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Chapter 2

Towards an Optimal Design for Ecosystem-Level Ocean Observatories

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TOWARDS AN OPTIMAL DESIGN FOR ECOSYSTEM-LEVEL OCEAN OBSERVATORIES

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Abstract   Four operational factors, together with high development cost, currently limit the use of ocean observatories in ecological and fisheries applications: 1) limited spatial coverage, 2) limited integration of multiple types of technologies, 3) limitations in the experimental design for *in situ* studies, and 4) potential unpredicted bias in monitoring outcomes due to the infrastructure's presence and functioning footprint. To address these limitations, we propose a novel concept of a standardised 'ecosystem observatory module' structure composed of a central node and three tethered satellite pods together with permanent mobile platforms. The module would be designed with a rigid spatial configuration to optimise overlap among multiple observation technologies, each providing 360° coverage of a cylindrical or hemi-spherical volume around the module, including permanent stereo video cameras, acoustic imaging sonar cameras, horizontal multibeam echosounders, and a passive acoustic array. The incorporation of multiple integrated observation technologies would enable unprecedented quantification of macrofaunal composition, abundance, and density surrounding the module, as well as the ability to track the movements of individual fishes and macroinvertebrates. Such a standardised modular design would allow for the hierarchical spatial connection of observatory modules into local module clusters and larger geographic module networks providing synoptic data within and across linked ecosystems suitable for fisheries and ecosystem-level monitoring on multiple scales.

Keywords: Ocean observatories, Ocean technology, Ecological monitoring, Networks, Coenoclines, Deep-sea, Behaviour, Optoacoustic technologies, Passive acoustic, Fish sounds, Cyber interfaces

Introduction

Ocean observatories have become important resources for oceanographic observations around the world and consist of networks of instruments primarily designed to collect data on oceanographic and geophysical conditions in real time over long durations (Tunnicliffe et al. 2003, Schofield & Glenn 2004, Aguzzi et al. 2012, Gould et al. 2013). However, increasingly, observatories are

becoming useful tools for biologists interested in animal behaviour, ecosystem ecology, and fisheries applications (ACT 2007, Aguzzi et al. 2011b, 2015a, Barns et al. 2013). Four operational factors, besides development costs, limit applicability of existing ocean observations systems for use as tools in fisheries and ecosystem level applications: 1) limited spatial coverage, 2) limited integration of multiple types of technologies (i.e. multiple modalities of observation), 3) limitations in the experimental design for *in situ* studies, and 4) potential unpredicted bias in monitoring outcomes due to the infrastructure's presence and functioning footprint. These limitations have slowed the spread of ocean observatory use for fisheries and other ecological applications (e.g. benthopelagic connectivity), highlighting the need for efforts to improve observatory design (e.g. Handegard et al. 2013, Locascio et al. 2018).

The objective of this review is to show how ocean observatories, combined with other observational sampling technologies, can be better designed from fisheries and ecology perspectives for the monitoring of marine ecosystems and their connectivity through coenoclines (i.e. gradients of communities) formed along depth, latitude, and geographic gradients. What is unique about the suggested approach is that systems would be designed from the beginning for ecosystem-level observations on large spatial and temporal scales and would be replicated in many locations for global coverage. In order to meet these objectives, observatories need to be highly standardised and produce quantitative observations that are comparable among locations and over time. The present review presents a concept of standardised modular platform design that is intended to stimulate discussion and refinement within the scientific community. The ecosystem observatory module (EOM) concept (hereafter simply referred to as the 'module') consists of a central node and three tethered satellite pods (hereafter referred to as 'satellites'). A modular design means that the platforms should be designed so that they can be prefabricated, and therefore produced at lower cost, but be flexible enough to allow customisation and implementation in different habitats. Such a design serves two purposes: first, it provides directly comparable data among different locations, and second, it will encourage wider implementation of observatories around the globe. Most of the instrumentation proposed for each module has already been developed and implemented in some existing cabled observatories, though significant improvements in capabilities and reduction in cost are needed (see review in Aguzzi et al. 2019). In addition, much of the software needed to realise large-scale observatory networks that are useful to fisheries scientists, resource managers, and ecologists are still in the early stages of development (Allken et al. 2018, Juanes 2018, Marini et al. 2018a,b). Therefore, the development of data delivery systems that are accessible to a wide range of stakeholders from different disciplines and backgrounds is of vital importance for the effective use of ocean observatories for fisheries and ecological applications (Pearlman et al. 2019). It is therefore important to design data packaging and delivery systems in concert with the observatory structural and instrumentation design, rather than as an afterthought.

The implementation of permanent monitoring systems should deliver data on animal movement across habitat gradients (Aguzzi et al. 2015a) and energy flux interchange (Thomsen et al. 2017), providing measures of ecosystem functioning (Aguzzi et al. 2019). Time series of visual counts for different species by different monitoring modules and their satellites of a network may provide spatially meaningful representations of a population's abundance fluctuations when data are summed (i.e. scaled) together (Aguzzi et al. 2019). Spatiotemporal variations in population abundances could then be used to track the status of ecosystem services such as fisheries resources. Major requirements for ecosystem-level ocean observatory networks include 1) spatial quantification of organism abundance, density, and biomass through cross-referencing of data obtained from multiple observation technologies; 2) quantification of the impact of the observatory structure and operation of its instruments on the local biota; 3) a design for use of observatories as *in situ* laboratories; 4) spatial clustering of observatories/devices to optimise observation on multiple spatial scales over appropriate coenoclines; 5) integration of ocean observatory data with observational data collected through other sampling methodologies (e.g. ship, satellite, drifter, and buoy-based surveys and

animal-borne devices); 6) automatic data processing, such as detection of fish images or sounds to enhance data analysis by end-users; and 7) seamless presentation of multiple data streams to end-users that are synchronised in time across all instruments within a module and ultimately across all module locations.

This review starts with a brief summary of ocean habitat connectivity to provide context, followed by a description of a proposed ecosystem observatory system, including modules, components, and ways of combining modules into clusters and networks to allow monitoring along habitat gradients and coenoclines. A description of monitoring modelling and forecasting of observatory data is followed by an explanation of how observatories could be integrated with animal-borne technologies and the cyber developments needed to support monitoring networks accessible to users of different backgrounds. The final section is a rationale for the incorporation of observatory systems into commercial developments such as windfarms and oil platforms (e.g. Fujii & Jamieson 2016) to serve as partial mitigation for potential ecosystem impacts by extending marine ecosystem monitoring capability beyond what would otherwise be financially feasible.

Background: Ecosystem connectivity

Current ocean observatories have limited applicability to fisheries and ecosystem monitoring, in part because marine habitats exhibit complex linkages that operate on many different scales. A brief summary of ocean ecosystem connectivity helps to provide context for the rationale for highly standardised observatories that are organised in hierarchical spatial configurations to enhance quantification of ecosystem attributes along habitat gradients or coenoclines.

Researchers have long known that marine ecosystems are intricately linked through passive and active mechanisms for matter and energy transference. For example, estuaries serve as an important direct and indirect source of nutrients for coastal marine waters and thereby help to sustain coastal and deep-water fisheries (e.g. Teal 1962, Haines 1979, Nixon 1980, Odum 1980, Pomeroy & Wiegert 1981, Dame et al. 1986). Passive processes involve bi-directional fluxes of nutrients, pollutants, and plankton carried by water movements such as runoff, river flow, tides, up- and down-welling, storm events, and dense shelf-water cascading, all acting along a habitat gradient from freshwater to coastal areas and to the deep sea (Figure 1; Canals et al. 2006, Afonso et al. 2014, Puig et al. 2014, Rogers 2015, Thomsen et al. 2017). Active processes also contribute to energy/matter transference in the form of rhythmic and arrhythmic population movements across seabed and water column depth gradients, such as diel vertical migrations (DVMs), which represent the largest natural daily movement of biomass on the planet (e.g. Graeme et al. 2010, Doya et al. 2014, Aguzzi et al. 2015b, De Leo et al. 2018; Figures 1 and 2).

