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Press Release

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A Large Amount of Nutrient is Upwelled near 10-km diameter cold eddies formed by the Kuroshio Flowing Closely to Yakushima Island in the Tokara Strait

Cyclonic eddies generated by the Kuroshio at the south of Yakushima propagate downstream along the current and may support near 10% of the primary production in regions as far as 400 km downstream.

Keyword

- ✓ For the first time, high-resolution continuous observations using a free-fall tow-yo profiler[1)] successfully captured a tongue-shaped upwelling of nutrient-rich waters near 10-km size cyclonic eddies generated off the south coast of Yakushima Island.
- ✓ The nutrients introduced by these eddies into the oligotrophic surface layer of the Kuroshio were not immediately consumed by phytoplankton due to grazing by zooplankton. As a result, a large fraction of the nutrients remained available, suggesting that they could contribute to sustain biological productivity over a broad area toward downstream Kuroshio region.

A research conducted by Gloria Silvana Duran Gomez, third-year doctoral student in the Course of Applied Marine Environmental Studies at the Graduate School of Tokyo University of Marine Science and Technology (President: Toshio Iseki), with Associate Professor Takeyoshi Nagai of the same university, has revealed that as the Kuroshio Current flows near Yakushima Island—located in the Tokara Strait, south of Kyushu—it generates cyclonic eddies approximately 10 km in diameter. These eddies induce upwelling of great amounts of nutrients from deeper layers.

The Kuroshio, a western boundary current of the North Pacific, flows northward along the southern coast of Japan, transporting a large volume of heat and tracers toward higher latitudes. Although its surface waters are poor in nutrients, which are essential for phytoplankton growth, the upstream region serves as a major spawning ground for pelagic fish and a vital habitat and corridor for a variety of migratory species. Recent studies have reported that, in contrast to its nutrient-depleted surface layer, the subsurface layer of the Kuroshio functions as a "nutrient stream," transporting substantial quantities of nutrients downstream. Furthermore, because the Kuroshio frequently flows over complex topography and passes near islands, intense turbulent mixing and the formation of eddies are expected to enhance the upward transport of nutrients from deeper layers to sunlit surface layer, where phytoplankton can use light for photosynthesis. However, observational evidence specifically demonstrating nutrient upwelling associated with eddy activity has been lacking, and the detailed mechanisms and ecological impacts of such processes have remained poorly understood.

The research group has conducted high-resolution observations over multiple years in the Kuroshio Current flowing over seamounts in the Tokara Strait, using free-fall to-yow profilers. They successfully captured for the first-time observational evidence showing that the Kuroshio frequently generates cyclonic eddies of roughly 10 km in diameter south of Yakushima Island in the Tokara Strait, around which nutrients are brought upward with a tongue-shaped filament. Furthermore, detailed investigation using numerical simulations revealed the underlying

mechanisms and ecological impacts, suggesting that the supplied nutrients, after triggering complex low trophic-level ecosystem responses[1)], potentially support biological productivity over a wide area in the downstream Kuroshio region.

These research findings have been published online on July 2, 2025 (UK time) in the scientific journal *Scientific Reports*.

<Research background>

The Kuroshio Current transports warm, high-salinity, and nutrient-poor surface waters northward. Despite the lack of nutrients essential for phytoplankton growth in its surface layer, the upstream region of the Kuroshio supports abundant spawning of pelagic fish and serves as critical nursery grounds and migratory routes for various migratory species. How these fish utilize the nutrient-poor Kuroshio, and by what mechanisms their prey—phytoplankton and zooplankton—are sustained, have long remained unresolved in oceanography. Recent studies have reported that, in contrast to the nutrient-poor surface, the subsurface layer of the Kuroshio acts as a "nutrient stream," transporting significant quantities of nutrients downstream. Furthermore, the Kuroshio frequently flows over complex seafloor topography, and recent in-situ observations by the authors have begun to clarify that when the Kuroshio passes over seamounts in the Tokara Strait, intense turbulent mixing occurs, accompanied by nutrient supply from deeper layers. However, it is not only turbulent mixing that plays a role; it is also known that when the Kuroshio flows near islands, eddies form in their wakes. The extent to which these eddies bring nutrients upward from deeper layers and induce nutrient upwelling, as well as how phytoplankton and zooplankton respond to such processes, remains poorly understood. Moreover, although recent numerical simulations have suggested that nutrients upwell in tongue-shaped structures along the edges of such eddies, observational evidence capturing this phenomenon has been lacking until now.

