BAMS Article

More Room at the Top: How Small Buoys Help Reveal the Detailed Dynamics of the Air–Sea Interface

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ABSTRACT: The sea surface and air–sea exchange processes have been identified as essential for both short- and long-term atmospheric and ocean forecasts. The two phases of the fluid layer covering our planet interact across a vast range of scales that we need to explore to achieve a better understanding of the exchange processes. While satellites provide a distributed large-scale view of the sea surface situation, highly detailed measurements, e.g., from oceanographic towers, are necessarily local. An intermediate solution can be provided by swarms of miniature surface buoys that measure waves and other key parameters. As size, weight, and cost are reduced, these can be deployed in large numbers to investigate specific processes that are at present only crudely parameterized in our models, also because of the scarcity of good measurements. Perhaps the most crucial process is white capping in stormy conditions, where air–sea exchanges are enhanced by one or two orders of magnitude. Other applications include wave–current interactions, wave–ice interactions, and plunging breakers in the coastal zone. Stimulated by a dedicated workshop, we summarize here the main findings and possibilities derived from the different approaches and, in particular, the state of the art for a selection of miniature buoys. We list the presented solutions, as well as other, similar and larger, buoys, with their main characteristics and range of application. We describe the various possibilities of practical use and the scientific and engineering problems to be solved. Looking to the future, we also point out where the present technological improvements are leading to.

SIGNIFICANCE STATEMENT: The interactions between ocean and atmosphere, with the continuous and intense exchanges of energy, humidity, air, and spray, are fundamental in controlling Earth's climate. Their correct quantification is one of the key pieces of information for any long-term forecast. Satellites provide large-scale views of the situation, but we need detailed local measurements at the sea surface to have the full physical picture. Some isolated oceanographic towers do provide detailed pictures of their local conditions, but distributed high-density information is also needed. In this respect, the present best solution is provided by small, even miniaturized, instrumented, telemetering buoys, cheap and potentially expendable, to be distributed in large numbers (tens of them or more) where a specific forecast (e.g., hurricanes) or a scientific purpose (e.g., wave breaking in a stormy sea) suggest to act. While the present smallest order of magnitude of the size of these buoys is around 10 × 10 × 10 cm^3, the continuous technological improvement suggests that in near future volumes could be one or two orders of magnitude smaller, opening up possibilities to attack new problems.

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1. The need for more measurements at the sea surface

Air–sea exchange processes are widely recognized as essential for both short- and long-term atmospheric and ocean forecasts (see ECMWF 2020). This holds for processes ranging from the local generation of wind waves to the development of a low pressure atmospheric system or of a tropical storm, and all the way to planetary-scale processes such as the Gulf Stream or El Niño. Whichever the scale, all these processes depend on the exchange of thermal and mechanical energy, momentum, and mass between the two fluid layers that envelop our planet. The exchanges are driven by gradients and mediated by surface gravity waves.

Such recognition has not always been the case. In the 1970s, Erik Mollo-Christensen (MIT; see the appendix for a list of acronyms) quipped that "for the oceanographers the atmosphere is a place where wind blows—for the meteorologists the ocean is a wet surface" (Cavaleri et al. 2012). In the realm of air–sea interactions, a turning point came around 1990 when the European Centre for Medium-Range Weather Forecasts (ECMWF) showed that coupling the wave and atmospheric models led to improved weather forecasts (Janssen 1991). Of course, we have come a long way since then. Presently, satellites monitor the ocean surface daily, providing extensive data for the initialization of coupled atmospheric and ocean medium-range and seasonal forecasts. However, the problem is still to find a sufficiently detailed description of the physics at the interface. One of the relevant questions is how wind and the waves it generates interact, strongly affecting many of the exchanges that control the evolution of both the atmosphere and the ocean.

