Drones address an observational blind spot for biological oceanography

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Marine biological communities are dynamic across many scales in both space and time. Such multi-scale complexity complicates efforts to fully characterize these communities. Critical processes unfold on the order of 0.1–10 kilometers and 0.1–10 days, but conventional oceanographic techniques generally do not observe or model at this scale. Small aerial drones conveniently achieve scales of observation between satellite resolutions and in-situ sampling, and effectively diminish the "blind spot" between these established measurement techniques. Despite this promise, drone-based techniques face challenges inherent to optical oceanography, as well as logistical and regulatory barriers relating to both aerial and marine operations. Such obstacles have slowed adoption of drones for marine biological study, but best practices are emerging alongside new techniques that facilitate robust study designs and rigorous data collection. With such advancements, drones promise to complement conventional approaches in biological oceanography to more fully capture the spatiotemporal complexity of the marine environment.

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The biophysical processes that define ocean biological productivity resolve into emergent patterns at a variety of spatial scales, and the integrated observation and monitoring of these processes and patterns pose fundamental and critical objectives to the field of biological oceanography. The entire biomass of oceanic phytoplankton is consumed and regenerated every 2 to 6 days, with growth regulated by dynamic physical (including meteorological and solar) conditions (Behrenfeld *et al*. 2006); this yields patterns that are spatially and temporally variable, and often elusive (Figure 1). Diminutive in size but not impact, phytoplankton account for nearly one-half of the Earth's total net primary production and play a major role in the interconnected Earth system (Field *et al*. 1998).

In a nutshell:

- Predominant methods of observing marine biological communities leave a "blind spot" where critical submesoscale and fine-scale processes cannot be adequately characterized by satellite or in-situ observations
- Small aerial drones can observe fine spatial resolutions and can be deployed at frequencies that fill this observational gap
- Technical, logistical, and regulatory challenges have slowed the adoption of drones in biological oceanography, but these are declining as new systems and best practices emerge
- Drones are now demonstrating valuable contributions to biological oceanography in select applications, with many possibilities on the horizon, promising to become a mainstay of marine biological research

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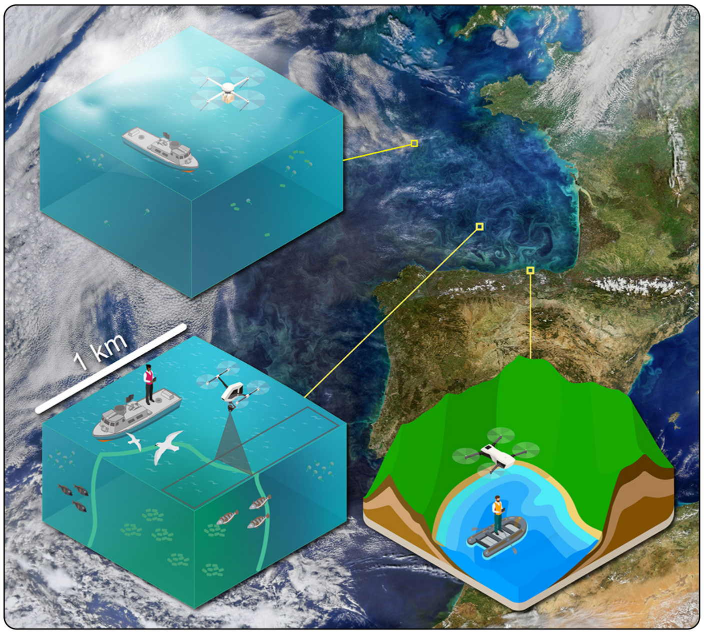
There is intense interest in and concern about how phytoplankton communities – given their outsized ecological importance and sensitivity to environmental conditions – will support marine ecosystems under predicted future climate states (Doney *et al*. 2012). Globally, rising temperatures from increasing atmospheric concentrations of carbon dioxide (CO_2) are predicted to increase ocean stratification, ultimately lowering transfer of nutrient supply from the ocean depths to the well-lit surface, reducing phytoplankton growth (Behrenfeld *et al*. 2006) and modifying community composition (Thomas *et al*. 2012).

In the coming decades, reductions in phytoplankton productivity and biodiversity could diminish the ocean's biological carbon pump, weakening a critical mechanism for removing atmospheric CO_2 and destabilizing marine food webs, adding stress to already overfished and overheated fishery stocks (Doney *et al*. 2012). Models of where and how shifts in marine ecosystems will manifest are not well constrained (Barton *et al*. 2016) and rarely capture the impacts of submesoscale physical dynamics, which likely contribute substantially to the productivity and diversity of phytoplankton (Mahadevan 2016; Lévy *et al*. 2018).