<Research content>

The research group has conducted high-resolution observations over multiple years focusing on turbulence generated by the Kuroshio above seamounts in the Tokara Strait, as well as looking for cyclonic eddies structures behind islands, nutrient concentration, and chlorophyll-a concentrations as an indicator of phytoplankton biomass, using free-fall tow-yo profilers. The observational results revealed for the first time that as the Kuroshio approaches Yakushima Island in the Tokara Strait, it frequently generates cyclonic eddies roughtly 10 km in diameter, around which nutrients upwell in a tongue-shaped structure. Further investigation using a coupled physical-ecosystem numerical simulation, which incorporates phytoplankton, zooplankton, and nutrient dynamics, clarified the underlying mechanisms and ecological impacts. The simulations showed that on the eastern side of the eddies generated south of Yakushima, divergent flows[2)] occur, causing a substantial net upwelling of nutrients (nitrate) on the order of tens of millimoles per meter square per day (10 mmol m^{-2} day^{-1}). Moreover, the simulations indicated that while the nutrients supplied to the surface layer are consumed by small phytoplankton, these phytoplankton are rapidly grazed upon by small zooplankton. This means that although nutrient upwelling supports an increase in small phytoplankton biomass for about one to two days, the phytoplankton population does not show a marked increase due to grazing pressure. Consequently, much of the supplied nutrients remain unused and are transported downstream by the Kuroshio. An additional hypothetical simulation excluding zooplankton grazing demonstrated that in the absence of zooplankton, phytoplankton biomass could increase to about three

times the level observed when grazing is considered. These findings provide a highly intriguing insight into nutrient supply in the oligotrophic surface waters of the Kuroshio region, suggesting that nutrient input triggers complex lower trophic-level ecosystem responses. Importantly, a significant portion of the supplied nutrients remains unused and is transported downstream, potentially sustaining biological productivity over a wide area of the downstream Kuroshio region.

<Future directions>

This study successfully captured, for the first time through direct observation, a tongue-shaped upwelling of nutrients along the edges of cyclonic eddies—previously indicated only through numerical simulations. Furthermore, ecosystem model simulations suggested that rapid grazing by zooplankton suppresses the growth of phytoplankton and limits the consumption of nutrients supplied by eddies to surface layers, thereby allowing these nutrients to be transported further downstream and potentially supporting biological productivity over a broader region. However, direct in-situ observational evidence supporting these complex lower-trophic-level ecosystem responses remains lacking. Additionally, the extent and locations at which vertical fluxes of organic carbon—critical for the sequestration of atmospheric CO_2 into the deep ocean—as a result of eddy-induced nutrient supply are still not well understood. Future studies should aim to elucidate the magnitude and distribution of organic carbon export along the Kuroshio nutrient stream[3] by conducting continuous imaging of zooplankton (as primary grazers) and marine snow (as particulate organic carbon) using camera systems.

The cyclonic eddies observed in this study south of Yakushima were generated during the autumn and winter seasons. Further investigation is needed into their seasonal variability, as well as how their formation and characteristics may change in response to long-term variations in the Kuroshio axis[4] and volume transport in the Tokara Strait under climate change.

Additionally, eddies formed near islands by the Kuroshio are not limited to the surface layer; subsurface eddies—with no visible surface signature—have also been identified. Advancing our understanding of the formation mechanisms and roles of these subsurface eddies in material transport and nutrient supply will be a key focus of future research.

