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Title: Tiny comets under the sea, An ocean of marine snow and comets, A sea of comets, or similar
Tagline: Mucus “tails” slow down sinking marine particles, possibly with big biogeochemical implications
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Marine particles form in the sunlit upper ocean from organic material produced by plankton ecosystems, then sink to the deep ocean. The carbon transferred into the deep ocean by sinking particles sustains a vast deep-sea carbon reservoir and supplies energy to deep-sea ecosystems(1). Many physical, chemical, and biological processes are involved in particles’ formation, sinking, and consumption. Due to these processes’ collective complexity, the overall impact of sinking particles on the ocean’s carbon cycle remains highly uncertain and poorly understood(2). Deciphering the controls on carbon transfer by marine particles has been a central question in oceanography since the 80’s, and has regained considerable attention in recent years partly due to technological advances. On page XXX of this issue, Chajwa *et al.*(3) report the presence of mucus “comet-tails” surrounding sinking marine particles that double their residence time in the upper ocean. These results provide new insights into how the composition of marine particles influences ocean ecology and biogeochemistry .

Decades of research into marine particles’ physical and ecological properties has helped disentangle their intricate nature. Physically, particles often exhibit complex “fractal”–like shapes(4), substantially influencing their sinking speed, formation(5) and fragmentation(6), and the flow dynamics within them. Ecologically, particles are known to emit long chemical plumes that aid motile organisms in locating them(7), as well as being islands of bacterial activity and interactions(8). Chawja *et al.*(3), building on advances in tracking microscopy(9) and laboratory-based investigation of particle-flow interactions(10), employ a novel method to resolve the hydrodynamics of naturally occurring particles. By trapping sinking particles at sea, then letting them “sink” continuously in a controlled wheel of fluid, they tracked fluid flow around particles. This allowed for the detailed resolution of flow fields within and surrounding particles. This revealed invisible “comet-tails” coating particles and trailing behind them. Chawja *et al.*(3) developed a fluid mechanical theory to derive the drag applied by these comet-tails, and estimated that it nearly doubled the residence time in the upper ocean of sinking particles at their study site. It is known that marine particles often incorporate transparent exopolymers(11), but Chawja *et al.*(3) for the first time resolve their detailed fluid flow impacts and model their influence on particle sinking. These findings could have substantial implications for both the physical and ecological understanding of marine particles.

If particles’ comet-tails reduce their sinking speed, then they also reduce how deep these sinking particles can transfer carbon, thereby serving to increase Earth’s atmospheric CO₂ concentration(12). If such comet-tails are ubiquitous, as suggested by the authors’ preliminary findings from other research cruises, then the drag these comet-tails apply to particles could substantially reduce both the amount of carbon exported out of the upper ocean by sinking particles and how long that exported material is sequestered from the atmosphere. Chawja *et al.*(3)’s results (see their Fig. 4F) suggest that atmospheric CO₂ is on the order of ~40 parts per million than it would be if marine particles did not have comet-tails, or equivalently that sinking particles sequester a couple hundred gigatons less carbon from the atmosphere (see Figure). While such estimates are very approximate at this stage, their magnitude highlights the need to study this phenomenon further. This also raises several further questions. Are particles’ comet-tails only found at shallow depths, or do they persist to deep ocean depths? Is the size or prevalence of these comet-tails affected by particle formation factors that vary between environments, such as the structure of plankton communities, and therefore the amount of carbon sequestration by sinking marine particles in Earth’s past or future?

Comet-tails could also influence other important aspects of marine particle dynamics and related ocean biogeochemical processes. Physically, mucus-bound particles should be more likely to aggregate and less likely to fragment because of the strong binding nature. The existence of an “invisible” volume filled by comet-tails should make particles far less porous to fluid flow than their sparse shapes suggest. Estimating

this “invisible” volume could also help constrain the variable relationship between particles’ size and sinking speed. However, the biogeochemical consequences of these comet-tails may ultimately be more important. Comet-tails that impede flow of material through particles may facilitate the microenvironments that are hotspots for key anaerobic reactions such as denitrification(13). They may also influence how particulate material is consumed, both by making particles easier to detect for motile foragers and by influencing how material is consumed by bacteria within heterogeneous particles(14). If these mucus tails are also themselves a source of carbon and energy, they may help explain the missing gap in food demand versus supply in the deep ocean(15).