To increase the current understanding of phytoplankton's role in a changing ocean, scientists and resource managers must improve remote sensing of ocean color across scales (Platt *et al*. 2008). This can be achieved by supplementing existing global (but spatially, spectrally, and temporally coarse) observations with systems that sample at finer scales of ecological relevance. Small aerial drones are a promising avenue for extending spatially explicit methods from remote sensing toward these finer scales of observation (Figure 1). These systems are called different names by practitioners and regulatory



NASA

Figure 1. Three key advantages of drones: (top left) sensing sea-surface conditions under cloud cover, (bottom left) resolving fine-scale open-ocean features, such as a chlorophyll front, and (bottom right) resolving coastal ocean conditions that occur as mixed pixels (containing both land and sea) in satellite image products. Base imagery is from the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument on the Joint Polar Satellite System (JPSS-1) satellite, captured on 28 Mar 2019, and features phytoplankton patchiness at meso- and submesoscales in offshore currents along the Iberian Peninsula.

bodies, including Unoccupied Aircraft Systems (UAS), Unmanned Aerial Vehicles (UAVs), or Remotely Piloted Aircraft Systems (RPAS), but here we refer to them singularly and collectively as drones, and focus specifically on small aerial drones (<25 kg) unless explicitly stated otherwise.

Remote sensing for biological oceanography

For the past 40 years, remote sensing of ocean color has described the spatial dynamics of ocean biology and the patchiness of phytoplankton across multiple spatial scales. Advancements in the understanding of ocean biology have proceeded in tandem with advancements in remote sensing, beginning with experimental sensors in personal airplanes, continuing through the Nimbus 7 satellite's distinguished Coastal Zone Color Scanner, the stalwart Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, and recently incorporating the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument to monitor the immense daily vertical migration of animals across the ocean (Behrenfeld *et al.* 2019).

Satellite remote sensing of ocean color continues to advance rapidly. Groundbreaking hyperspectral and geostationary sensors are planned for deployment in the coming decade, addressing spectral and temporal gaps in the existing suite of sensors. Major advancements in semi-analytical algorithms, supported by extensive field campaigns, will complement these new sensors and not only retrieve chlorophyll-*a* (chl-*a*) measurements but also characterize water biogeochemistry and phytoplankton communities (Dierssen *et al.* 2020). Despite these advancements, however, satellite sensors will remain incapable of resolving the full submesoscale range by the end of the 2020s.

Since the 1970s, occupied aircraft have effectively observed phytoplankton spatial patterns and concentrations, complementing satellite platforms with newer, more experimental sensors and higher spatiotemporal resolutions. Airborne platforms continue to feature prominently in oceanographic campaigns, particularly those studying submesoscale dynamics. The Submesoscale Experiment (SubEx) campaign recently collected airborne thermal imagery of a submesoscale eddy in the Southern California Bight to study surface flow and eddy dynamics (Marmorino *et al.* 2018). The Lateral Mixing (LatMix) program flew airborne light detection and ranging (LiDAR) systems to track dye released near the Gulf Stream with the overall objective of gaining further insight into submesoscale lateral mixing (Shcherbina *et al.* 2015). The North Atlantic Aerosols and Marine Ecosystems Study (NAAMES) campaign characterized various submesoscale features using aircraft that continually surveyed features using a Lagrangian scheme (Della Penna and Gaube 2019). However, given their expense and flight characteristics, occupied aircraft are rarely deployed to survey smaller areas with the temporal frequency and spatial resolution necessary to describe how physics and ocean biology interrelate across finer submesoscale structures.

Critically, observations captured at the wrong scale can misrepresent artifacts of scale as indications of the actual dynamics of a studied system (Wiens 1989). Employing drones in coordination with satellites and in-situ platforms may help resolve this challenge and disentangle superimposed processes. In one such example, across a 2-year observation period, a study region of giant kelp (*Macrocystis pyrifera*) off the coast of California was subject to (1) a gradual die-off of kelp due to seasonal nutrient limitation, (2) winter wave disturbances causing immediate reduction in kelp coverage, and (3) tidal states that influenced only the visibility of kelp. These three interacting effects could easily be aliased (in the sense of signal processing, where a high frequency signal is mistaken for a low frequency signal due to limited sampling rate or where multiple signals become indistinguishable) and misinterpreted when sampled at coarse spatial resolution and without flexibility in timing, but drone surveys specifically timed for certain tidal states and occurring at approximately 2-week intervals enabled distinguishing these processes for precise evaluation (Cavanaugh *et al.* 2021). With a relatively large extent and a fine grain, drone sensors and data products span a large range of potential scales at which many important ocean processes occur (Figure 2). The magnitude of these spatial and temporal scales relative to those of satellites (finer scales) and in-situ platforms (larger scales) is precisely where drones can fill gaps of observation and hypothesis testing in biological oceanography.