<Figures>

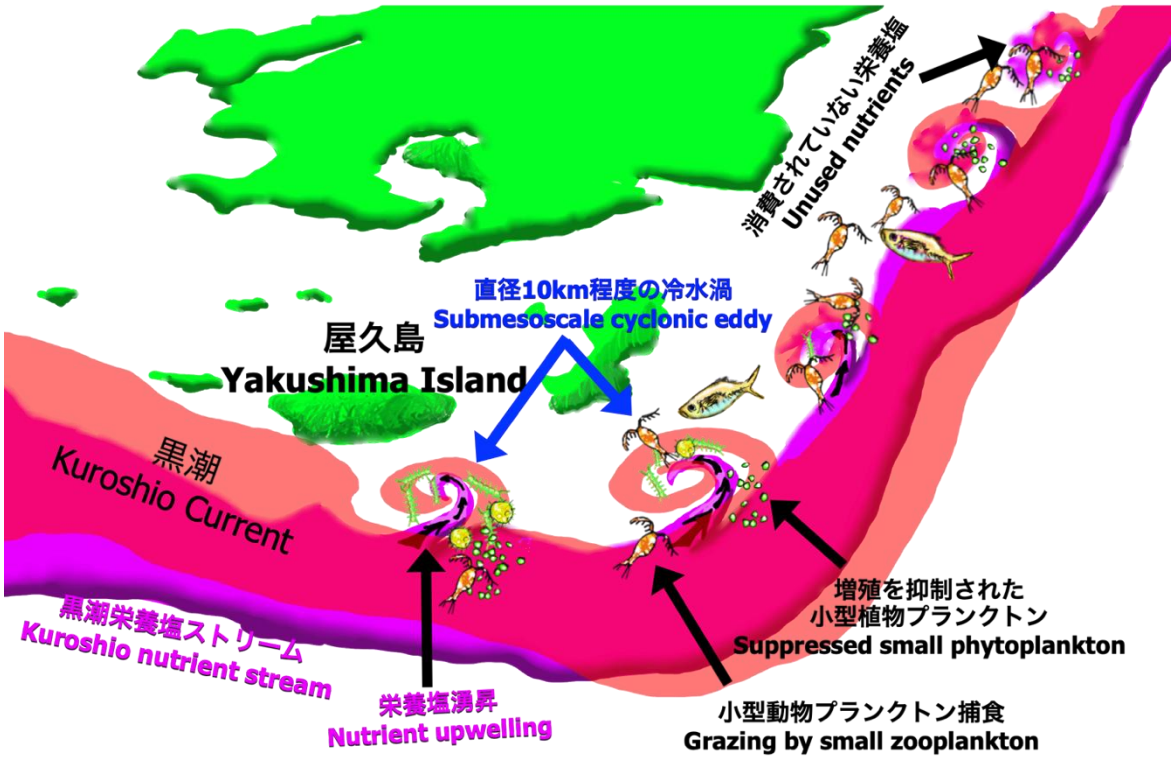

Fig. 1: Schematics of the present study.
Nutrient upwelling occurs on the eastern side of a cyclonic eddy of 10 km approx. in diameter, generated by the Kuroshio at the south of Yakushima. Initially, small phytoplankton increase, but they are quickly grazed by microzooplankton, resulting in a significant portion of the nutrients remained unused and being transported downstream.