Mechanisms that regulate nekton distribution and movements along bathymetric and latitudinal coenoclines are similar and involve interactions between environmental (e.g. temperature gradients and cyclic fluctuations) and biological conditions (e.g. food and shelter availability and predation risk) (see reviews in Rountree 1992, Deegan et al. 2000, Rountree & Able 2007, Aguzzi & Company 2010, Aguzzi et al. 2011a). Horizontal linkages have been referred to as the 'chain-of-migration' (Rountree 1992, Deegan et al. 2000, Rountree & Able 2007), while vertical migrations have been referred to as the 'ladder-of-migration' (Vinogradov 1953, 1955, 1971). Mechanisms for linkages along a depth coenocline from the photic to dysphotic pelagic zones and the deep-sea benthos include 'organic rain' (Vinogradov 1971, McCave 1975, Honjo 1980, Alldredge & Silver 1988, Thomsen et al. 2017), ontogenetic (i.e. with size or life-stage) vertical migration of organisms (e.g. Merrett 1978, Wakefield & Smith 1990, Kobari et al. 2008, De Leo et al. 2018), and cyclic vertical migrations such as observed in the deep scattering layers (DSLs, Vinogradov 1953, Marshall 1971, Longhurst 1976, Mauchline 1980, Aguzzi & Company 2010, Naylor 2010, Aguzzi et al. 2017). In particular, rhythmic depth strata movements similar to DVMs also occur within the benthic boundary layer across shelves and slopes by endobenthic burrowing organisms (Aguzzi & Company 2010). Indirect
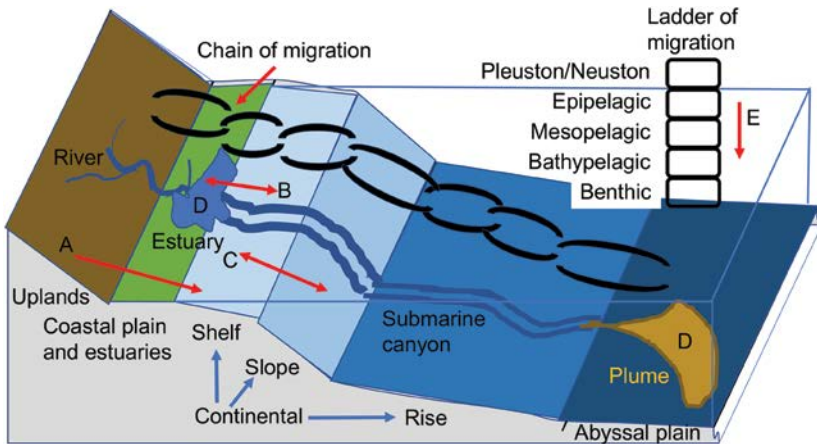
Figure 1 Example of some major linkages among habitats distributed along horizontal and vertical coenoclines connecting terrestrial to deep-sea ecosystems along a large river system. Major linkages are provided by a chain-of-migration connecting habitats horizontally, while a ladder-of-migration connects vertical habitats through ontogenetic and cyclical movements of organisms (see Figure 2). Other mechanisms of linkage include: (A) run-off from land to sea; (B) nutrient, detritus, and organism 'outwelling' and corresponding 'inwelling'; and (C) upwelling/downwelling occur largely due to water movements such as tides and storms; (D) deposition occurs where water velocity slows to allow precipitation of suspended materials and entrapment and mortality of organisms, as well as faecal deposition of migrating organism; and, finally, (E) organic and inorganic rain.
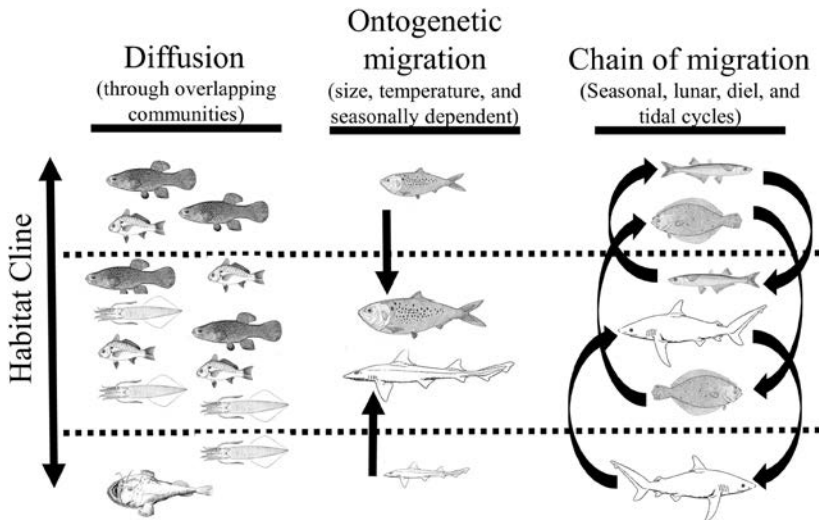
Figure 2 Example of mechanisms of energetic linkages among adjacent habitats or ecosystems through the distribution and movements of organisms. Major mechanisms include diffusion, ontogenetic migration, and chain-of-migration. Diffusion results from trophic transfer of energy among overlapping assemblages and is poorly understood. Ontogenetic migration results from movements of organisms among habitats as they grow and can be size, environmental condition (such as temperature), or seasonally mediated. The chain-of-migration (and analogous ladder-of-migration) results from rhythmic movements of organisms among habitats on seasonal, lunar, diel, or tidal cycles. The smallest links in the chain are between adjacent habitats, but links from direct movements of organisms can occur on any spatial scale among habitats located along the same coenocline. Major mechanisms of energy transfer include predator–prey interactions, spawning, faecal deposition, and local mortality.

day-night synchronisation of biological activity in deep-sea aphotic realms may also occur due to the movements of deep-scattering layer organisms (e.g. Irigoien et al. 2014). These rhythmic movements may also be accompanied by changes in background illumination at the seabed, when species making up the scattering layers are bioluminescent (i.e. bioluminescence panoramas; Aguzzi et al. 2017).

All these types of ontogenetic and rhythmic (e.g. diel and seasonal) movements produce energy fluxes that affect the functioning of ecosystems connected through a coenocline (Rountree & Able 2007, Aguzzi et al. 2011a; Figures 1 and 2), which are difficult to quantify with isolated ocean observatories. Accordingly, any technological development dedicated to ecosystem exploration, monitoring, and ultimately management (*sensu* Danovaro et al. 2017) should be planned by combining Lagrangian sampling strategies (i.e. capable of tracking individuals and population movements) as well as Eulerian approaches (i.e. a 'snapshot' capable of characterising locally the community changes produced by species displacements). For the former strategy, large-scale movements of animals are being studied through telemetry via satellite (Hussey et al. 2015). Nevertheless, only a few environmental parameters (e.g. depth and salinity) and no other ecological features (e.g. species interactions) are measured as explanatory factors of behaviour. For the latter strategy, a virtually holistic environmental monitoring approach is possible, but typically at a fine scale, which can be difficult to scale up to larger systems (Aguzzi et al. 2019). Accordingly, a merger of both strategies would be possible by the establishment of networks of monitoring stations that allow animal and population tracking at a high rate in a simultaneous fashion across large geographic scales and across latitudinal and depth gradients.

In this context, fisheries scientists have recognised the need to move from single species to ecosystem-based management approaches, but progress has been slow due to the complexity of coenoclines and the difficulty of obtaining synoptic data on appropriate scales (e.g. Marshall et al. 2018). Fishery management agencies can simultaneously advocate tracking and quantifying stocks as a monitoring action required to inform management measures and implement no-take zones (Maxwell et al. 2015). This point is crucial, as many essential fish habitats (EFHs, e.g. spawning or nursery areas) are not permanent; thus, the establishment of fishery restricted areas (FAO 2018) or other spatial management measures for fish and habitat protection could follow an adaptive approach (Walters 2007). Such a spatially dynamic approach will require different pathways for technological development in species and ecosystem monitoring. Such an approach is currently being pursued in the development of a cross-communication capability between cabled observatories and animal-borne technologies (e.g. hydrophones for acoustic tag recognition; Hussey et al. 2015).

Marine strategic areas are defined as ecologically iconic zones where multiannual surveying, as carried out by vessel-oriented technologies, is strongly recommended for scientific or management purposes (Aguzzi et al. 2019). Data on species demographic indicators (e.g. density, size and biomass), community composition (i.e. richness), and the effects of environmental controls on biodiversity obtained in this way for one iconic zone could be scaled to other areas with similar geomorphologic and oceanographic features as similar seascapes (Danovaro et al. 2017). Relevant areas have been and continue to be instrumented with different types of pelagic and benthic multiparametric platforms as part of observational networks (Tunnicliffe et al. 2003, Barnes et al. 2013), providing different levels of monitoring capability and manipulative interventions (e.g. ONC 2019, OOI 2019). However, such large networks could be improved by the development of the ecosystem observatory module design, with its increased focus on obtaining temporally and spatially overlapping data from multiple observation technologies.

Observatories are invasive technologies that produce noise, lighting, and motions that can be foreign to the habitat under study. In addition, it is important that observatories be designed to better understand their invasive impact to comply with international legislation (e.g. underwater noise as an ecological descriptor; Audoly et al. 2016, 2017). Therefore, there is a need for observatories to have built-in capabilities to monitor their own effect on the surrounding habitat and biota. The

EOM design seeks to provide self-monitoring capabilities for two reasons: 1) measurement bias and 2) degree of impact by the structures' presence and functioning on the local environment (typical sizes of the main components of observatory systems are likely to be around 3–5 m on each side and 2–4 m in height). Since any observatory will function as an artificial reef and thereby modify the local habitat characteristics that are being measured (Vardaro et al. 2007, Blanco et al. 2013), more attention is needed to understand the attraction, repulsion, and residency effects of the structures and their operations (e.g. pan-tilt camera motor noise, mobile platform noise, and illumination at imaging) on sessile and motile species and their interactions with each other (e.g. the establishment of fouling communities on the structure could influence the local trophic structure). Over time, such developments can result in enough changes that the observatory data will no longer reflect the habitat that it was designed to observe.

The ecosystem observatory module

A conceptual schematic of a proposed ecosystem observatory module and its components is provided in Figure 3, and the function of each sensor and component device is outlined in Table 1. Standard components of each module would include: 1) central node and associated instruments, 2) mobile platforms, 3) three satellite pods, 4) a passive acoustic array, 5) a spatial configuration and software to optimise cross-referencing among observational data, and 6) autonomous instruments. Optionally, some modules would be enhanced with the addition of a pelagic satellite to collect data on sea-surface and water-column organisms and conditions.