Opportunities for drones in biological oceanography

Owing to their appealing scope, characteristics, modular sensing capabilities, and on-demand deployment, drones are increasingly used in several areas of marine science including animal monitoring (Johnston 2019), coral health analysis (Casella *et al.* 2017), marine geomorphology (Seymour *et al.* 2017), and coastal habitat mapping (Gray *et al.* 2018). However, both operational and optical challenges have limited their use for oceanographic applications, particularly in biological oceanography.

Large and sophisticated drones of military design are increasingly being deployed for oceanographic applications, such as monitoring ocean surface processes (Reineman *et al.* 2016) and tropical cyclone observations (Guimond *et al.* 2016). These larger platforms will surely continue to contribute sustained observations of the ocean, but they typically require extensive ship- or shore-based infrastructure and logistical support, with accompanying extensive financial requirements. At the same time, researchers are adopting drones to observe fine-scale physical oceanography. Example applications include examining boundary layer processes (Zappa *et al.* 2020), observing ocean–atmosphere interactions (Cassano *et al.* 2016), and monitoring groundwater discharge through thermal imagery (Mallast and Siebert 2018).

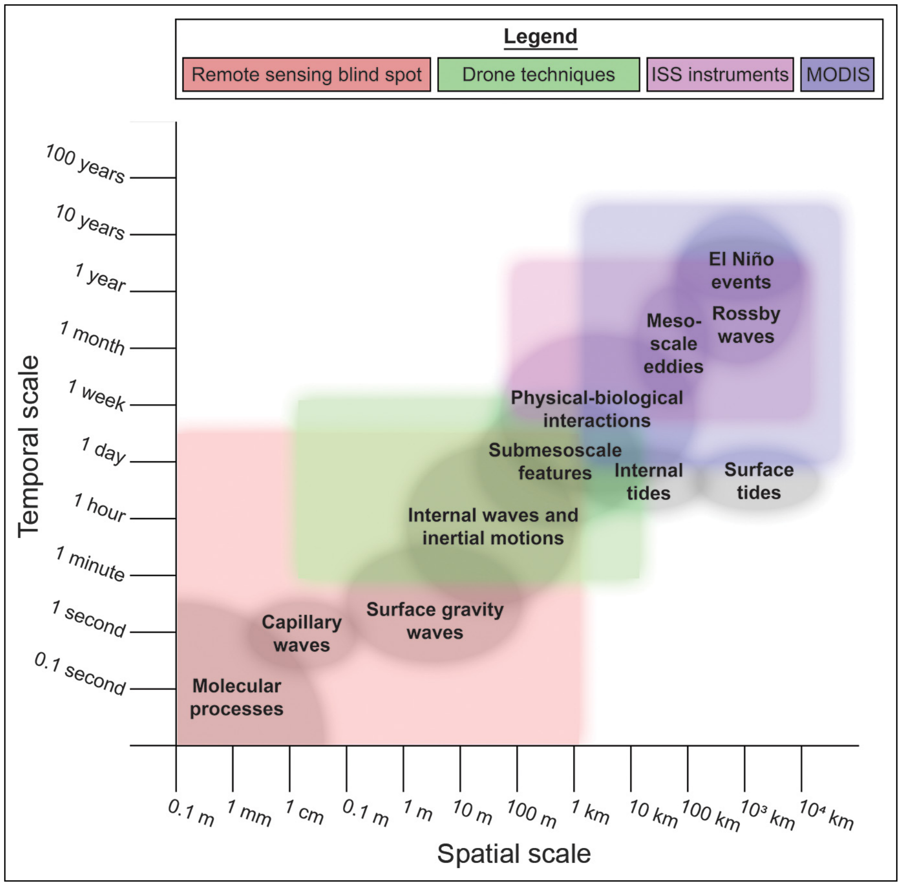


Figure 2. Stommel diagram of physical and biological processes studied in biological oceanography. Many occur within spatial and temporal resolutions of science-grade satellite platforms, here represented by Moderate Resolution Imaging Spectroradiometer (MODIS; blue rectangle) and instruments aboard the International Space Station (ISS; purple), but large ground sample distances and long revisit intervals relegate many more to a "remote-sensing blind spot" (red). Drone techniques (green) address the larger scales of this blind spot with fine spatial resolutions and the ability to be deployed multiple times within a day or multiday period.