Possibly the strongest limit to the accuracy of the long- and short-term forecasts is given by the accuracy with which we are able to define the sea surface exchanges (Magnusson et al. 2019). Many parameterizations exist, mostly based historically on wind speed (e.g., Ma et al. 2017; Lee et al. 2022; Troitskaya et al. 2023) and more recently also dependent on sea state [Breivik et al. (2015), see also Edson et al. (2013), and the Coupled Ocean–Atmosphere Response Experiment (COARE 3.6) algorithm at https://github.com/NOAA-PSL/COARE-algorithm, as well as Pineau-Guillou et al. (2018)]. These are, however, still parameterizations that suffer from a lack of detailed observations. We do have well-equipped platforms to measure air, water, and surface characteristics, e.g., the Acqua Alta tower in the Gulf of Venice (Cavaleri et al. 2021), Ekofisk in the central North Sea (Malila et al. 2022b), the Air–Sea Interaction Tower (ASIT; see https://mvco.whoi.edu/infrastructure/) south of Martha's Vineyard, Massachusetts, United States, and the Ocean Station Papa in the northeastern Pacific (Schwendeman and Thomson 2017). However, these are too few and limited in their ability to yield accurate measurements of the wave field under a sufficiently varied range of conditions.

The crucial point is that it is not yet clear at which resolution we need to resolve the interaction of wind and waves in the open ocean. Wave breaking entrains air bubbles at scales of millimeters and smaller. Laboratory experiments have clearly shown (Troitskaya et al. 2017) how we need to go down to the micrometer scale to describe the spray production in wind–wave generation. These are not problems we can fully solve tomorrow, but they show the direction we need to go if we want to improve our physical description and parameterizations of the processes at the interface.

A large part of the present data at the interface is acquired by buoys, from the largest specimens such as the Floating Instrument Platform (FLIP, now decommissioned; see Lenain and Melville 2017) or the W1M3A multidisciplinary observatory (Cavaleri 1984, www.w1m3a.cnr.it/OI1/modules/site_pages/about.php), to the smaller ones such as the Waverider [see Joosten (2013) for a historical account of the Waverider buoy] that at the time revolutionized wave data collection. Other examples from the literature include Air–Sea Interaction Spar (ASIS; Graber et al. 2000), Extreme Air–Sea Interaction (EASI; Drennan et al. 2014), and Ocean Coupled to Atmosphere, Research at the Interface with a Novel Autonomous platform (OCARINA; Bourras et al. 2014).

Focusing on measuring buoys, the technological evolution has led from the once classical size, on the order of 1 m and a few hundred kilograms, to the smaller and lighter Spotter buoy (Raghukumar et al. 2019, https://www.sofarocean.com) and the Air-Deployed Wave Surface Drifter (Centurioni et al. 2017). These are presently deployed in large numbers in the world's oceans, providing measurements for data assimilation and forecast validation (Houghton et al. 2021, 2022). It is interesting to note that 10 000 of these buoys would, for an overall cost of 50 million USD, provide much of the information available from a typical satellite which costs 10 times as much. Such buoys could not replace satellites, but the cost of such a complementary deployment is now well within the reach of a large-scale scientific program.

However, these smaller buoys have only been an intermediate step. Technology moves ahead, and it is now possible to make most of, if not all, these measurements with even smaller, lighter, and hence cheaper buoys. Following a dedicated meeting on Wave Buoys and Open Source Platforms (WOOP24) in Finse, Norway, in February 2024, the purpose of this paper is to describe some of the presently available solutions and to point out the scientific opportunities that come with these miniature buoys.

Small buoys are largely made possible by the collapse in price (thanks to mass-market consumer-grade products using similar chips) and ease of use (thanks to open source and "makers" communities) of Global Navigation Satellite System (GNSS) units, inertial measurement units (IMUs), microcontroller units (MCUs), and electronics components in general. The same trend is found in, e.g., thermistors, conductivity (salinity), hygrometry, and wind sensors. This allows us to build affordable buoys collecting a full range of data and parameters.

Physical oceanography has benefited enormously from new technology over the past century. As Walter Munk said in the documentary "One Man's Noise: Stories of An Adventuresome Oceanographer" (1994, https://www.youtube.com/watch?v=je3QvqNdHl0), "most of the progress that's been done in oceanography was the result of applying some new technology, not because somebody had some great new ideas." He went on saying "A new technology almost always leads to new understanding." We believe that by making our buoys smaller, lighter, cheaper, and open source, progress will be made by more people having access to more observations at ever smaller scales. However, as the same Walter Munk repetitively pointed out, we must always be aware of the limitations of the instruments we use. Consequently, after pointing out in the next two sections what the market can presently offer and the related instrumental advantages, in the final section 4, while looking at the future possibilities, we also discuss the limitations associated to their miniaturization.