The central node and its instruments

The central node serves as the primary instrumentation platform, power supply, and data link for the module. It also houses dockage, data transfer links, and power supply for three types of mobile
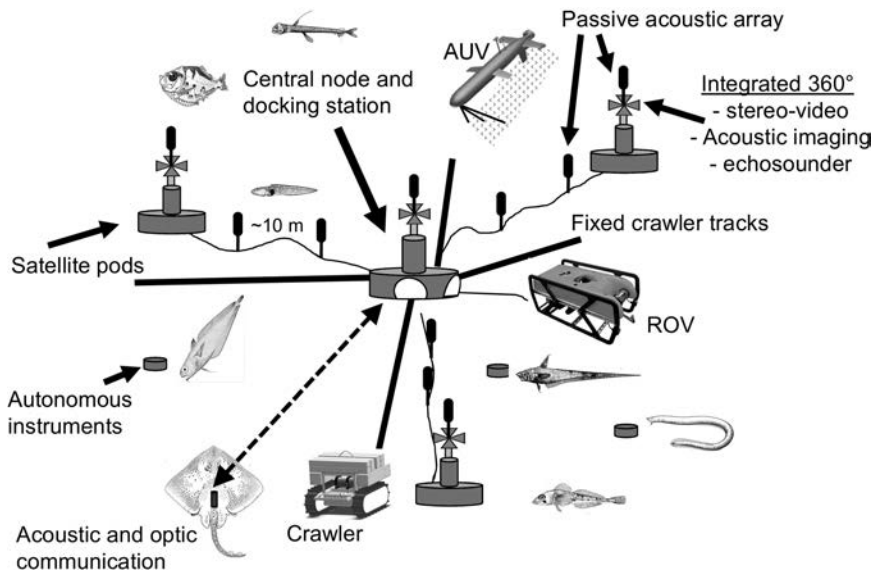
Figure 3 Schematic illustration of the proposed standard ecosystem observatory module consisting of a central node, three satellites, AUV, ROV and crawler mobile platforms and their dockage, and various autonomous devices. Hydrophones on the central node and each satellite form a 3-dimensional passive acoustic array. Crawlers would operate on predetermined tracks lines to reduce their impact on the substrate.

Table 1 Optoacoustic-image and passive acoustic sensors installed on the standard cabled ecosystem observatory module and its associated mobile docked platforms

| Components	Instruments	Purpose
Central node	Multiple	Module power supply, data deposition and transmission, instrument platform, and mobile dockage platform.
	Hydrophones	Passive acoustic monitoring, including recording of environmental noise, system noise, and biological sounds over the biologically relevant frequency range of 1 Hz to 150 kHz. Component of the module's 3-dimensional passive acoustic array for sound source location; cross-reference with video, acoustic imaging sonar, and echosounder for species identification, tracking, and target strength quantification.
	Stereo-video cameras	Video recording of conditions and organisms over 360° around the central node to determine the size and spatial location of individual organisms. Use for identifying or confirming the source of sounds, targets in the acoustic image, and bioacoustic echosounder targets.
	Pan-tilt HD cameras	User-controlled video cameras with pan-tilt control, zoom capability, and lighting control, for use in investigating selected field of view areas, infrastructure elements, and to zoom in on selected passive acoustic, acoustic image, and echosounder targets for identification and behavioural observations.
	Acoustic imaging sonar cameras	Recording the presence and movements of animals in a 360° cylindrical volume surrounding the central node during all visibility conditions; cross-reference with passive acoustic array source location, stereo camera location, pan-tilt cameras, and echosounder targets for species identification, tracking, and target strength quantification.
	Rotary horizontal multibeam echosounder	Bioacoustic echosounder to quantify distribution of organisms in the water column within a 360° zone surrounding the central node and extending outward for a radius of 100–800 m. Cross-reference with passive acoustic array source location, stereo camera localisation, and pan-tilt cameras, for species identification, tracking, and target strength quantification.
	Environmental sensor package	Continuous recording of habitat variables, for example, pressure, temperature, salinity, current speed and direction, methane, oxygen, nitrates, pH, chlorophyll, and turbidity.
	Acoustic and optic receivers and transponders	Acoustic receivers for animal- and instrument-borne telemetry signals. Also including receivers for acoustic modem-based or optical communication and data transmission. In some cases, transponders can be used for two-way communication with animal- and instrument-borne devices.
	Crawler and dockage	Placing and servicing autonomous devices and satellite experimental payloads; conduct physical and biological sampling in the area surrounding central node along fixed and predetermined tracks.
	ROV and dockage	Central node servicing; place and service autonomous devices and satellite experimental payloads, conduct physical and biological sampling in area surrounding node, conduct video transect surveys, document fouling organism and species associations with infrastructure, investigate unknown targets detected by observation technologies.
	AUV and dockage	Conduct benthic habitat and biota distribution mapping transects around the central node and throughout area between modules within an observatory cluster. Investigate unknown echosounder targets beyond the range of the crawler and ROV and of video and acoustic imaging sonar ranges.

(*Continued*)

Table 1 (*Continued*) Optoacoustic-image and passive acoustic sensors installed on the standard cabled ecosystem observatory module and its associated mobile docked platforms

Components	Instruments	Purpose
Satellite pods	Hydrophones	Passive acoustic recording of ambient sounds (see previously). Components of the module's passive acoustic array for sound localisation.
	Stereo-video cameras	360° calibrated visual recording of organisms (see previously) around the satellite and cross-reference with observational data from the central node.
	Pan-tilt video cameras	User-controlled video cameras (see previously). Also, to supplement and cross-reference observational data from the central node instruments.
	Environmental sensors	Record microdistribution of physical parameters (see previously) expected to vary within the module area.
	Experiment or observation payload	Exchangeable 'plug-and-play' payload containing instruments for user-designed data collection or experimentation, such as settlement trays with different substrates (e.g. carbon, wood, or bones and even litter), experimentation on light effect on species, tagging, and so on.
Autonomous devices	Mission dependent	Stand-alone sound recorders, cameras, cages, mesocosms, and other devices to be placed by ROV or crawler to monitor short- and long-term conditions at a specific location such as monitoring a fish nest or sessile invertebrates. Other possible devices include animal collection traps and stand-alone small-scale experimental packages.

platforms (Figure 3, Table 1). Standard observation instruments on the central node would include stereo video cameras, acoustic imaging sonar cameras (e.g. dual-frequency identification sonar: DIDSON), and bioacoustic echosounders, as well as a passive acoustic system capable of recording sounds over a biologically relevant bandwidth (1 Hz to 150 kHz). In order for these systems to provide observations useful for ecosystem-level monitoring, they must provide spatially and temporally quantifiable data. For example, pan-tilt high-definition cameras that are often standard on observatories are not conducive to the collection of occurrence data on even a presence/absence level because the direction, depth, and angle of the field of view are constantly changing and hence the absence of organisms cannot be determined.