The limited use of drones in biological oceanography contrasts with the advantages they offer for spatial ecology (Anderson and Gaston 2013) and their rapid uptake among many geoscience-related fields (Kelleher *et al.* 2018). Although example applications exist, most notably in monitoring harmful algal blooms, such work is often conducted in inland or estuarine waters (Kislik *et al.* 2018). This pattern may stem from the engineering challenges, operational complexities, and high cost of research-grade sensors, as well as characteristics of the ocean surface that challenge passive light-based sensing (wind-generated waves, varying glare, foam presence), the complexity of retrieval algorithms (Ruddick *et al.* 2019), and operational constraints imposed by the marine environment (ship-based launch and takeoff; risk of wind, rain, and sea spray) (Johnston 2019).

Fortunately, lessons learned by the optical oceanography community for satellites, occupied aircraft, and low-altitude platforms (Neeley and Mannino 2019) can be applied to help overcome several of these hurdles. However, integrating appropriate sensors at proper viewing geometries (Figure 3) and accounting for sun glint and reflected skylight remain obstacles for many biological oceanographers who might otherwise consider drones to observe and measure at fine scales. Best practices need to be shared to mitigate these obstacles (WebPanel 1). Notably, even with these best practices, glint and reflected skylight are often not fully eliminated. On occasion, flights must (unavoidably) be conducted around solar noon, when glint is most intense, and many low-cost drones do not have the capacity for a sensor to be mounted on a gimbal in order for that sensor to be maintained at appropriate viewing angles. Recently, an image-processing approach using image texture as a glint indicator was developed for removing glint from imagery (Cavanaugh *et al.* 2021). This promising approach, alongside other recent work evaluating common techniques for removing reflected

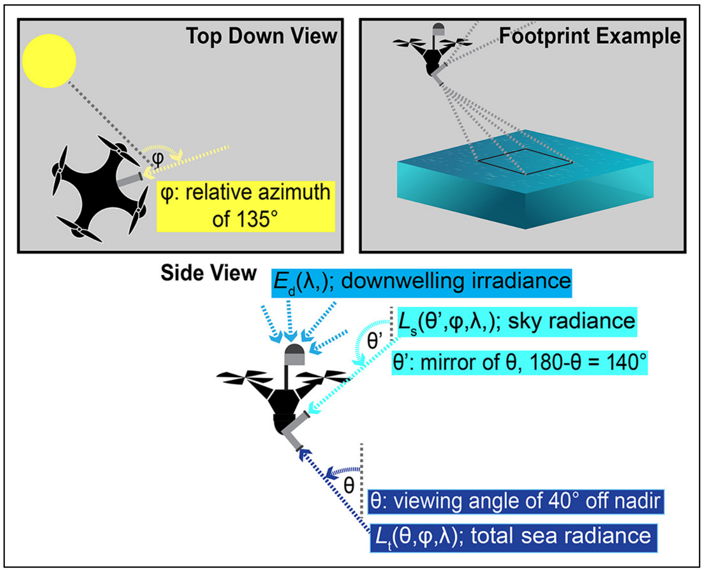


Figure 3. Three measurements are necessary to retrieve remote-sensing reflectance of water (that is, ocean color) from an above-water sensor: total sea radiance (L_t), sky radiance (L_s), and downwelling irradiance (E_d). Based on these measurements, the angles of sensor orientation relative to the sun and the water's surface can be optimized to an ideal viewing geometry (Neeley and Mannino 2019). θ and φ are the polar and azimuthal viewing angles, respectively, and λ is the wavelength.

skylight (Windle and Silsbe 2021), can help ensure high-quality data for a variety of drone platform and sensor combinations.

Affordable multispectral sensors with spectral bands similar to those of the US National Aeronautics and Space Administration's (NASA's) ocean color observing satellites, such as SeaWiFS and MODIS, show promise for retrieving chl-*a* concentrations when following these best practices (WebPanel 1) and then applying the current NASA chl-*a* algorithm (Kim *et al.* 2020; NASA 2021). Drones are also being outfitted with precision hyperspectral sensors (Aasen *et al.* 2018) accompanied by well-calibrated algorithms to retrieve hyperspectral remote-sensing reflectance (R_{rs}) (Shang *et al.* 2017; O'Shea *et al.* 2020), which will help lead to detailed water column compositions and phytoplankton types. The growing application of drones in biological oceanography is enabling scientists to exploit the overlap between the spatiotemporal operational scope of drones and the spatiotemporal complexity of the marine environment.