2. The present technological solutions

As an introduction to such devices, we list and briefly describe here the main characteristics of the buoys presented at WOOP24. The purpose is to provide the background for the

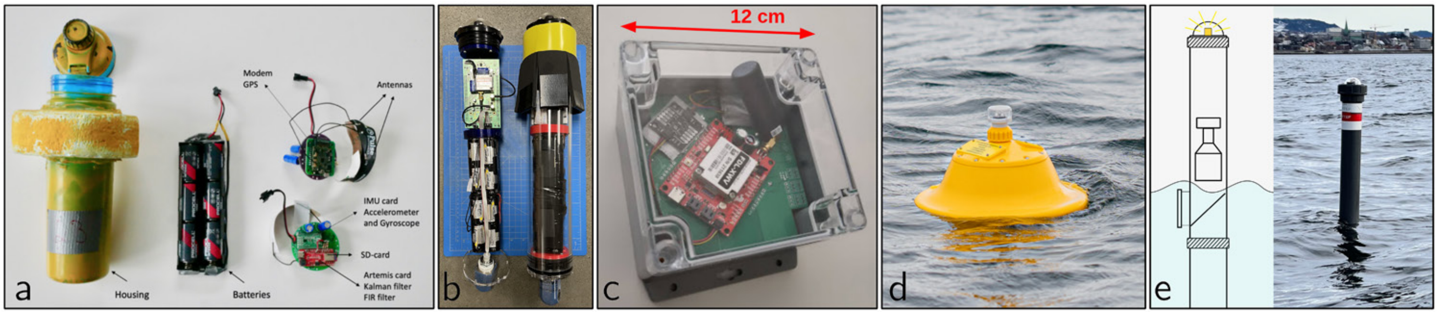

Fig. 1. **The five buoys whose performance and characteristics have been discussed at the Finse meeting. Their main characteristics are detailed in Table 1 from left to right: (a) SFY, (b) microSWIFT, (c) OMB, (d) LainePoiss, and (e) Spartacus.**

related experiments and data described in the following section. A compact description of these buoys, compared to the existing larger solutions, may help the reader to better grasp the present and forthcoming possibilities of the whole range of buoys presently in use to explore the oceans.

Figure 1 shows the five buoys whose details are given in Table 1. Note that this selection of five buoys is by no means comprehensive. There are many other miniature buoys in common usage today; see Collins et al. (2024) for a technical evaluation of wave measurements from several additional buoys.

a. SFY. The small friendly buoy (SFY; Hope et al. 2025) is a lightweight wave buoy (~0.5 kg) aimed at coastal deployments within coverage of the cellular network. The buoy measures waves using an IMU at 208 Hz and can transmit back the time series of the sea surface acceleration at 52 Hz. The very high frequency and the low cost due to using the cellular network enable the buoy to measure the waves and wave field in a phase-resolved way. The individual phases and breaking events can be tracked across buoys, and the high frequency makes it possible to study the trajectory of a buoy also through plunging waves at beaches. In total, 48 SFYs have been built so far and tested in Europe, Africa, Asia, on Hawaii in the Pacific Ocean, and in the North Sea with connectivity from oil platforms. All code and processing

Table 1. **Main characteristics of the five described buoys, as shown in Fig. 1. Acronyms definition: pos. = position measurement; temp. = temperature measurement; TCO = total cost of ownership; FOSSH = free open-source software and hardware; FOSS = free open-source software.**

	SFY	MicroSWIFT	OMB	LainePoiss	Spartacus
Size	8 cm × 8 cm × 30 cm	9 cm × 9 cm × 50 cm	10 cm × 10 cm × 12 cm	36 cm × 36 cm × 30 cm	11 cm × 11 cm × 600 cm
Weight	0.5 kg	2.9 kg	0.5–1 kg (batt. choice)	5.5 kg	~30 kg
Parameters measured	Acceleration time series and pos	2D wave spec., SST, SSS, pos	1D wave spec, pos., temp.	2D wave spec., acceleration	Particles and bubbles, buoy motion and position
Sampling frequency	208 Hz	4 Hz	800-Hz raw, 10-Hz spectrum	50 Hz	Configurable, up to 20 Hz
Communication methods	GSM	Iridium	Iridium	GSM, Iridium	GSM
Power source	D-cell, Li. or Alk.	C-cell	D-cell, Li or Alk.	Rechargeable batteries	D-cell, Li or Alk.
Autonomy		2 months	Up to 1+ year	>8 months	Weeks or months
Cost estimate (USD)	250	1000	650 hardware, 1000 TCO	5500	5000
License	FOSSH	FOSS	FOSSH	MIT license for processing scripts	Under development

scripts, including hardware schematics, are available at https://github.com/gauteh/sfy. The water-following capability of the buoy has allowed it to measure accelerations in excess of 10 g within plunging breakers (Hope et al. 2025).