To achieve the desired quantification, the module should be designed so that each technology provides 3-dimensional data over 360° around the module and overlaps with others to the maximum degree possible (Figure 4). However, each device will have different ranges, beam angles, and time resolutions which must be integrated to provide seamless views to the end-user (see section on cyber developments subsequently). Comparison of data from the overlapping 3-dimensional views provides the ability to cross-reference data to improve identification and measurement accuracy (Figure 4). Stereo video cameras should be used to obtain the 360° view around the central node because they also provide 3-dimensional location and organism size data (Bosch et al. 2019). Although we are not aware of previous stereo video camera applications on existing observatories, they have been widely used in fisheries and ecological applications, including deep-sea applications (e.g. Harvey & Shortis 1998, Shortis et al. 2008, Williams et al. 2010, 2018, Bonin et al. 2011, Merritt et al. 2011, Shortis & Abdo 2016). It is important that these devices not be under user control, because they must provide the maximum stability of views over time (i.e. constant field of view within the device's limits). However, it is advisable for each module's central node to contain at least one pan-tilt video camera under user control to allow the examination of specific phenomena (e.g. burrow emergence of different individuals or rate of access to carrion) and to help validate the identification of organisms observed with the fixed video or other observation instrument.
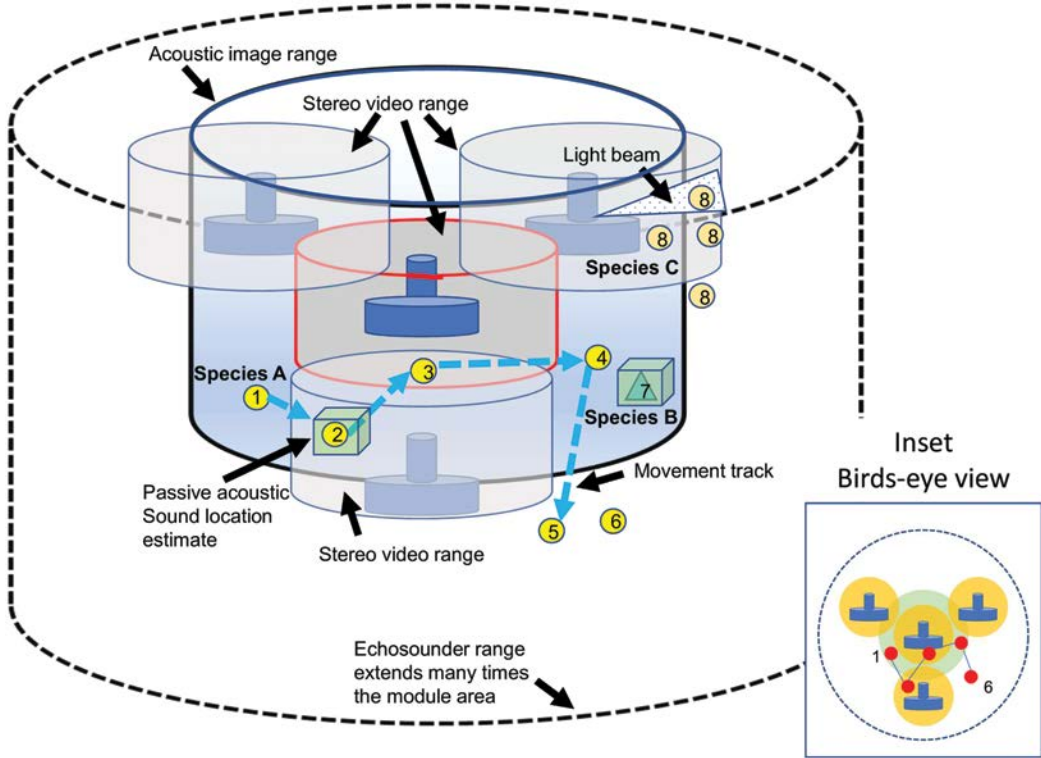
Figure 4 Schematic 3-dimensional illustration (not to scale) of the spatial configuration of the central node and satellites of a module and the overlap among video, acoustic imaging sonar, and echosounder spatial coverage areas (inset provides a bird's-eye-view of the spatial configuration). Integration of multiple 3-dimensional observation modalities in a module provides cross-referencing data to identify and track organisms. (1–6) a single individual of species A is tracked as it moves through the module area. Changes in echosounder target strength due to orientation changes can be quantified by comparison of different observations at each location, enhancing our ability to determine fish identification from target strength data. (1) Silent individual detected by echosounder and acoustic imaging sonar, provides target strength, orientation, location, and size estimates. (2) Same individual produces sound loud enough to be localised by the passive acoustic array, actual location and identification confirmed by stereo-video, acoustic image, and echosounder. Sound received level can then be corrected for exact location to obtain sound source level and detection range. (3) Now silent, it is detected by stereo video, acoustic imaging sonar, and echosounder from the central node, as well as stereo-video from a satellite. (4) The individual moves out of camera range but continues to be tracked by acoustic imaging sonar and echosounder. (5) As the individual leaves the module area, it continues to be tracked by echosounder. (6) Separate individual of species A is detected on echosounder only, but target strength consistency of species A at other locations permits accurate attribution to species within the wider area covered by the echosounder. (7) A second unknown species is detected by acoustic imaging sonar and echosounder and is identified based on localisation on a known sound. (8) The reaction of multiple fish of species C to light is quantified by acoustic imaging sonar and echosounder.

Mobile platforms

Three types of mobile platforms would be docked at the central node of each module, including a seafloor 'crawler', neutrally buoyant remotely operated vehicle (ROV), and autonomous underwater vehicle (AUV). Although there is some redundancy among ROV, AUV, and crawler platforms, each provides unique capabilities and disadvantages. All three types of platforms are useful for surveying habitat and organism distribution surrounding the module, and each can be used to investigate

specific phenomena observed around the module and can aid in the identification of unknown targets detected by the video, acoustic imaging sonar, echosounder, and passive acoustic array.

ROVs and AUVs are both mobile assets; the AUV has a much greater range and is not limited by its tether. In contrast, although hampered in some ways by a tether, the ROV has manipulative capabilities (i.e. by robotic arms), can carry larger payloads, and can be directly controlled by a user in real time. The AUV provides the best mechanism for mapping and monitoring habitat and biota (benthic and pelagic) of the area surrounding a module and the larger area encompassed by the module's satellites. In addition to providing habitat-mapping capabilities of the area immediately surrounding the central node, the ROV can also be used to place autonomous instruments, exchange satellite payload packages, and service all infrastructure components of the module (Sivčev et al. 2018). The ROV can also be equipped with push-corers in order to sample sediments. The ROV's high mobility also allows important functions such as the monitoring of the fouling community, interactions of organisms with the infrastructure and its instruments, and faunal residence (e.g. sheltering).

A drawback of both AUVs and ROVs is that thrusters must be in operation even when hovering at a station, thus creating high levels of noise and turbulence that limit their ability to conduct unbiased sampling and observations at a specific location for any period of time (Rountree & Juanes 2010; Durden et al. 2016a). An important, but often overlooked, noise problem with ROVs is that their acoustic tracking and guidance systems produce intense broadband noise that may influence animal behaviour and can also bias measurements of the acoustic properties of biological sounds (Rountree & Juanes 2010). In addition, the intense tracking pings make it harder for a human user to process soundscape data (R.A. Rountree pers. obs.). Another drawback of ROVs is the need for lights for operations (Rountree & Juanes 2010). The main limitations of AUVs are related to the development of suitable docking infrastructures that can provide for data downloading and fast inductive recharging of batteries to increase AUV operating time.

A crawler can more effectively conduct point-census surveys that can provide data at specific locations for extended time periods (minutes to hours), during which noise production and turbulence can be substantially reduced compared with the other mobile platforms. A drawback to the crawler is its physical disturbance of the benthic habitat and impact on benthic organisms along its movement track, but this can be reduced to a narrow strip of seabed by limiting the crawler to a constant corridor for displacement (Chatzievangelou et al. 2016). Since such potential impacts would be magnified in the area around a permanent observatory, we recommend that crawlers be operated on predetermined and constant tracks to minimise habitat disturbance (Figure 3).

Tethered satellite pods

The three standardised satellites of each module would have several functions: 1) provide observational redundancy and spatial overlap of observations with the central node observations to assist in organism detection, identification, and development of 3-dimensional distribution maps in the area surrounding the module (Figure 4), 2) provide observation of biotic responses to the central node and its mobile platform presence and operations; and 3) serve as platforms for changeable instrument packages designed to address specific research hypotheses.

A central premise of the proposed ecosystem observatory module design is that it includes multiple modalities of observation that are synchronised in time and provide the maximum spatial overlap. Therefore, the spatial configuration is dependent on optimising the overlap among the systems under local conditions, as well as limitations of tethering with regard to ROV and crawler access to the satellites. In many locations, satellites placed at 120° intervals and at distances on the order of 10 m from the central node would be most suitable (Figure 4). Minimally, each satellite would be equipped with stereo video cameras capable of capturing a 360° cylindrical or hemispherical view around the satellite. Ideally, they would also include the same acoustic imaging sonar and bioacoustic

echosounder instruments as those on the central node, but at the present time, these systems are prohibitively costly to achieve the ideal redundancy and overlap within the module area. As these technologies advance sufficiently to allow cost-effective 360° coverage, they should be added to the satellites to improve spatial overlap over a larger area surrounding the central node.

Observational data obtained by the satellites of the area surrounding the central node and by the central node of the area surrounding each satellite would provide a powerful means of determining faunal interactions with the structures, including behavioural reactions to instrument operations (e.g. lights and sounds, Figure 4).

Ocean observatories should be thought of as permanently instrumented areas where scientists of different backgrounds have an opportunity to perform manipulative experiments, favouring iconic environments such as the deep sea, for example, and resulting in a transition from a still largely descriptive science toward a more experimental, hypothesis-driven, approach. In order to better serve as platforms for hypothesis-driven research objectives, the satellites need to be designed with an infrastructure that allows for 'slide-in slide-out' exchange of experimental payloads for hook-up to power and data transfer. Examples of potential payloads might include settlement trays, experiments on the response of biota to artificial light regimes (useful for behaviour studies but also to examine the impact of observatory lights), observation of biota response to bioluminescent light, response to various baits, response to sound playback experiments (useful to understand behaviour and also the impact of observatory generated noise on the biota), experimental attempts to mark or tag biota through ingestion of tags or automatic capture, tag and release mechanisms (having the dual purpose of studying fish movements and residency and using the observatory structure as habitat), the effects of new colonised substrates on species and succession experiments, habitat manipulation experiments such as predator exclusions, microcosm and mesocosm experiments, and many other possibilities.