Operational capabilities of drones

The growing potential of drones in biological oceanography is driven by several factors that stem from their immediacy, efficiency, affordability, quality, and safety. Drones can be rapidly deployed and recovered by hand from both large ships and small boats in response to dynamic features without substantial delay to other ship operations (Figure 4), and can be quickly integrated into a diverse set of sampling regimes across polar, temperate, and tropical marine environments (Johnston 2019). Drones can be equipped with a range of sensors – often passive remote sensing using optical and thermal wavelengths, but occasionally active remote-sensing systems (such as LiDAR) for water column profiling and bathymetric mapping (Collin *et al.* 2018). Although limited, samplers for marine aerosols, water quality, and passive acoustic monitoring have also been deployed (Corrigan *et al.* 2008; Lloyd *et al.* 2017; Terada *et al.* 2018). Drone sensor technology is rapidly evolving and there is increasing convergence on a small number of research-grade multispectral and hyperspectral sensors. This convergence will facilitate further development and calibration of accurate ocean color algorithms for such commonly used sensors (Figure 5) leading to consistent retrievals across studies, less duplicated effort to calibrate and validate various sensors, and greater ease of use for new users.

Spatial and temporal coverage and scales of drone operations are defined partially by battery life and flight efficiency, partially by wind and weather, and partially by regulatory limitations. Typical drones fly at 10–15 meters per second ($m\ s^{-1}$) with battery life ranging from 30 to 90 minutes. Due to their more efficient mode of flight, fixed-wing aircraft tend to have longer range and endurance than multi-rotor platforms; however, for ship-based operations, retrieval of fixed-wing platforms is more challenging than retrieval of multi-rotor platforms and other systems capable of vertical takeoff and landing (VTOL). The increasing availability of VTOL-capable fixed-wing drones may help bridge this gap between mission time and ease of launch and recovery. Under a nominal flight time of 60 minutes and at a ground speed of 10 $m\ s^{-1}$, a drone can cover a linear distance of 36 km, but the precise deployment of this 36 km is often limited by regulation; for example, as of 2021, operations under the US National Airspace System must fly no more than 120 m above ground level, within visible line of sight (typically <2 km), and only during daytime under mandate of the US Federal Aviation Administration (FAA). These restrictions can be lifted via waivers, and regulations are evolving.

Even considering these limiting parameters – regulatory constraints, aircraft endurance, and flight speed – many submesoscale oceanographic features can be covered by drone observations in a single day. This new ability to observe repeatedly, within a day, features that span dozens of kilometers can address entirely new questions concerning intra-day biological variability, diel vertical migrations, and rates of change in the physical environment.

Within the range and endurance of a typical low-cost drone there are flexible and wide-ranging options for survey design. Typical grid patterns can be flown over small features, long transects can intersect over features of interest, Lagrangian approaches can repeatedly survey the same patch of water as indicated by a float, and running a "radiator" pattern along the path of a research vessel can add width

Figure 4. Marine drone operations often require launch and recovery by hand from (a and c) a research vessel or (b and d) a small craft, as in these examples: (c) during an ocean color survey from the Research Vessel (R/V) *Shearwater* near Cape Lookout, North Carolina, and (d) during a sea-ice survey from a Zodiac F580 supported by the Antarctic Research and Supply Vessel (ARSV) *Laurence M Gould* on the West Antarctic Peninsula. Images (c) and (d) courtesy of the Duke Marine Robotics and Remote Sensing Lab.

to the ship's data stream and act as a complementary stream or calibration set (Figure 6).

Affordable, portable, and simple to fly, drones will become a regular tool in the oceanographer's portfolio, much as conductivity–temperature–depth profilers (CTDs), ocean gliders, and autonomous surface vehicles have in recent years. Drones have matured beyond the prototype phase to join the growing suite of instruments available and often necessary to observe the spatiotemporal complexity of ocean features.