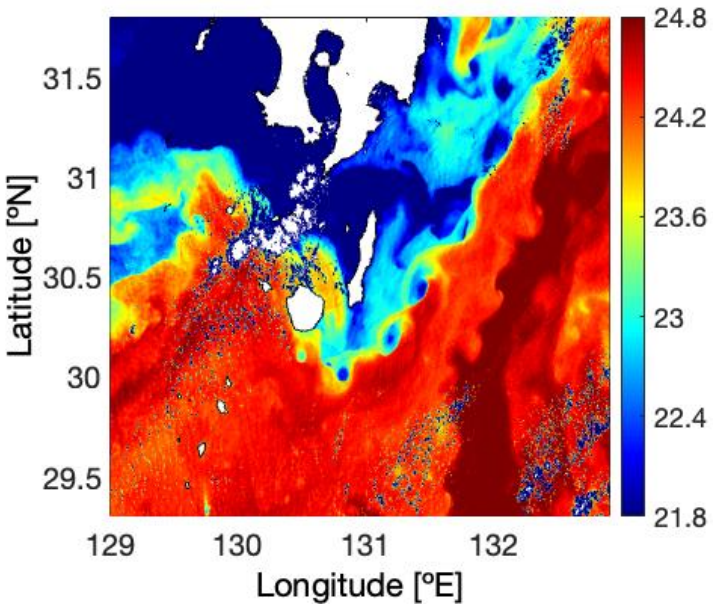

Fig. 2: A series of cyclonic eddies extending along the Kuroshio Current from the south of Yakushima is visible in the sea surface temperature image captured by the satellite “Shikisai” in December 2024. Numerical experiments conducted in this study revealed that approximately six cold eddies form each month in the waters south of Yakushima during the autumn to winter season, consistent with the

satellite image.

