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EDITORIAL

Autonomous instrumentation and big data: New windows, knowledge, and breakthroughs in the aquatic sciences

In recent years, the integration of autonomous sensors and big data analytics has revolutionized our understanding of aquatic systems in both oceanography and limnology by advancing, for example, our three-dimensional comprehension of historically data-poor regions using Argo floats and gliders (Claustre et al. 2020; Vance et al. 2024). These cutting-edge technologies provide unprecedented insights into the complex interplay of physical, chemical, and biological processes in aquatic systems (Chai et al. 2025). Autonomous systems equipped with the appropriate sensors are capable of continuous, in-situ monitoring and can capture vast datasets across various temporal and spatial scales, from small-scale changes in water chemistry to global-scale patterns. Meanwhile, big data techniques enable the processing and analysis of this immense volume of information, revealing new patterns at large spatial and temporal scales and facilitating predictive modeling of aquatic environments (Durden et al. 2017).

This special issue builds upon the foundational work presented in the previous Autonomous and Lagrangian Platforms and Sensors special issue (Dickey et al. 2008), which highlighted the potential of various autonomous platforms in aquatic research. The companion virtual issue gathers additional articles previously published in *Limnology and Oceanography* with topics related to Autonomous Instrumentations and Big Data, and is now available at https://aslopubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1939-5590.big-data. This virtual issue currently comprises 90 articles, a number that will grow as new papers related to this field are published in the journal.

In the present special issue, we present diverse studies that showcase the application, development, and use of autonomous sensors, machine learning, and big data analyses in investigations of various thematics such as plankton and carbon export, phytoplankton and marine heatwaves, primary productivity, parasitism, lake oxygen and methane dynamics, and water mass structures.

Studies on zooplankton and the related marine snow have greatly benefited from the development of autonomous instrumentations permitting the automatic identification and classification of plankton and particles. In the study by Panaïotis et al. (2025), the relationship between mesoscale features and plankton dynamics is explored using high-frequency in situ images obtained with an Underwater Vision Profiler. The authors assess how a persistent mesoscale front influenced both plankton concentrations and particle distribution throughout a bloom period and highlight the implications for biogeochemical processes. Complementing this work, Gastauer and Ohman (2025) study the transitions of zooplankton communities across frontal gradients in the California Current system. By employing an autonomous Zooglider, an underwater glider equipped with a shadowgraph camera, they identify shifts in community composition and abundance related to hydrodynamic changes and emphasize the role of environmental gradients in structuring zooplankton populations. Going further than the identification of species, Pata and Hunt (2025) introduced a centralized database of zooplankton traits, consolidating 33 disparate datasets into a harmonized framework. This newly created database will promote sharing of trait data, and could allow a deeper understanding of the ecological roles of zooplankton.

Three contributions also used autonomous instrumentation to study phytoplankton and carbon export dynamics. Girdner and Sprague (2025) used autonomous profiling instruments to examine how photoacclimation can affect estimates of biomass from chlorophyll *a* data in lakes. Patterns found in their study reveal changes in photoacclimation across different time scales (daily to interannual), demonstrating that cellular pigment density responds dynamically to environmental conditions. Using a combination of DNA meta-barcoding and automated imaging-in-flow cytometry, Catlett et al. (2025) explore diatom parasitism. They document the infection

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dynamics of the diatom *Guinardia delicatula* by two parasites and demonstrate that environmental factors such as salinity and temperature shape parasitisms, with significant implications for diatom community dynamics. Finally, Traylor et al. (2025) contrast phytoplankton production and carbon export in an iron-limited, highly regenerative regime in the North Pacific, and during the spring bloom in the North Atlantic where efficient carbon export is expected. They combined autonomous Biogeochemical Argo profiling float, underwater glider, and shipboard measurements from the EXPORTS campaigns, and demonstrate that almost all production was routed to sinking particle export in the North Pacific, whereas near-equal proportions were routed to sinking particles and dissolved organic carbon in the North Atlantic.

Two additional studies focused on heatwaves and their impact on phytoplankton dynamics. In their study, Black et al. (2025) analyzed large amounts of open-access data to quantify the effects of marine heatwaves on coastal phytoplankton biomass off the Oregon coast. They reveal that, during marine heatwave years, phytoplankton distribution is significantly altered, with biomass being compressed closer to shore, which has profound implications for nutrient dynamics and the overall productivity of the ecosystem. Fischer et al. (2025) investigate the relationship between marine heatwaves and harmful algal blooms caused by diatom species of the genus *Pseudo-nitzschia*. Using images from a FlowCytobot, they compare bloom dynamics during a marine heatwave year to a temperature-neutral year to highlight the nuanced interplay between environmental conditions and algal toxin production. They show that the timing of the heatwave relative to seasonal upwelling controls the occurrence of harmful algal blooms.

The integration of big data analytics into aquatic research were here used to derive insights from complex datasets on water mass and ecology. Iles et al. (2025) applied machine learning techniques to a variety of oceanographic datasets collected by underwater gliders to differentiate water masses of species distributions and interactions. Their research exemplifies the promise of computational techniques in analyzing large volumes of environmental data, thereby enhancing predictive modeling capabilities. The role of big data in ecological research is also illustrated by Pata and Hunt (2025) with the development of a centralized database for marine zooplankton traits constructed with aggregating 33 datasets. This harmonized database provides the base of a centralized compilation of thousands of trait records which can be extended by additional resources. The database will allow exploring new ecological patterns and ecosystemic roles played by zooplankton.

The use of autonomous instrumentation also allows studying the biogeochemistry of lakes and notably dissolved oxygen and methane dynamics. Using a novel in-situ incubation method, Hudspeth et al. (2025) assessed aerobic methane oxidation in freshwater environments and determined reaction kinetics over varying environmental conditions. Their observations suggest that methane oxidation rates are closely coupled to dissolved oxygen levels. Robbins et al. (2025) use autonomous oxygen and temperature profilers to study oxygen dynamics by comparing oxygen predictability across various reservoir types. Their analyses reveal that thermally stratified reservoirs exhibit more consistent oxygen patterns compared to polymictic counterparts and highlight that the interplay between thermal stratification and oxygen levels can dictate the biological and chemical processes in reservoirs. These results underscore the importance of understanding reservoir properties and their implications for water quality management and ecological integrity.

In conclusion, the integration of autonomous instrumentation and big data analytics continue to transform aquatic research, allowing us to unravel complex ecological, physical, and biogeochemical dynamics with unprecedented spatial and temporal resolution. The articles of this special issue, as well as in the accompanying virtual issue, illustrate the vast potential of these technologies across a range of themes—from plankton dynamics and carbon export to the impacts of marine heatwaves and biogeochemical processes in freshwater environments. They also highlight the increased potential of autonomous data when combined with shipboard data to further our understanding of complex aquatic processes.

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