Emerging applications of drones in biological oceanography

Submesoscale and finer features

Ocean water moving at high vertical velocities (up to 100 meters per day) in the submesoscale range (on the order of 0.3–30 km) drives nutrient fluxes across the mixed layer, subducts particles from the mixed layer below the thermocline, and increases stratification by tilting density layers (Mahadevan 2016). Such submesoscale processes operate on similar scales of time and space as the life cycles of phytoplankton, and accordingly they appear to strongly modulate primary productivity, ecosystem structure, and marine biodiversity (Lévy *et al.* 2018). This alignment of scale has inspired extensive study over the past two decades into the biological importance of submesoscale physical processes (Lévy *et al.* 2001; D'Ovidio *et al.* 2010; Ruiz *et al.* 2019). This growing focus of research and understanding has highlighted a need for remote-sensing instruments that complement existing satellite observations taking place at the scale of ocean basins by resolving submesoscale dynamics at their necessary temporal and spatial scales.

Drones can be used to address this gap in observational capacity (Figure 6) because of their ability to record fine spatial resolutions and repeat observations within a single day, as is

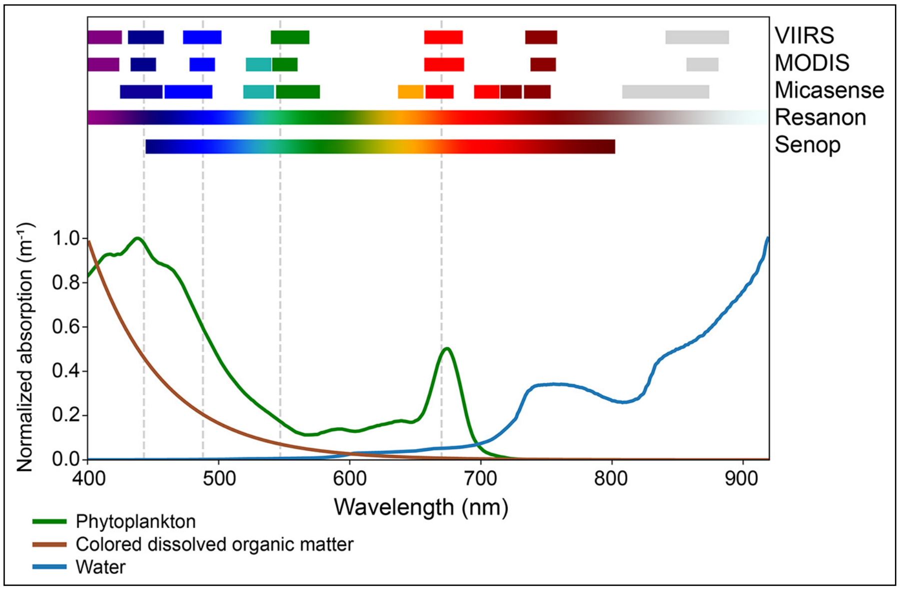


Figure 5. Range of the electromagnetic spectrum used for most ocean remote sensing (x-axis) with normalized absorption spectra (y-axis); center wavelength of MODIS bands used for chlorophyll-*a* (chl-*a*) retrieval (gray dashed lines); band locations (top) for VIIRS ocean color bands, MODIS ocean color bands, Micasense Dual Camera System bands, Resanon Pika L sensor coverage (pushbroom imager), and Senop HSC-2 Sensor coverage (full-frame imager). Chl-*a*, seawater, and colored dissolved organic matter absorption data from PJ Werdell.

necessary to adequately characterize submesoscale processes. Diel variability, such as a changing phytoplankton fluorescence signal, can contain useful information about physiological status, and sub-kilometer oscillations in chl-*a* concentration may reflect physical processes like Langmuir cells, both of which can be easily missed or misinterpreted with observations even slightly too coarse in space or time. Conventional methods of ocean observation and measurement confront a "synopticity problem" (Martin 2003), wherein current sensors cannot measure target variables in the system at sufficient resolution to describe target processes before the flow has redistributed the system and its values. Drones can be a cost-effective solution to this problem, complementing satellites and acquiring the synoptic view necessary to describe physical–biological interactions at the submesoscale.

Coastal regions

Coastal regions are among the most productive, dynamic, and economically important areas in the oceans (Seitz *et al*. 2014) yet are often neglected by the ocean color community due to multiple confounding factors. Coastal areas often feature more optically complex water constituents than open-ocean regions, which are typically dominated by chl-*a* and rapid flows that may substantially and chaotically change spatial patterns between satellite observations. In addition, single pixels from satellite imagery often capture both water and land within the few kilometers closest to a shoreline, which prevents accurate remote sensing by satellite (McClain 2009). Such limitations are readily addressed by the higher spatial and temporal resolutions of drone sensors and deployment capabilities. The ability to launch a drone from both land and at-sea platforms has already established nearshore monitoring as a growing application of drones within the field of biological oceanography (Shang *et al*. 2017; Kislik *et al*. 2018). Future applications may include using drones to monitor across multiple timepoints in a tidal cycle (sensu Cavanaugh *et al*. 2021), for comparing water quality before and after storms, and in routine monitoring as part of long-term ecological research programs.