b. microSWIFT. The microSWIFT buoy is a miniaturization of the Surface Wave Instrument Float with Tracking (SWIFT) first introduced in Thomson (2012) and revised in Thomson et al. (2019). The microSWIFT is described in detail within Thomson et al. (2024). The primary features are GNSS-based directional 2D wave spectra and modular additional sensor payloads (presently water temperature and conductivity, from which salinity is calculated). Intended future payloads include light and turbidity sensors. The form factor of the microSWIFT is specifically designed for aerial deployments; the cylindrical shape fits the dropsonde tube of most research aircraft. To date, 110 microSWIFTs have been built and deployed worldwide. A repository of quality-controlled data is maintained at Dryad (https://doi.org/10.5061/dryad.jdfn2z3j1), and all codes are publicly available (https://github.com/SASlabgroup).

c. OMB. The OpenMetBuoy (OMB; see Rabault et al. 2022) is a small (typically 10 cm × 10 cm × 12 cm), lightweight (around 0.5–1 kg), low-cost, low-power (3 Li D-cells last more than 6 months), Iridium-Short Burst Data (SBD)-connected, open software and hardware (https://github.com/jerabaul29/, OpenMetBuoy-v2021a) buoy, developed from previous waves-in-ice instruments (Rabault et al. 2016, 2017, 2020). Since sea ice typically blocks the horizontal wave orbital motion, OMB uses vertical IMU acceleration to estimate the 1D wave spectrum. Particular care is taken to resolve small motion in calm conditions. Waves typically under 0.5 cm amplitude at 16 s period have been resolved (Rabault et al. 2022). The OMB is also able to accurately resolve 1D spectra of open ocean waves in all conditions.

The OMB design is fully open, and it has, for example, been modified to log sets of several temperature sensors (Müller et al. 2024). Fully assembled OMBs can also be purchased from a commercial company (https://www.labmaker.org/products/openmetbuoy—no commercial ties to the authors).

d. LainePoiss. The development of LainePoiss (Alari et al. 2022) wave buoys started in early 2018 aiming at a robust instrument to measure waves in a wide range of ice conditions. After several iterations on hardware and software design with wave tank experiments confirming its capability up to 1.28 Hz, 35 buoys have since been built and used in practical and scientific applications (Pärt et al. 2023; Rikka et al. 2024). The current version allows operations for more than 14 months with primary batteries while transferring real-time wave data over the Iridium or long-term evolution (LTE) networks every 22 min. The technical specifications are available online (www.lainepoiss.eu).

e. Spartacus. Spartacus is a comparatively small and light spar buoy, being developed to measure bubbles and other particles close to the surface, under breaking waves. Made from a standard polyvinyl chloride (PVC) pressure pipe, it has an 11 cm outside diameter and a 6-m length. Bubbles and other particles are measured by imaging with the Silhouette Camera previously developed by SINTEF (Davies et al. 2017). The camera, telecentric lens, computer, and batteries are housed inside the body of the buoy. The camera and lens look out of the buoy via a 45° mirror and a window, and directly onto a white, uniform light emitting diode (LED) backlight. The system captures bright-field images, where any particles show up as dark against a white background. Every image captures a known volume of water, allowing concentrations of particles and bubbles to be calculated.

Unlike the buoys discussed above, the purpose of Spartacus is not to directly measure waves, but to provide a relatively stable and minimally invasive platform, in limited wave conditions, from which other parameters can be measured at a known average depth under breaking waves. In the first deployment in spring 2024, we obtained sharp images of entrained bubbles in wind up to 20 m s^{-1} gusts. In addition to the described bubble and particle measurements, other sensors can be mounted at intervals along the body of the buoy to get near-surface profiles.