Passive acoustic array

Passive acoustic monitoring of fishes and invertebrates has become an important tool in fisheries and ecosystem studies (Rountree et al. 2006, Luczkovich et al. 2008); however, inherent problems have slowed its more widespread application, including lack of catalogues of fish sound data (Rountree et al. 2002), lack of information on source levels and detection ranges, and lack of sufficiently developed autodetection software (Rountree et al. 2006, Luczkovich et al. 2008). The use of multiple observation technologies to aid in the *in situ* validation of sound source identity, source level, and detection ranges is in its infancy (Rountree et al. 2003, Rountree 2008, Rountree & Juanes 2010), but a combination of using a passive acoustic array with video for the *in situ* identification of unknown fish sounds has recently been demonstrated (Mouy et al. 2018). The application of passive acoustic arrays for localisation and cross-reference with other forms of observation on ocean observatories are particularly promising, especially in the deep sea where many fishes possess sonic muscles that are presumably used for sound production (Rountree et al. 2012, Wall et al. 2013). Calls for the increased use of passive acoustics for fishes and invertebrates to be incorporated into ocean observing systems have been made at workshops for decades (Rountree et al. 2003, ACT 2007, R.A. Rountree pers. obs.), but implementation has been slow (Locascio et al. 2018). It should be emphasised that incidental sounds produced by fishes and invertebrates as by-products of movement, feeding, or physiological processes can be important markers of species identity and useful for monitoring temporal and spatial patterns in the associated behaviour (Rountree et al. 2006, 2018). Thus, passive acoustics can be a useful tool for monitoring both vocal and non-vocal organisms and their behaviours at observatories.

Because of the potential importance of passive acoustic monitoring as an important tool in ocean observatories, it is essential to include a hydrophone array in the EOM design. At the minimum, hydrophones should be placed on the central node and each satellite to create a four-element 3-dimensional array that can localise sounds originating near the central node. However, a greatly

improved ability to localise the low-amplitude sounds created by many fishes and invertebrates could be achieved by placing compact arrays of six hydrophones on each element (*sensu* Mouy et al. 2018) or by placing additional hydrophones at intervals along the tethers from the central node to each satellite (Figure 3).

Stand-alone sensors and other devices

Autonomous instruments and recording devices (e.g. Corgnati et al. 2016, Marini et al. 2018a) deployed and serviced by the mobile platforms would be incorporated into the area surrounding the module to provide unique data on biota in the surrounding habitat and additional opportunities for *in situ* experimentation (Figure 3). For example, autonomous video recorders could be placed close enough to individual fish nest sites, or individual sessile invertebrates, to use short-range infra-red lighting to make long-term observations on microhabitat use, behaviour, and species associations. Autonomous instruments could also be used to measure gradients in conditions at increasing distances from the central node or specific satellites in an effort to quantify the effects of habitat heterogeneity on animal presence and habitat use and the observatory's influence on environmental conditions, habitat structure, and organism distribution (i.e. to distinguish between natural variation and artefacts resulting from effects of the module). Many other types of autonomous devices can be envisioned to carry out hypothesis-driven experiments, such as small mesocosms, settlement trays, exclusion cages, and benthic animal traps.

Importance of observation data overlap

Time synchronisation and spatial overlap of all observation data, within the resolution limits of each type of instrument, within a standardised spatial configuration, is one of the most important attributes of the proposed ecosystem observatory module design, as it allows for the cross-referencing needed for species detection, identification, and tracking (Figure 4). Consideration of how best to optimise the spatial coverage and overlap of observation data and how it can be packaged for users should be part of the design process for implementation of the EOM concept.

Ideal spacing between the central node and satellites is determined by optimising overlap among spatial coverage of all instruments for local conditions. Stereo video cameras provide the highest accuracy of species identification, size, and location in the area surrounding the module but are limited to periods of natural or artificial lighting during hours of darkness or in the aphotic zone. Acoustic imaging sonar provides accurate location of targets but poorer species identification (Aguzzi et al. 2019). However, it is not limited by lighting. Horizontal multibeam echosounders provide highly accurate 3-dimensional location over a large spatial area surrounding the module, but identification is limited by the accuracy of back-scatter target strength data, which are influenced by fish size and orientation to the acoustic beam, creating uncertainty in multispecies scenarios (Juanes 2018). Sounds detected by the passive acoustic array can be used to identify species when sounds are well known, but until detailed catalogues of fish and invertebrate sounds become available, most sounds detected and localised will be from unknown sources.

Cross-referencing of echosounder data with acoustic imaging sonar, video, and passive acoustic data can provide valuable validation of target strength data for organisms and thereby enhance biomass estimations around the observatory, as well as providing target strength data for other independent conventional bioacoustics surveys (e.g. traditional fisheries pelagic surveys that rely on accurate target strength data for bioacoustic assessment of fish stocks). Similarly, cross-referencing of acoustic imaging sonar with echosounder, video, and passive acoustic data can provide identification validation of acoustic image targets in the near field (ranges of up to the limit of visibility) and echosounder targets in the far field (ranges up to 1000 m). Finally, cross-references of unknown sounds localised by the passive acoustic array with video, acoustic imaging sonar, and echosounder

data can provide sound source identification and quantification of source level and detection range (Rountree 2008, Mouy et al. 2018).

Simultaneous observations from all technologies would make it possible to track organisms continuously as they move around the module (Figure 4). Therefore, at each location, data on changes in fish orientation and location can be used to quantify their influence on echosounder target strength. As more and more data are compiled, accuracy of identification and tracking and estimates of fish size, abundance, density, sound source level, and sound detection range can be improved. A 360° view around the observatory by multiple observation technologies allows users to estimate the abundance of biota per unit volume while correcting for movements of individual fish and other organisms. A fish swimming in circles around the structure can be counted accurately as one individual, rather than multiple individuals moving in and out of a video field of view. To obtain these type of data, modules must be configured with satellites in close enough proximity to provide adequate coverage of mobile biota (Figure 4).
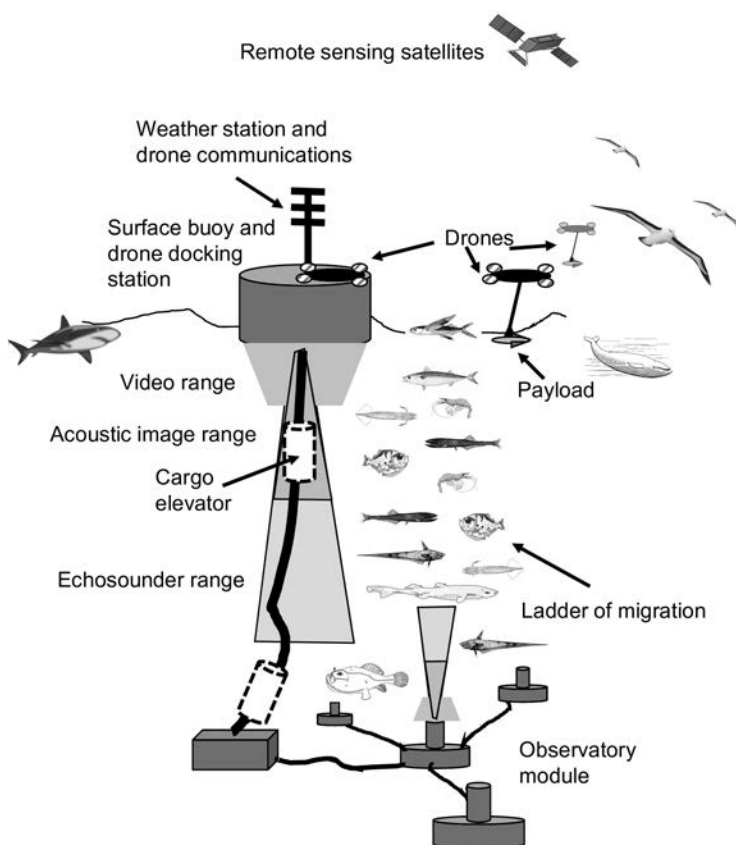
Optional pelagic satellite

The ecological monitoring of modules can be significantly enhanced by the addition of surface and water-column assets that can combine benthic observations with water-column and surface observations to monitor both surface-associated organisms and conditions as well as those of the water column (Figure 5). Besides providing a monitoring capability of the pelagic ecosystems, ecosystem observatory modules enhanced with a pelagic satellite can provide unprecedented information on pelagic-benthic ecosystem connectivity. This can be accomplished by placing a buoyed surface platform in contact with a module via an instrumented mooring line. Surface buoys and mooring lines have the potential capacity for numerous instruments to be distributed throughout the water column to synoptically monitor fine-scale hydrographic and biogeochemical parameters as, for example, corrosive (i.e. low pH, high pCO_2) oxygen minimum zone waters that intrude seasonally onto continental shelf-edge zones (Juniper et al. 2016). Instruments can be either fixed (e.g. Bahamon et al. 2011) or movable as yo-yo systems for fish monitoring from decommissioned platforms (Fujii & Jamieson 2016). They can also serve as access platforms to allow some types of maintenance of observatories placed on the seabed (depending on depth and conditions).

Each buoy would be fitted with a weather station, microphone, and video camera to monitor surface conditions and shipping activity (e.g. Aguzzi et al. 2011b, OBSEA 2019). Recordings of aerial noises associated with weather, sea state, and shipping can be validated by the video and compared with simultaneous acoustic recordings from hydrophones to provide important insight into the source of underwater sounds and help to quantify noise impacts on the aquatic soundscape. The surface buoy would also support downward-projecting video, acoustic imaging sonar, and echosounder instruments to provide similar capabilities to those of the bottom mounted instruments and hence valuable data on pelagic components of the ecosystem. All instruments would be connected to the cabled observatory for data transmission and power supply, with no need for satellite communication.