Additionally, cloudiness is a common challenge to optical satellite remote sensing over nearly all oceans. This is a particularly thorny problem in coastal regions (where cloud cover can obscure rapid changes in water composition) and in polar regions (where persistent cloud cover severely restricts optical satellite coverage). Integrating drones into coastal and polar oceanographic campaigns can help bridge these cloud-covered gaps between satellite observations, especially in scenarios where occupied aircraft are impractical or unaffordable.

Calibration and validation of satellite products

In addition to their complementary qualities, drones provide novel methods for directly improving the data products derived from oceanographic remote sensing. Satellite calibration and validation is a challenging task given the typical ground-sample-distance of a pixel (0.5–10 km) compared to in-situ point samples. While point sampling is effective in several reasonably homogenous open-ocean environments (like the marine optical buoy [MOBY] off Hawaii), it has limited value for calibrating a 2-km^2 satellite-derived pixel in coastal regions, fronts, or eddies with dramatic gradients and heterogeneity. A drone survey, which can rapidly capture a much larger scope with a diversity of sensor payloads, will provide a more robust validation of the same satellite data. Many drones are capable of operating far beyond the operator's line-of-sight (subject to FAA waiver in the US), enabling simple and cost-effective operations to collect coastal data that could calibrate and validate the next generation of ocean color satellites, which aim to improve observations of productivity and water properties in complex coastal waters.

Drone techniques may also help define the relationship between phytoplankton diversity and ocean color. The primary obstacles to observations of algal biodiversity from space include mismatches between satellite and in-situ composition measurements, poor uncertainty estimates in satellite products stemming particularly from atmospheric distortion, spectral limitations of satellite sensors, and inexact retrieval algorithms for coastal and inland waters (Dierssen *et al.* 2020). Drones are not a panacea, but their spatially extensive capabilities with high spectral resolution will help advance the state-of-the-art for the next generation of satellites.

High-resolution data for model comparison and parameterization

Drone techniques can also improve other mainstays of biological oceanography by informing oceanographic models. There is often a disparity between model outputs and satellite-based ocean color products (generally stemming from uncertainty in satellite optical measurements) (Werdell *et al.* 2018), a dimensional mismatch between remote-sensing products (two-dimensional) and model outputs (three-dimensional [3D]), and a scale discrepancy between the highest resolutions of models and satellite products (Dutkiewicz 2020). These mismatches, exacerbated by sparse sampling in cloudy regions, challenge modelers trying to use satellite data to assess model skill and uncertainty (Dutkiewicz 2020). For example, satellite climatologies are often compared to model outputs, but in polar regions a satellite-based climatology may miss entire months of low productivity due to cloud cover, leading to overestimates of annual productivity (Gregg and Casey 2007). Although 1–4-km resolution satellite data of the open ocean are typically finer than output from an Earth system model (~1°), in coastal areas, where models output at resolutions well below 1 km^2, satellite products may not be appropriate for comparison. Finally, when neither models nor satellite products capture important fine-scale or transient features that may drive production and carbon export, a validation scheme of models with satellite data will continue to overlook these dynamics (Dutkiewicz 2020).

Once again, ocean color measurements from drones can help address this issue by improving calibration of satellite products to reduce uncertainty, ultimately yielding more robust datasets for model comparison and data assimilation. Drones can also provide the finer-scale measurements needed to improve understanding of processes and dynamics that are missed in models, informing better parameterizations of global models; fine-scale drone measurements can also be used to validate high-resolution models in regions such as open-ocean fronts and coastal waters. Integration of such spatially explicit measurements can reduce the uncertainty that impedes comparison between outputs of ecosystem or biogeochemical models and ocean color data products (Dutkiewicz 2020).

