Researchers address ocean paradox with 55 gallons of fluorescent dye

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A special high-speed winch that the researchers used to swiftly raise and lower instruments to track the dye's movements underwater. Credit: San Nguyen. Credit: San Nguyen

For the first time, researchers from UC San Diego's Scripps Institution of Oceanography led an international team that directly measured cold, deep water upwelling via turbulent mixing along the slope of a submarine canyon in the Atlantic Ocean.

The pace of upwelling the researchers observed was more than 10,000 times the global average rate predicted by the late renowned oceanographer Walter Munk in the 1960s.

The results appear in a new study led by Scripps postdoctoral fellow Bethan Wynne-Cattanach and published in the journal *Nature*.

The findings begin to unravel a vexing mystery in oceanography and could eventually help improve humanity's ability to forecast climate change. The research was supported by grants from the Natural Environment Research Council and the National Science Foundation.

The world as we know it requires large-scale ocean circulation, often called conveyor belt circulation, in which seawater becomes cold and dense near the poles, sinks into the deep, and eventually rises back up to the surface where it warms, beginning the cycle again. These broad patterns maintain a turnover of heat, nutrients, and carbon that underpins global climate, marine ecosystems, and the ocean's ability to mitigate human-caused climate change.

Despite the conveyor belt's importance, however, a component of it known as meridional overturning circulation (MOC), has proven difficult to observe. In particular, the return of cold water from the deep ocean to the surface through upwelling has been theorized and inferred but never directly measured.

In 1966, Munk calculated a global average pace of upwelling using the rate at which cold, deep water was formed near Antarctica. He estimated the speed of upwelling at one centimeter per day. The volume of water transported by this rate of upwelling would be huge, said Matthew Alford, professor of physical oceanography at Scripps and senior author of the study, "but spread out over the entire global ocean, that flow is too slow to measure directly."

Munk proposed that this upwelling occurred via turbulent mixing caused by breaking internal waves under the ocean's surface. About 25 years ago, measurements began to reveal that undersea turbulence was higher near the seafloor, but this presented oceanographers with a paradox, Alford said.

If turbulence is strongest near the bottom where the water is coldest, then a given parcel of water would experience stronger mixing beneath it where the water is colder. This would have the effect of making bottom waters even colder and denser, pushing water down instead of lifting it toward the surface.

This theoretical prediction, since confirmed by measurements, appears to contradict the observed fact that the deep ocean has not simply filled up with the cold, dense water formed at the poles.

This barrel is filled with non-toxic fluorescent dye, which researchers released just above the sea floor to answer a longstanding question in oceanography. Credit: San Nguyen

In 2016, researchers including Raffaele Ferrari, oceanographer at the Massachusetts Institute of Technology and co-author of the current study, proposed a new theory that had the potential to resolve this paradox. The idea was that steep slopes on the seafloor in places like the walls of underwater canyons might produce the right kind of turbulence to cause upwelling.

Wynne-Cattanach, Alford, and their collaborators set out to see if they could directly observe this phenomenon by conducting an experiment at sea with the help of a barrel of a non-toxic, fluorescent green dye called fluorescein. Beginning in 2021, the researchers visited a roughly 2,000-meter-deep undersea canyon in the Rockall Trough, about 370 kilometers (230 miles) northwest of Ireland.

"We selected this canyon out of the roughly 9,500 we know of in the oceans because this spot is pretty unremarkable as deep sea canyons go," said Alford. "The idea was for it to be as typical as possible to make our results more generalizable."

Floating above the submarine canyon in a research vessel, the team lowered a 55-gallon (208-liter) drum of fluorescein to 10 meters (32.8 feet) above the seafloor and then remotely triggered the release of the dye.

Then the team tracked the dye for two and a half days until it dissipated using several instruments adapted in-house at Scripps for the demands of the experiment. The researchers were able to track the dye's movement at high resolution by slowly moving the ship up and down the canyon's slope.

The key measurements came from devices called fluorometers that are capable of detecting the presence of tiny amounts of the fluorescent dye—down to less than 1 part per billion—but other instruments also measured changes in water temperature and turbulence.

Tracking the dye's movements revealed turbulence-driven upwelling along the slope of the canyon, confirming Ferrari's proposed resolution of the paradox with direct observations for the first time. Not only did the team measure upwelling along the canyon's slope, that upwelling was much faster than Munk's 1966 calculations predicted.

Where Munk inferred a global average of one centimeter per day, measurements at Rockall Trough found upwelling proceeding at 100 meters per day. Additionally, the team observed some dye migrating away from the canyon's slope and toward its interior, suggesting the physics of the turbulent upwelling were more complex than Ferrari originally theorized.

"We've observed upwelling that's never been directly measured before," said Wynne-Cattanach. "The rate of that upwelling is also really fast, which, along with measurements of downwelling elsewhere in the oceans, suggests there are hotspots of upwelling."

Bethan Wynne-Cattanach and Matthew Alford observe operations aboard the research vessel during the experiment. Credit: San Nguyen

Alford called the study's findings "a call to arms for the physical oceanography community to understand ocean turbulence a lot better."

Wynne-Cattanach said that it was a huge honor for her, as a graduate student, to lead a project that represents the culmination of decades of work from scientists across the field with such prominent researchers as collaborators. Based on the team's preliminary findings, Wynne-Cattanach became the first student to be invited to speak at the prestigious Gordon Research Conference on Ocean Mixing in 2022.

The next step will be to test whether there is similar upwelling in other submarine canyons around the world. Given the canyon's unremarkable features, Alford said it seems reasonable to expect the phenomenon to be relatively common.

If the results hold true elsewhere, Alford said global climate simulations will need to begin explicitly accounting for this type of turbulence-driven upwelling at ocean floor topographical features. "This work is the first step to adding in missing ocean physics to our climate models that will ultimately improve the ability of those models to predict climate change," he said.

The route to improving the scientific understanding of ocean turbulence is two-fold, according to Alford.

First, "we need to be doing more high-tech, high-resolution experiments like this one in key parts of the ocean to better understand the physical processes." Second, he said, "we need to be measuring turbulence in as many different places as possible with autonomous instruments like the Argo floats."

The researchers are already in the process of conducting a similar dye-release experiment just off the coast of the Scripps campus in the La Jolla submarine canyon.

More information: Bethan Wynne-Cattanach, Observations of

diapycnal upwelling within a sloping submarine canyon, *Nature* (2024).
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