The development of a new cargo elevator technology (Figure 5) would allow the rapid delivery and retrieval of instruments and materials to and from the module. For example, in combination with the module's ROV or crawler, scientists could deliver a new experimental payload to one of the satellites and remove the old unit. Another example would be to deliver fresh bait to a baited camera system or to retrieve organisms captured by instruments at the module. An elevator system could dramatically increase our ability to deploy and retrieve materials to the module because it would no longer depend solely on the use of expensive ship-based submersibles or ROV bottom time.

Pelagic satellites can also be used as docking and communication stations for specially adapted aerial drones (Figure 5). One of the most important applications of drones would be to map spatial and temporal distributions of marine birds, mammals, turtles, and large pelagic fishes (e.g. Toonen & Bush 2018). Pleustonic and neustonic components of the ecosystem could also be mapped,

Figure 5 Schematic of an ecosystem observatory module enhanced with a pelagic satellite composed of a surface buoy and associated instruments to monitor vertical distribution of organisms and physical properties. The surface buoy would be equipped with downward-looking video camera, acoustic imaging sonar system, and echosounder similar to those deployed on the benthic module components. It would also include a microphone and 360° video to capture above-water audio and video data of weather and shipping conditions for correlation with underwater recordings. The mooring line would be variously equipped with monitoring instruments at different depths and a cargo elevator system to transport materials, such as new scientific payloads for satellite nodes between benthic and surface systems. The pelagic satellite includes a drone system to map aerial (e.g. birds) and aquatic megafauna (mammals, fish, turtles), as well as neustonic and pleustonic organisms and pollutants. Drones can also be used to carry an instrument payload such as a hydrophone or fluorometer and other instrumentation for spatial mapping.

including distributions of jellyfish, *Sargassum*, and other surface organisms and the development of windrows. In addition, they can map the distribution of organic matter subsidies, including kelp and marine mammal carcasses, and also track pollution, such as floating plastics, oil slicks, and other buoyant pollutants. This can also be crucial to monitor alien species and forecast potential areas of invasion, as plastic debris and other floating materials contribute to the transfer of non-native species (Vetger et al. 2014). Drone systems are already being successfully developed to conduct passive acoustic surveys (Lloyd et al. 2017). A communication tower on the buoy would enable researchers to communicate with the drones through a relay from the cabled observatory and also provide short-range communication with research ships and aircraft.

Satellite remote sensing has become an important tool in oceanography and fisheries monitoring (e.g. Santos 2000, Blondeau-Patissier et al. 2014), but ground-truthing of data is critical for accurate

interpretation and modelling (Congalton 1991). The Southeast Atlantic Coastal Ocean Observing System (SEACOOS) included a pilot study of the potential for integration of satellite remote sensing and ocean observation systems (Nelson & Weisberg 2008), which found that coordination among data providers, management, modellers, and users was a critical bottleneck. Field validation efforts are important but expensive and difficult to coordinate. Observatory-based drone sampling can also be used to enhance satellite remote sensing programs by conducting some types of coordinated field validation sampling. Ecosystem observatory-based drones could provide a more cost-effective tool for obtaining oceanographic data for a wide range of measurements from sea surface temperature to primary production in order to tune satellite data interpretation and modelling. Some drones could be equipped with a payload of specialised equipment for specific projects, such as a chlorophyll fluorometer, or for deployment of sonobuoys, drifters, and expandable vertical profilers. Thus, integration of ocean observatories with remote sensing satellite systems can improve the accuracy of spatial mapping of large-scale environmental conditions.
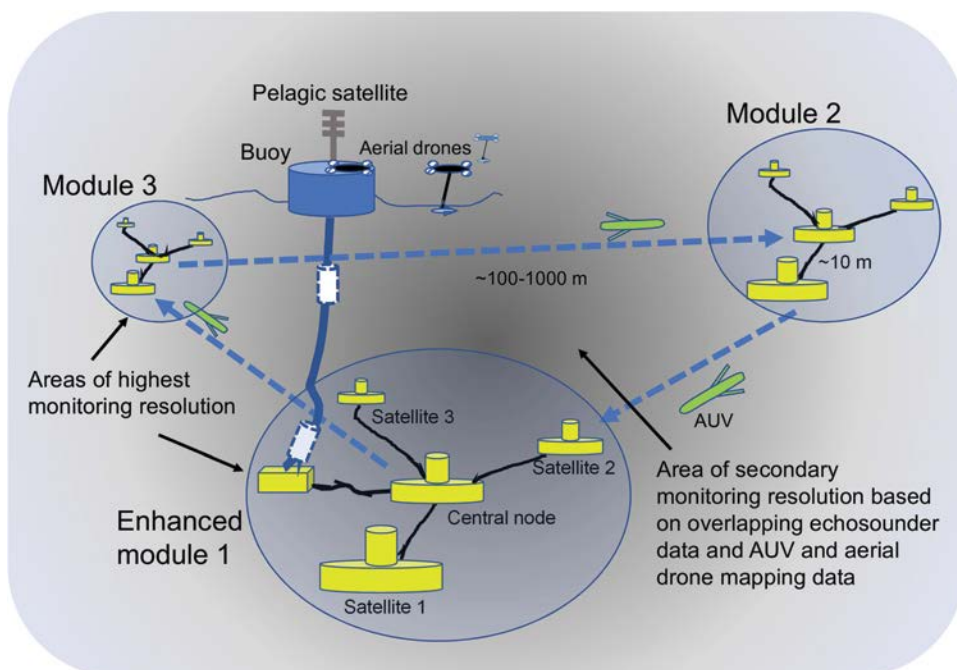
Ecosystem observatory module clusters and networks

To be able to provide meaningful ecological data at different spatial scales (i.e. from local conditions to geographic areas) accounting for key factors such as habitat heterogeneity along a coenocline (e.g. Rex & Etter 2010, Lecours et al. 2015, Zeppilli et al. 2016), local modules should be associated into a spatial hierarchy of clusters and networks, called ecosystem observatory module clusters and ecosystem observatory module networks. Adopting a highly reproducible module design for observatories should reduce costs and allow for replication of data at different locations.

The spatial configuration of modules within clusters and clusters within networks is critical to providing spatial and temporal overlap among the various observation technologies required for cross-referencing and validation. Experiments are needed to determine the optimal configuration under local conditions. In these experiments, a minimum of three modules within clusters and three clusters within networks are needed to ensure at least minimal coverage and overlap. A cluster design of three modules separated on the order of hundreds of metres would be an effective way to scale up data collection from individual sites to habitat (Figure 6). At distances of hundreds of metres, bioacoustics coverage among the modules in a cluster would overlap to provide the ability to estimate water-column biota density in a homogenous fashion over a large area (0.5–1 km^2 or more; Figure 6) and to quantify the effect of module structure and operations on biota occurrence and behaviour. Cross-reference data from each module would greatly improve the accuracy of the identification and density estimation of biota within the cluster area, but well outside of individual modules, and allow for detailed benthic habitat mapping over the larger area encompassed by the cluster. Such coverage would facilitate accurate faunal abundance and density estimates necessary for fisheries and other applications and reduce observatory bias on measurements due to attraction and avoidance responses of organisms to the observatory structures.

Finally, advanced AUV capabilities would enable the AUV to be used to map habitat and benthic biota distributions between and among modules within the cluster. In some scenarios, all modules within a cluster might share one AUV that patrols among them and can dock at any module. In other scenarios, AUVs provided by each module would provide the cluster with multiple AUVs for more rapid and detailed mapping. Observational data obtained from the AUV tracks can further increase our ability to validate the identity of bioacoustic and passive acoustic targets outside of the modules but within the cluster area. In some cases, AUVs might be programmed to investigate passive acoustic or echosounder targets beyond the range of the other observational instruments within a cluster area to improve identification and density estimates. Where feasible, an observatory cluster would include one module equipped with a pelagic satellite that could provide drone support for the entire cluster to enhance studies of vertical connectivity from the surface to the benthos at the cluster location.

Figure 6 Schematic illustration of an ecosystem observatory module cluster designed to provide synoptic data on differing spatial scales within the cluster area. Three or more modules should be arranged in geometric clusters to allow detailed spatial comparisons within a larger spatial array. Spacing between modules is dependent on local conditions, AUV range, and optimal echosounder coverage. Clusters with module spacing allowing for overlap among bioacoustics echosounders, with greatest overlap in the centre of the cluster, enable highly accurate identification of water column organisms over a large spatial area. One or more AUVs would be designed to navigate among modules in the cluster to map habitat and organism distributions within the cluster area and provide additional ground-truth data for organism identification based on their target strength. Demersal and benthic organism and habitat mapping resolution is greatest around the modules but is also high within the wider area encompassed by the observatory module cluster.