The study by Chajwa *et al.*(3) is focused on the detailed scale of individual particles. The authors’ work opens a wide array of questions that must be addressed to enhance our mechanistic understanding of marine particle sinking, as well as to assess whether particles’ comet-tails have substantial global biogeochemical consequences. First, similar studies are needed across various environments to determine how general these comet-tails might be, and to validate the broader applicability of the authors’ results. A key limitation of the current study is its focus on a single location during a bloom, where particle populations are more likely to be homogenous in both their physical and biological properties. To scale up to the global ocean quantitatively and accurately, it is essential to perform similar measurements across different locations, depths, and times. Fortunately, this should be achievable with the method presented by Chajwa *et al.*(3). Doing so could provide a collection of observations with the statistical power necessary to translate detailed process-based insights into broader biogeochemical estimates. Additionally, it would be beneficial to pair these measurements with *in-situ* analyses of sinking particles, such as fractal dimension assessments, to account for any potential handling effects on samples. Comparison of particle properties as measured in the current study against other *in-situ* measurements, such as the structure of the plankton community out of which these particles are formed, or the magnitude of fluid turbulence to which particles are exposed, may also yield important insights.

Altogether, this novel approach to marine particles’ fluid mechanics may yield globally important insights into how the ocean carbon cycle operates. The method presented in Chajwa *et al.*(3) paves a path towards long-elusive process understanding for marine particle dynamics. Realizing this potential next requires a global database of such measurements, so that oceanographers can determine how to scale up these insights into biogeochemical models.

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Figure

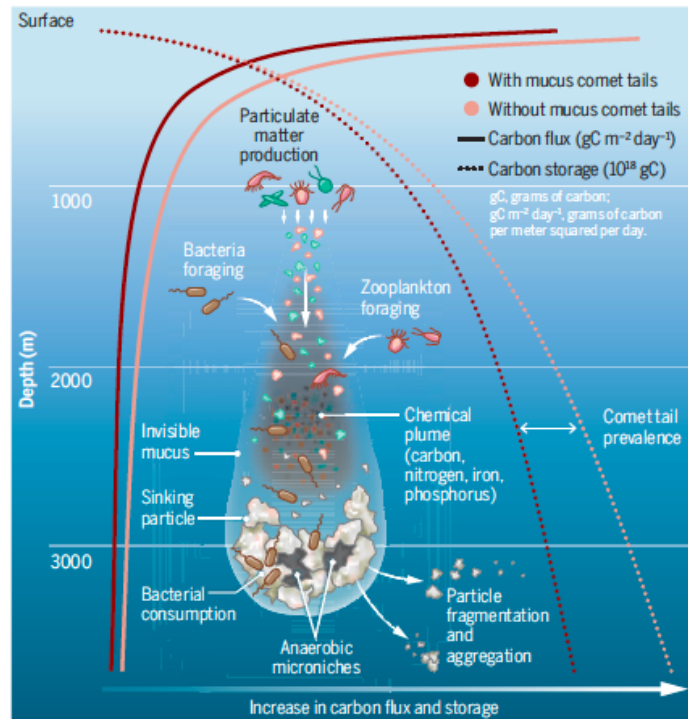


Figure caption

Impact of "mucus "comet-tails" on ocean carbon transfer and storage. Vertical profiles of the flux of carbon by sinking particles (solid lines) and the carbon reservoir sustained by this flux (dotted lines) are shown. Blue lines correspond to an ocean where particles have comet-tails as observed by Chajwa et al.(3); orange lines correspond to an ocean where particles do not have comet-tails, therefore sink faster and transfer more carbon to deeper depths, yielding increased ocean carbon storage. The inset illustration represents a particle with a mucus "comet-tails" and its potential impact on various physical and biogeochemical processes.