snow corresponded almost exactly with experimental results obtained by Alldredge and the late Professor Tommy Dickey. “Usually, scientists assume that data collected in a relatively small container in the lab does not represent the conditions of the ocean very well,” Passow said. “However, in this case the experimental values aligned closely with the values we observed during the expedition.”

Bites from billions of tiny mouths

The team also looked at the fate of this marine snow as it sank beyond the ocean surface, at depths between 200 and 500 meters. They found that the number of particles smaller than 0.5 mm roughly doubled over the month-long experiment. But particles that small can’t sink quickly enough to account for this, so they must come from the marine snow breaking up. On the other hand, turbulence at these depths is too small to be driving the production of smaller particles, Siegel explained.

So what could break up the marine snow in the cool, quiet waters of the deep? The authors found that biological processes must be breaking down large particles at roughly 12% per day.

They then looked at the abundance of zooplankton — the consumer counterparts to the photosynthetic phytoplankton — and the rate at which they encountered sinking marine snow. UCSB Professor Alyson Santoro and her doctoral student, Nicola Paul, calculated that microbes consumed less than half of the consumed marine snow from observations they made during EXPORTS cruise. This means that zooplankton are responsible for most of the consumption.

Scientists knew about the interaction between zooplankton and marine snow, but it hadn't been quantified from field observations until now. Current Earth systems models don't account for this and, in fact, researchers had thought microbes played a much larger role than plankton in breaking down marine snow. With this information, the research community can begin to incorporate zooplankton into climate models.

The bigger picture

Scientists knew that marine snow experiences many changes as it drifts into the deep sea; however, this paper reveals the dynamism inherent in this process. Though small, these nuances are magnified by the scale of the ocean, leading to large discrepancies in our models. "The results help explain the difficulty we have in generating solid predictions of carbon flux," Passow said.

The second phase of the EXPORTS mission is ongoing, and aims to integrate this hard-won knowledge into models of the carbon cycle, which themselves feed into our climate models. EXPORTS investigators and biological-pump researchers from many countries will convene in Glasgow, UK for a workshop in March 2026 to discuss this exact task.

These findings were a long time coming, both scientifically and logistically. "We were incredibly fortunate that NASA assembled a team for EXPORTS who could address all the aspects of this problem," Siegel said. "I've been working on this topic for decades, and it took forever to figure out how this all fit together."

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