Sentinel system

Observatory systems combining multiple EOM clusters along a coenocline form a 'sentinel system' observatory network (Figure 7). A minimum of three EOM clusters (i.e. nine modules arranged in a spatial hierarchy) would be needed to elevate the monitoring network from examination of local habitats to ecosystems and large geographic regions (Figure 7). It should be clear that such a sentinel system would ideally be one component of a larger monitoring effort that coordinates data from conventional ship, satellite, buoy-based, and animal-borne survey programmes. For example, establishing a sentinel system composed of clusters (each of which provides high-resolution monitoring on a scale of 0.5–1 km^2) in the upper and lower sections of a major estuary (e.g. the Chesapeake Bay) and another on the continental shelf just offshore would be effective at monitoring movements of coastal fishes that utilise the estuary as seasonal feeding or nursery grounds. Similarly, deployment along coastlines can provide information on the timing of seasonal movements of fishes and habitat connectivity along migration corridors. Sentinel systems would be useful to monitor migration patterns of fishes and invertebrates by documenting first detection, last detection, and residence period at different points along the gradient. Such a system would also be useful for monitoring the invasion of organisms into new territories (Juanes 2018) by placing clusters along the predicted invasion pathway.
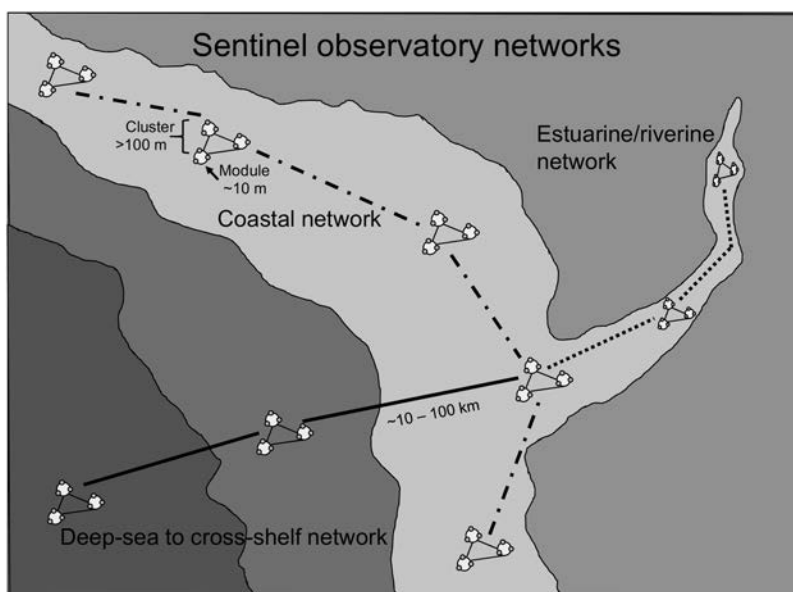
Figure 7 Sentinel ecosystem observatory networks (not to scale) composed of multiple module clusters distributed across a habitat gradient or coenocline occurring from estuarine/riverine areas to coastal zones and the shelf, down to the deep-continental margin of the slope and abyssal plain.

Ecosystem surveillance, modelling, and forecasting

Fixed and mobile platforms allow for an experimental approach to the study and monitoring of ecosystem functioning at different spatiotemporal scales (over kilometres and years). The combination of stereo video, acoustic imaging, and echosounder imaging provides the ability to quantify abundance, size, and biomass of organisms over a wide size range, as well as to identify multiple types of behavioural reactions to natural or artificial stimuli. In addition, the simultaneous acquisition of biochemical and oceanographic data can inform researchers of potential causative factors for observed behaviour and abundance patterns. However, automatic processing of the high volumes of data generated by the observatories would be essential. Automated detection and classification methodologies based on the various observation technologies are rapidly advancing (e.g. Allken et al. 2018, Juanes 2018, Marini et al. 2018b). However, we suggest that the concept of an ecosystem observatory user data interface would greatly enhance the application, testing, and quality control of detection algorithms by providing a simple computer interface for user-aided system learning (see 'Cyber developments in support of monitoring networks' section subsequently; Figure 8).

Ecosystem observatory networks can be used to estimate local species abundances derived from the image-based identification and counting of individuals, made possible through integration of multiple observation technologies (see Figures 4 and 8). In addition, the methodology provides an ability to develop size-class frequency data and species biomass estimation based on the estimated size and counts of individuals (Durden et al. 2016b). Cross-referencing of data from ROV, crawler, AUV, and echosounder data with validation data from each module provides the ability to obtain standardised abundance and biomass data for the entire observatory network area (Figures 4, 6 and 7). Simultaneous monitoring of a large suite of environmental factors such as temperature, turbidity, chlorophyll concentration, and other biochemical factors, together with fine-scale temporal and spatial distribution patterns of organisms, would provide important data on environmental regulators of species population structure and behavioural patterns. Temporal patterns in species
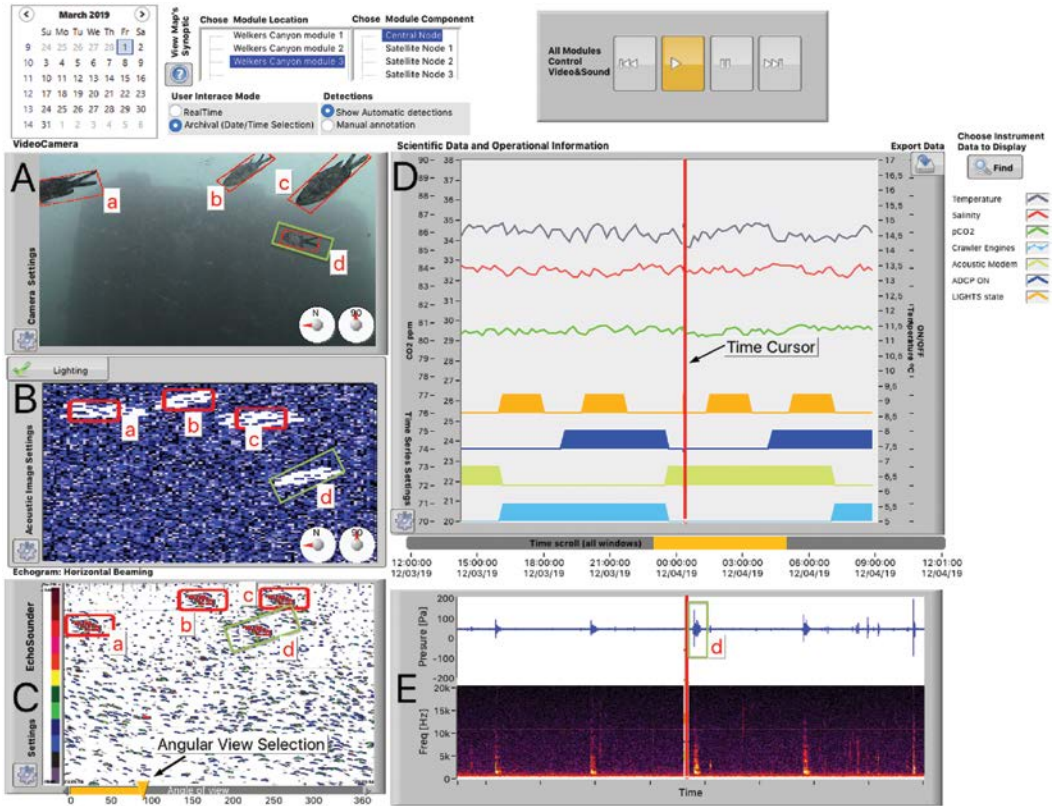
Figure 8 Hypothetical user interface of data from an ecosystem observatory module, composed of the central node plus the three satellites. All data windows (A–E) play in time simultaneously, as indicated by the time cursor in the scientific data and passive acoustic sound windows (D–E). Video, acoustic image, and echosounder displays show only the portion of the 360° area surrounding the module which has been selected by the user, with the angular view selection bar common to all three (below C). However, when the playback is paused, the user can simultaneously scroll through all 360° surrounding the module in the video, acoustic image, and echosounder windows (A–C). The overlapping observation modalities and integrated visual displays are a powerful tool for examining correspondences among environmental conditions, observatory operations, and animal behaviour. When autodetection is available for one or more of the observation technologies, the user can validate detections in other windows, for example, targets 'a–d' are detected in video (A), acoustic image (B), and echosounder data (C). Data from each instrument can then be compiled to provide the most accurate information on species identification, 3-dimensional location, size, and target strength together with environmental conditions at the time of detection. In addition, sound source targets localised by the passive acoustic array and shown in the sound window (sound labelled 'd' in E) can be identified by its corresponding location in the other windows (A–C).

richness, abundance, biomass, size-class structure, and role of environmental regulators within an observatory network, supplemented with data from other monitoring programmes, could provide the raw data needed to develop ecosystem modelling and forecasting programs for the habitat or region surrounding the network.

Data from multiple observatory networks could then be linked to make comparisons among areas, populations, and environmental regulatory factors to develop regional and ultimately global monitoring programmes. Spatially representative and long-term monitoring provides the ability to distinguish between population/community regulation by repetitive phenomena (e.g. rhythmic abundance variations due to seasonal environmental changes and ontogenetic migrations, spawning

migrations; Aguzzi & Company 2010, Aguzzi et al. 2011a) from long-term (decadal and longer) processes such as shifts in species distributions due to climate change and changes in resource exploitation. If the information obtained from the observatory network system and associated modelling and forecasting programs is automated, it may be possible to develop ecosystem alarm protocols that detect anomalies in ecosystem parameters that might signal undesired environmental states such as impending population collapse of keystone species.