f. Other similar buoys in the literature. As already mentioned and also noted during WOOP24, many more buoys with generally similar designs to the ones discussed at the workshop are currently under development by a variety of groups. While it is challenging to come up with an exhaustive list, we can point to, e.g., the ultralight (total weight 52 g) Micro Electrical Mechanical System (MEMS)-based short wind–wave sensing buoy of Yurovsky and Dulov (2020) that can be deployed from a fishing rod, the ultralow-cost education-focused smart buoy from T3chFlicks (2021), the FZ series of buoys (Kodaira et al. 2022, 2024), or the ultracompact wavedrifter that has been used to measure wave plungers by Feddersen et al. (2024). These come in addition to established commercial affordable buoys, such as the already mentioned Sofar Spotter (Raghukumar et al. 2019), and new emerging buoys as Miniaturized Electronics Lagrangian Oceanographic Drifter (MELODI) (Charron and Mironov 2023). There are also the air-deployed wave surface drifters (ADWSDs) buoys (Centurioni et al. 2017, 2021), suitable for both ship and air deployment, and the miniwave buoys (Collins et al. 2024) produced by separate groups at the Scripps Institute of Oceanography. Collins et al. (2024) present a review and intercomparison of several small wave buoys now in common usage.

3. Experiments and applications

After describing the range of presently available solutions for atmosphere and ocean measuring buoys, it is now instructive to cite and discuss the different environments and situations where these buoys can be and have been used. The ocean, for its scale and relevance for climate, may remain the dominant area of interest. However, the increasing attention toward the poles implies that interaction with ice is now a "hot" topic. Here, in particular, easily deployed and expendable solutions are the winning instrument. For different, but also partially similar, reasons, it is now easier to explore transient or localized situations such as areas of strong wave–current interactions. Finally, although not an exhaustive list, wave breaking, both as white capping in stormy conditions and shoaling waves at the coast, is a crucial element for climate (atmosphere–ocean interactions) and coastal erosion. Both not uniformly distributed but highly localized in space, they appear as a perfect environment where dense and distributed swarms of measuring buoys can provide still missing information.

a. Tropical cyclones and extreme conditions. Tropical cyclones (e.g., hurricanes, typhoons) are notoriously difficult to sample, given their rapid evolution in time and localization in space. Existing networks of moored buoys are unlikely to capture the full complexity of these storms. Targeted deployments of minibuoys are a promising approach to fill this gap, as demonstrated by Schönau et al. (2024). This is the approach of the National Oceanographic Partnership Program (NOPP) Hurricane Coastal Impacts project (https://nopphurricane.sofarocean.com), which deploys Spotters, microSWIFTs, and ADWSD from aircraft into the path of land-falling hurricanes. A first important result from this project is the confirmation of the saturation of wave slopes (and the sea surface roughness that causes drag) at high winds (Davis et al. 2023), a feature first reported by Holthuijsen et al. (2012) using airplane-deployed atmospheric sondes. Ongoing work uses dense arrays of minibuoys to explore spatial patterns within the storms, including effects of wind–wave alignment on wave slopes and drag. These results require spatially distributed and synoptic measurements of waves within the storm and thus are an ideal use case for many small wave buoys. At present, these buoys do not directly measure air–sea fluxes, though a few at least measure some of the bulk parameters necessary to use algorithms such as COARE (Edson et al. 2013). Direct measurements of air–sea fluxes are better suited to larger autonomous surface vehicles, such as Saildrones (Zhao et al. 2024; Zhang et al. 2023) and Wave Gliders (Thomson et al. 2018; Grare et al. 2021), which have sufficient size and mast height for flux instrumentation. This point is further addressed in section 4.

b. Wave–ice interactions. Many previous studies have used buoys to measure wave attenuation in sea ice (Doble et al. 2006; Rogers et al. 2016; Thomson et al. 2018; Cheng et al. 2017; Kohout et al. 2020; Ardhuin et al. 2020). These studies had typically less than 10 buoys, partially due to the high cost of full-sized wave buoys. The low number of buoys has prevented these studies from resolving strong gradients at the ice edge (Hosekova et al. 2020), forcing the assumption of homogeneity in the attenuation, something probably not warranted (Herman 2024). Specifically, the classic formulation for an exponential decay of wave energy following a spatially homogeneous attenuation rate is ripe for revision. The advent of low-cost minibuoys that can be deployed in large numbers (>10) has the potential to transform our understanding of both wave growth and attenuation in the presence of sea ice and to provide more representative datasets of waves in polar environments.