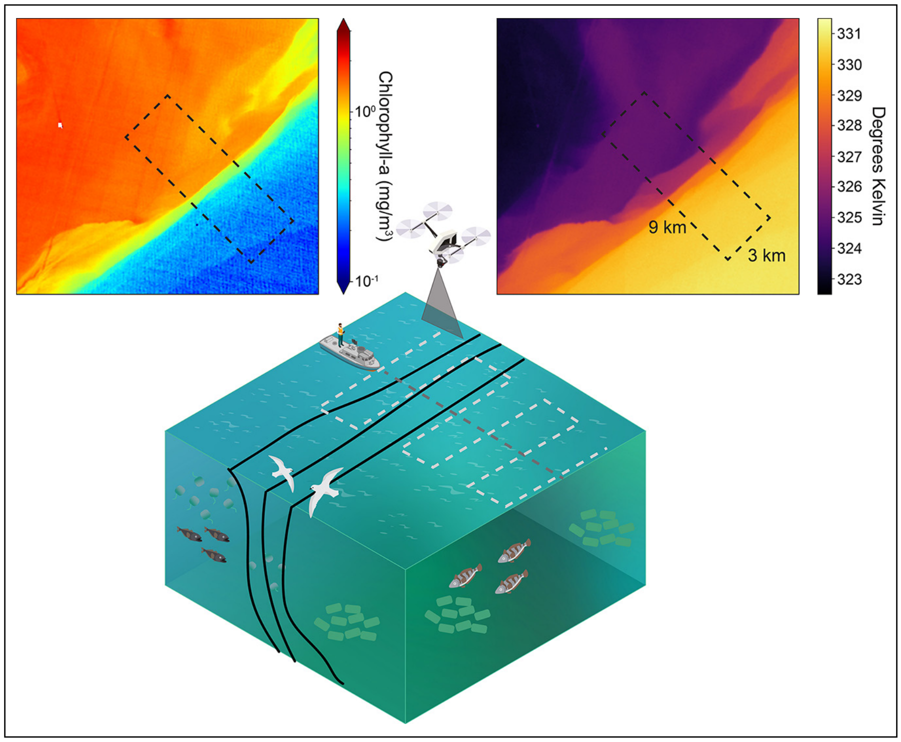


Figure 6. Drone flights can be coordinated with a research vessel to collect complementary data streams across features of interest. For example, (bottom) a drone flying a "radiator pattern" can add spatial context to linear flow-through sampling by a research vessel. Such efforts across features like the Gulf Stream front (top) can capture submesoscale dynamics and fine-scale phytoplankton patchiness not discernible in chl-*a* (left) and sea-surface temperature (right) satellite data products – here, Landsat 8 provisional aquatic reflectance (run through the OCx algorithm) and band 10 (10.6–11.19 μm) from Collection 1 Level 1 captured on 9 Mar 2020.

Caveats

Despite the great promise of drones for applications in biological oceanography, adoption is limited by three key methodological challenges: (1) the inherent complexities of optical oceanography, including sun glint and reflected skylight removal, maintaining appropriate viewing geometries, and the need to calibrate and calculate uncertainties on a per sensor basis; (2) logistical challenges of operating at sea, including unfavorable weather, sea-spray, and limited operational space; and (3) personnel and regulatory hurdles, including pilot training, necessary engineering and maintenance skills, and regulatory restrictions. While advancements in technology and implementation of best practices, particularly with respect to the optical and logistical hurdles, are being made, these challenges continue to hinder adoption of drone-based methods and the scientific advantages that they offer. In the US, oceanographic research would benefit from the ability to operate at distances farther than a few kilometers, which would require adjustments to the FAA's "beyond visual line of sight" restriction.

Conclusion

The field of biological oceanography progresses in tandem with advancements in observational capabilities. Drones represent a major advancement that will become a primary scientific tool for oceanographic research at fine scales, supporting robust measurements and modeling across scales and complementing conventional, intensive, large-scale oceanographic campaigns. Profiling floats (such as the Argo program) have revealed how temperature and salinity vary at depth across the globe (Riser *et al.* 2016), and long-endurance gliders have provided sustained observations of 3D structure and biogeochemistry across mesoscales (Rudnick 2016); complementing these capabilities, drones can deliver detailed measurements on ocean color, biogeochemistry, and temperature at fine spatial scales and temporal cadences, addressing largely unrecognized or understudied processes and biophysical dynamics. New oceanographic tools are adopted once they become accessible and proven. Although drones are currently accessible and capable of providing previously unavailable data, additional deployments are necessary to more broadly demonstrate their value.

Increased drone adoption will generate greater synergy with complementary methods. An integrated fleet of gliders and drones guided by the global context from Argo floats and ocean-observing satellites will help realize Henry Stommel's vision of a "networked ocean" (Stommel 1989). Such a synthesis of data streams could someday capture the ocean's spatiotemporal heterogeneity across orders of magnitude, advancing oceanography and providing a more complete understanding of the Earth system.

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Data Availability Statement

No data were collected for this study.

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