Integration of benthopelagic networks with animal-borne technologies

Cross-connection of ecosystem observatory module networks with free-moving animal-borne sensor (ABS) technologies can also be envisaged. Inclusion of technology into the module design that allows communication with independent ABS (Figure 3) is particularly promising for obtaining data on animal behaviour as well as data from animal-borne environmental monitoring programmes (see, for example, the Animal Telemetry Network Implementation Plan 2016–2021, NOC 2016). Presently, data loggers connected to animals are getting ever more miniaturised (e.g. Nassar et al. 2018) and still primarily store oceanographic information about travelled seascapes (Wilmer et al. 2015, Fehlmann & King 2016) but only limited ecological information on intra- and interspecific interactions experienced by the traveller. This weakness is being corrected in part by the development of animal-borne cameras. Animal-borne video collection directly allows the derivation of ecological information based on what is seen by individuals during their displacements (Moll et al. 2007). Moreover, the progressive miniaturisation of implant components will eventually allow camera installation on animals of very different sizes (although filming may be constrained at night or in deep water).

If both the observatory module and animal-borne technologies are capable of two-way communication, then data-intensive video-sampling by animal-borne technologies can be enhanced by dumping data to the observatory, thereby freeing up data storage and increasing their useful lifespan. Similarly, modules can be tuned to receive telemetric data from tagged animals freely moving across depths and basins (Hussey et al. 2015). This cross-communication can complement the monitoring capability of already existing pelagic and coastal-shallow networks (e.g. OTN 2019). Presently, for the development of technological tracking of epibenthic animals carrying an acoustic emitter, displacements can be measured into a network of moored receiving hydrophone stations (Rotllant et al. 2014, Tuck et al. 2015). Such development is necessarily limited by the range of hydrophone detection capabilities and could be potentially expanded when animal tracking is assisted by moving platforms, delivering real-time data on their positioning. Tracking expansion is presently pursued by using wave-gliders and AUVs (e.g. Lin et al. 2016, Masmitja et al. 2017).

Cyber developments in support of monitoring networks

Networks of fixed and mobile units for coordinated ecological monitoring require not only hardware development but a concomitant suitable cyber architecture for data communication, processing, storage, and visualisation of interrelated multidisciplinary data of different types (Florea & Buiu 2017). Moreover, cyber infrastructures should provide proper 'virtual research environments' (VREs), which can be described as online collaborative environments that allow open access and program development for best science practices (Martin et al. 2019, Morris et al. 2019, Pearlman et al. 2019). These VREs should be built on top of interrelated multiparametric data access platforms similar to those developed for the Ocean Networks Canada Web services application program interface (API) and Sandbox tool set (Rempel & Cabrera 2018). It is critical that such VREs serve as libraries of multiparametric data (e.g. imaging, acoustics, physical, biochemical) derived from the observatories, as well as open-source automated classification and statistical analysis programs.

As ecology researchers increasingly deploy embedded sensor networks, they are being confronted with an array of challenges in capturing, organising, and managing large amounts of data (Borgman et al. 2007). User navigation into network data banks and analysis capability requires the design of efficient interfaces between people and computers. Such a design should include all steps of information flow, from data collection at each sensor and platform to its global elaboration. This type of information flow framework is well described by ecoinformatics (Michener & Jones 2012), which arose from the need to integrate environmental and information sciences to provide the language tools and standardisation practices necessary to access and analyse massive amounts of heterogeneous data (e.g. by developing data banking).

Data integration would include several disciplines related to information technology that allow control of data collection, processing, integration, and use in VRE systems by multiple sensor technologies. The sensor web enablement (SWE) approach defined by the Open Geospatial Consortium (OGC) standards (Del Río et al. 2018, Chaturvedi & Kolbe 2019) is a low-level specification of functionalities that allow any kind of compliant sensor to interact with other sensors, with human users, or with properly defined intelligent services. Networks of SWE-compliant sensors allow for a remote interaction by simply triggering them on and off or by changing their acquisition configuration in order to adapt the monitoring activities for specific purposes. The intelligent services capable of interacting with the SWE-compliant sensors are generally defined according to the Internet of Things (IoT) technology paradigm (Qin et al. 2016, Čolaković & Hadžialić 2018), which refers to the capability of making content and services understandable by devices without human involvement. To achieve this goal within the marine science and technology community, data science methodologies (Skiena 2017) based on artificial intelligence should be capable of extracting the relevant content from the acquired data, then using this content for interacting with the SWE-compliant observatory or for populating appropriate data repositories (e.g. the Copernicus or the SeaDataNet initiatives). For example, data acquired by SWE sensors and managed by intelligent services could be of the biophony (sounds of known fishes, cetaceans, birds, unknown biological sounds, etc.), the geophony (natural sounds like wind, rain, thunder, waves, etc.), and the anthropophony (noise from ships, seismic surveys, and the observatory itself), which would then be utilised by sound type classification software to document spatial and temporal patterns in sound occurrence and correlations between biophony and anthrophony to assess noise impacts. SWE sensors could similarly be used for biogeochemical data or visual data acquired by stand-alone devices capable of communicating the relevant acquired information (Marini et al. 2018a).

Since all marine monitoring networks are increasingly service- and end-user oriented, their data management cyber infrastructures are also being upgraded to retrieve, store, and process data in real time, acting as a cognitive system for data interpretation for humankind (Shenoi et al. 2015). Systems should enable any end-user worldwide to investigate ecological processes via interactive web interfaces, allowing navigation into banks of multiparametric 'big' biological and environmental data (Figure 8). Responses should be visualised in the form of synthetic graphic outputs, highlighting significant global trends and cause–effect relationships. Such visualisation would be based on high-level data science activities performed within VRE capable of allowing non-expert users to compose complex workflows based on tools with high technological and scientific content (Buck et al. 2019). Data output could be based on automated time series analysis (Aguzzi et al. 2012, Skiena 2017, Recknagel & Michener 2018) as well as on multivariate statistics, which would then allow modelling of biological responses to key environmental variables. The use of such powerful software tools on big biological and environmental data will transition ocean observatory systems from a largely observational to a more quantitative monitoring platform for ecological and fisheries applications.

Data flow management from multiple observation technologies

It is critical that data streams from all the observation instruments and sensors be synchronised and maintained as relationally integrated data that are interoperable with other observation networks

(e.g. the ONC's Oceans 2.0 program; ONC 2019). Data should be enriched with the appropriate semantic information that allows their retrieval by semantic-based search engines (Aguzzi et al. 2015a). A user annotating events in one dataset should be able to seamlessly populate the same annotation in all other data streams (Figure 8). For example, a user marking the location of a sound in the hydrophone recording should be able to locate the corresponding data position automatically in video, acoustic image, echosounder, and environmental datasets (e.g. 'd' in Figure 8). Although observatories currently provide metadata containing information on observatory instrumentation functioning performance, maintenance status and functioning history, data quality assurance and control, calibration, and other aspects (e.g. ONC 2019), this may not be sufficient for end-users who are not capable of cross-referencing all this information automatically, because it must first be downloaded and integrated by the users themselves.

A user interface that provides all module data integrated together in an interactive visual display would be a powerful tool for researchers (Figure 8). For example, a user viewing a video would immediately see not only environmental and other observational data but also the activity state of all instrumentation (e.g. lights on, rotary motor active, ADCP active, ROV thrusters on or off). Comparison of data from the overlapping 3-dimensional views in video, acoustic image, and echosounder windows provides the ability to cross-reference data to improve identification and measurement accuracy. For example, if a video detector identifies targets 'a' to 'd', its 'ghost' target can be displayed in the acoustic image and echosounder windows to look for matches or to compare with automatic detections in those datasets. That will help a user determine if some detections are valid or to identify unknown detection targets. The user could then download a dataset containing all the attributes of the target based on the different observation types as well as corresponding environmental and operational state data. Such information can provide valuable clues to understand species response to the observatory and potential biases in behavioural observations, in addition to providing data on biotic responses to environmental conditions and the raw data necessary to compile species abundance and volume density maps. The ability to download data seamlessly in these kinds of relational datasets is of the utmost importance to encouraging widespread utilisation of observatory data among scientists, resource managers, and educators.

Observatory integration within commercial development projects

Scientists around the world struggle to obtain funding for even small observatory systems. The cost of observatory infrastructure, such as the platform and dedicated data/power transmission cables to shore, often constitutes the largest expense and greatly limits observatory capabilities. Offshore development projects (e.g. telecommunication cables, wind farms, tidal/current turbines, and oil/gas platforms) provide a unique opportunity for advancement of ocean science if government and industry leaders have the foresight to integrate ocean observatory systems into offshore development design (e.g. Danovaro et al. 2017). It is hoped that current large scientific actions are being conceived at higher institutional levels to combine the two visions and design offshore energy systems that can provide both much-needed renewable energy and also much-needed ocean observatory systems (e.g. see DELOS and LoVe initiatives as reviewed by Aguzzi et al. 2019). Offshore energy development can provide platforms for many EOMs at a location and thus the ability to construct large EOM cluster networks capable of delivering an unprecedented view of underwater life to scientists, fishers, and the public. Further, because power and data cables are a necessary part of the energy delivery system, scientists could have a fully functional data transfer network to shore already in place. If commercial industries incorporated observatory systems into project design from the beginning, rather than post-construction, and consider the advantages of an improved public image, the cost of required environmental monitoring and mitigation would likely be more palatable.

Acknowledgements

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