The deployment of low-cost buoys (including earlier versions of the OMB) has already had an impact on wave–ice interaction studies, helping to establish criteria for ice breaking under the influence of waves (Voermans et al. 2020b) and to validate and test wave-in-ice models (Voermans et al. 2021). These developments are further underway with deployments of the OMB (Rabault et al. 2023, 2024; Müller et al. 2024) and microSWIFTs (Thomson et al. 2024), and they are already revealing physical mechanisms at play in the marginal ice zone (Rabault et al. 2024), which has recently resulted in improvements to the accuracy of operational models (Aouf et al. 2024). Similarly, model weaknesses have been revealed by in situ data (Nose et al. 2023; Dreyer et al. 2024).

c. Wave–current interactions. Wave–current interactions are characterized by strong spatial gradients, with the main action focused on the limited, generally border, zone, often changing in time. The Agulhas Current and the jet of the Columbia River into the coastal Pacific Ocean are typical examples. As such, it has been historically difficult to have a comprehensive view of the full dynamics of the areas of interest. Previous work has used small numbers of drifting buoys to observe increases in wave steepness, wave breaking, and wave dissipation in the presence of strong opposing currents (Thomson et al. 2014; Zippel and Thomson 2017; Zippel et al. 2018; Guimarães et al. 2018; Saetra et al. 2021; Iyer et al. 2022; Halsne et al. 2024). Their experiments in the Columbia River mouth have shown clearly how a denser deployment can shed light on the impact of vertical current shear on wave-breaking dissipation. Repeating these experiments with even denser arrays will undoubtedly reveal new physics, especially in regions with strong mesoscale variability (Ardhuin et al. 2017; Kudryavtsev et al. 2017). The spatial coverage provided by arrays of small buoys will advance understanding of changes that occur on spatial scales of a few wavelengths, including breaking and blocking (Chawla and Kirby 2002). The effect of strong vertical shear is another topic that large numbers of buoys may illuminate (Banihashemi and Kirby 2019; Kirby and Chen 1989). The vertical shear sets the wavelengths which respond to the currents, which in turn sets the scale of wave breaking and subsequent release of wave momentum and energy.

d. Wave breaking and surfzone dynamics. Wave breaking in both deep and shallow water has long been a key challenge to observe in situ. As shown by the stereo-video work of Schwendeman and Thomson (2017), buoys, especially if large, require the assumption of linear dispersion to infer the steepness of propagating waves, and this obscures the evolution of individual crest steepening that leads to breaking. This becomes more severe in the coastal surfzone, where spatial and temporal gradients are likely to be higher. Recently, Rainville et al. (2023) used arrays of 50 microSWIFT buoys deployed simultaneously in the surfzone to reconstruct sea surface elevations, detect breaking, and investigate material transport during breaking. Up to 10-g accelerations have been measured in the surfzone (Feddersen et al. 2024: Hope et al. 2025), where large arrays of small buoys can at least identify the spatial and temporal gradients so relevant for the local dynamics and evolution. Indeed, one of the advantages of these small buoys is the possibility of adapting, hence optimizing, their performance to the environment we want to explore.

e. Entrainment by breaking waves. Breaking waves play an important role in the exchange of mass and momentum between the ocean and the atmosphere, also contributing to mixing in the upper water column. An important example is the absorption of CO_2 by the ocean, where bubbles created by breaking waves play an important role, while simultaneously being hard to measure in the field (Deike 2022). Similarly, during marine oil spills, breaking waves and vertical mixing have a key role in determining the fate of the spilled oil (Johansen et al. 2015; Röhrs et al. 2018). The new generation of buoys described here, by virtue of being small, cheap, and easy to deploy, can provide dense observations under a range of conditions, including during oil spills. With a buoy like Spartacus, which can also be deployed by hand from a small boat, entrainment of bubbles, oil droplets, and other particles can be measured at multiple depths. When combining wave measurements with entrainment measurements, truly novel datasets can be achieved that can push our understanding and our parameterizations of air bubble and oil droplet entrainment. A recent example is the characterization of bubble plume depths measured by echograms beneath drifting SWIFT buoys, which show strong relations of bubbles to wave conditions and wave dissipation (Derakhti et al. 2024).

4. Outlook

What we describe above is only a hint at the possibilities presently on offer. But technology keeps improving, and, focusing on size, it is reasonable to expect further miniaturization of these floating buoys in the years to come. This comes with the advantages we have illustrated, but also with a number of challenges for the possibly different hydrodynamic behaviors of very small buoys.