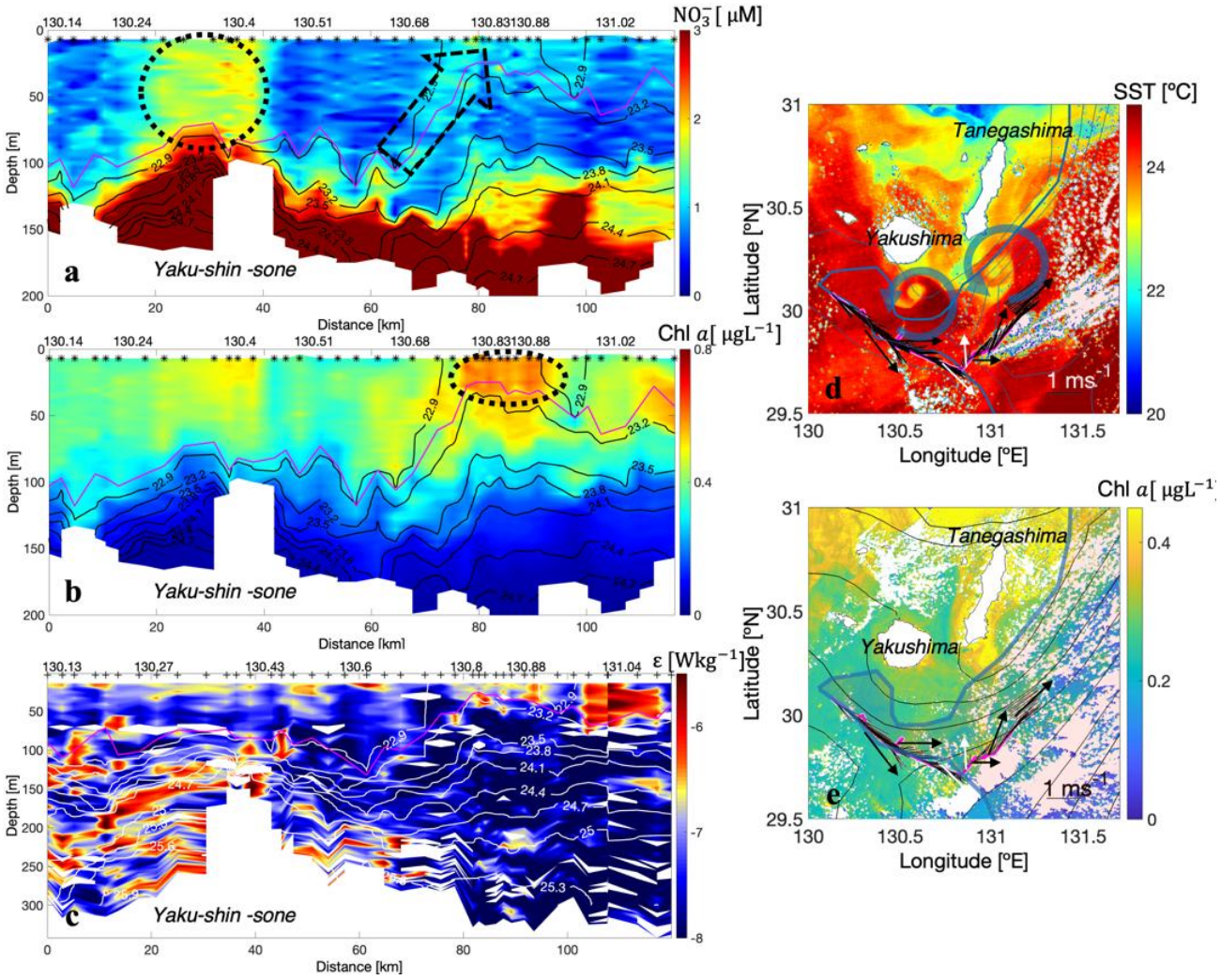

Fig. 3: The results of continuous profiling observations conducted on November 17, 2021, onboard the training vessel *Kagoshima-maru* of the Faculty of Fisheries, Kagoshima University, are presented for (a) nitrate concentration, (b) chlorophyll-a concentration, and (c) turbulent kinetic energy dissipation rate. The cross-section was obtained along the magenta line shown in panels (d–e). The sea surface temperature (SST) image shown corresponds to November 14, three days prior to the observation, in which two cyclonic eddies are evident south of Yakushima. In the vicinity of these eddies, the nitrate concentration displays a dome-like shape associated with density structures linked to an eddy (dashed circle in panel a), and tongue-like structures extending upward along sloping isopycnals (dashed arrows in panel a), suggesting the occurrence of nutrient upwelling.

<Glossary>

Note 1) Free-fall tow-yo profiler

The repeated vertical profiling of oceanographic instrument is called yo-yo profiling, which is named after the toy, yo-yo. On the other hand, lateral profiling by keeping instrument at depths with a rope attached to a winch at stern, while a ship is moving forward, is called towing. Free-fall tow-yoing is the repeated profiling amethod that combines yo-yoing and towing, letting the tethered instrument quasi-freely down to the target depth and recover it to the surface by rewinding

the winch, while a ship is moving.

Note 1) Low trophic-level ecosystem responses
The response of phytoplankton and zooplankton to the supply of nutrients essential for the growth of phytoplankton, which are primary producers in the ocean.

Note 2) Divergent flow
A flow that flows outward near the surface, causing seawater from the lower layers to rise.

Note 3) Kuroshio nutrient stream
The Kuroshio Current transports abundant nutrients in the sub-surface layer due to its strong northward flow, and this refers to as the Kuroshio nutrient stream.

Note 4) Kuroshio Axis
The fastest-flowing part of the Kuroshio Current is called the Kuroshio axis, and it often changes over time.

<References>

Nagai, T., Hasegawa, D., Tsutsumi, E. et al. The Kuroshio flowing over seamounts and associated submesoscale flows drive 100-km-wide 100-1000-fold enhancement of turbulence. ***Commun Earth Environ*** 2, 170 (2021). https://doi.org/10.1038/s43247-021-00230-7

<Title of the scientific paper>

"Submesoscale eddy induced nitrate upwelling and effect on biological production in the upstream Kuroshio Current", https://doi.org/10.1038/s41598-025-05269-6

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Institutional Information

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Established in 2003 through the merger of Tokyo University of Mercantile Marine and Tokyo University of Fisheries, this is the only university in Japan that specializes exclusively in marine sciences. Taking advantage of its unique focus on the ocean, the university strives to advance and enhance global academic research in the marine field under the motto: "Explore the Sea, Protect the Sea, and Utilize the Sea".
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