As shown in section 3d, size matters. When working in the surfzone, the smaller the better, and wave buoys should ideally be perfectly "sticky," i.e., water following, or rather surface following. There is progress in this field, with Feddersen et al. (2024) presenting a tennis-ball-sized buoy (though without the telemetry required to communicate the data back to shore) and, as mentioned, the SFY (Hope et al. 2025) measuring acceleration in surfzone breakers in excess of 10 g. It seems clear that shape, density, and center of gravity will remain important factors as we continue to shrink our equipment, until we get to a scale where turbulence may dominate over floating capability.

One of the exciting aspects of deploying miniature wave buoys is the possibility of combining them with other instruments. Traditional oceanographic experiments have tended to involve large buoys and fixed moorings. Small, expendable buoys that are quick and easy to deploy can more easily be combined with instruments that measure remotely from space or from fixed locations, such as stereo cameras (Benetazzo et al. 2012), radar altimeters

(Ewans et al. 2014), down-looking lasers (Malila et al. 2022a), and nautical radars (Malila et al. 2022b). The recent proliferation of aerial drones opens up the possibility of easily deploying lightweight buoys from shore or from research vessels (see, e.g., Alari et al. 2022). Drones also offer an appealing vantage point for remote sensing which dovetails nicely with surface buoys. We expect drones and miniature buoys to become a scientific power couple in the years to come.

Looking further into the future, what can we expect 10 or 20 years from now? A reasonable guess is that what is now a 10–15-cm box will be more or less the size of a table tennis ball. Arrays (organized) or swarms (unorganized) of drifting buoys show great promise in mapping wave–current interaction in regions with strong current gradients. Indeed, in regions with very strong currents, a feasible way of simultaneously mapping the flow and the wave field is by deploying a large number of (potentially phase resolving) drifting buoys. These processes are still poorly understood, and the related study is still only in its infancy (Halsne et al. 2022).

The drawback of these large expendable sets is that they will soon drift away from each other. Something to work on, as already done by MacCready (2015), is a system of communication and propulsion that would "pull" the buoys toward each other or align them on a grid, counteracting the randomness of the sea pushing for further distances. Calibration of the distance would lead to different experiments and analyses of the situation at different scales and resolution.

While oceanographic parameters (waves, current, temperature, etc.) are obvious targets for miniature buoys, a key question concerns the wind. The Spotter buoys provide a practical estimate of wind speed and direction, but this is derived from the wave spectra and thus not suitable for research applications (Voermans et al. 2020a). A small companion spar buoy could provide both the wind close to the sea surface and currents in the upper layers. The usage of either is sensitive to vertical location: a wind measurement may be sheltered by waves if the anemometer is too close to the surface (Donelan 2018), and the surface current will be integrated over a depth matching the draft (or drogue depth) of the buoy. Most buoys will also have some windage above the surface that causes an overestimate of drift speed.

Returning to our original subject of the miniature buoys, for many research topics, the key parameters are the stresses and fluxes at the surface. That is the true connection and what is felt by both the atmosphere and the ocean, but their quantification is still a very delicate matter. Rather than via direct measurements, fluxes are derived either via empirical formulas, or, better, from direct high-frequency measurements of the key variables. These include the vertical and horizontal components of wind speed and quantities of interest, determining the direct covariance of turbulent wind components (Edson et al. 1998; Janssen 1999; Flügge et al. 2016; Zippel et al. 2024). This is an extremely sensitive measurement because the horizontal component is dominant with respect to the vertical one, the more so the closer we are to the sea surface. It follows that any minor error in the position of the instruments may lead to errors easily comparable with the quantity of interest.

For buoys, the environment close to the sea surface, at distance comparable with the wave height, is a very dynamical one. Gradients in space and time are very high, and there is a permanent question about the significance of what we measure. So, while pushing for miniaturization has obvious advantages, we should always be aware of the trade-offs, in this case with respect to the stability of the platform.

The ocean is a fascinating, but very difficult, environment. The most successful approach will surely be to operate with all the instruments we have at our disposal. Miniaturization leads us closer and closer to the surface, but measuring the total atmospheric stress may actually require operating larger autonomous surface vehicles and spar platforms in concert with large numbers of miniature buoys.

A good experimentalist must always be aware of the limitations of the instrument at disposal, and quite often this comes from practical experience. So, after having described with justified enthusiasm the opening possibilities, it is correct to also analyze the limitations derived from miniaturization. Probably, the main concern for the minibuoys here discussed is how well they are representative of the integral motion, the full structure of, e.g., the breaking wave they move with and within. The cited 10-g acceleration or the prolonged rapid movement toward a coast following the foaming crest of a lasting breaker, while interesting in themselves, are representative of only one aspect of the field structure. In a way, the main advantage of miniaturization is the drastic cut of the cost and the practical possibility for any devoted laboratory to build its own instrument.

One limitation that is intrinsic with the name itself is that the buoys are by definition "limited" to the sea surface (but Spartacus measures orbital motion a few meters below the surface). Apart from the turbulence associated to breakers (that, however, does contain for itself valuable information), the instruments stick to the surface; hence, with the except of Spartacus, no "submerged" information is available. Of course, there can be connected sensors below the surface, but that would make them more vulnerable.

A similar limitation exists above the surface, i.e., for the atmospheric parameters. As already mentioned, Spotter does estimate wind, but only as information derived from the 2D wave spectrum. A limit in this respect is the diameter of the buoy and the consequent impossibility to properly measure waves shorter than, say, 4 times the buoy diameter. This implies a spectral cutoff at frequencies just above 1 Hz, that is the most sensitive part to represent the surface stress, hence the wind speed. In this respect, the motion of the minibuoys can edge better toward the high-frequency tail but is also too chaotic to provide fully valuable information.

Clearly, information exists for current, obviously in the uppermost layer. Granted that this layer itself can be particularly wind driven, the question is how sensitive a minibuoy motion is, by definition partly emerging from the surface, to the above wind. Devoted studies exist, see among others, Houghton et al. (2021), mostly showing that currents dominated over wind for what the buoy motion is concerned. Clearly, we do not expect high-quality data to evaluate, e.g., the precise bias and rms error of a circulation model. However, information does exist where formerly nothing was available, certainly not for the present costs.

Indeed, a key aspect of several of the recently designed small buoys is a focus on open-source software and hardware. This helps cutting the cost per buoy and improves scientific reproducibility and reliability since anybody can inspect and improve on the design. This also provides a reference platform to easily perform measurements of additional physical parameters, reducing the barrier to entry for new research groups. This also strongly reduces the barrier to entry for private companies to produce their own low-cost buoys, benefitting from all the complex, time-consuming, and costly research and development provided freely by the scientific community. This will likely result in a drastic increase in competition and a corresponding drop in price also of commercial instrumentation in the coming years.

While the availability of more and higher-resolution data is interesting per se for fundamental oceanographic studies, it also increasingly enables new methods from the realms of statistics, machine learning, and data-driven methods to be applied to old problems. The recent "Forecasting Floats in Turbulence Challenge" organized by the Defense Advanced Research Projects Agency (DARPA; see https://www.darpa.mil/news-events/2021-12-13), based on trajectories of Sofar Spotter buoys, is a case in point. With increasing numbers of low-cost buoys being deployed, we expect more opportunities will arise in the future.

We end with a challenge from one of the greats of physics. In Richard Feynman's 1959 lecture, "There's Plenty of Room At The Bottom" (Feynman 1961), he laid out the enormous potential for future discoveries that would come with miniaturization. So, at our more mundane dimensions, seven or eight orders of magnitude above the nanoscale envisioned by Feynman, let us go forth and miniaturize our buoys! There is plenty of "room at the bottom," for us at the top of the ocean, and we can rest assured that Walter Munk was right in his intuition that new discoveries will follow new technologies, especially so if we keep our science, our software, and our hardware open source.

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Data availability statement. All data are already published in the references cited—no new data are presented.

APPENDIX

Acronyms

ADWSD	Air-deployed wave surface drifters
COARE	Coupled Ocean Atmosphere Response Experiment
DARPA	Defence Advanced Research Project Agency
FOSS	Free open-source software
FOSSH	Free open-source software and hardware
GNSS	Global Navigation Satellite System
IMU	Inertial measurement unit
LED	Light emitting diode
LTE	Long-term evolution (transmission)
MCU	Microcontroller unit
MELODI	Miniaturized Electronics Lagrangian Oceanographic Drifter
MEMS	Micro Electrical Mechanical System
MIT	Massachusetts Institute of Technology
OMB	OpenMetBuoy
SFY	Small friendly buoy
SWIFT	Surface Wave Instrument Float with Tracking
TCO	Total cost of ownership

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