EMERGING TECHNOLOGIES FOR NOAA OCEAN RESEARCH, OPERATIONS AND MANAGEMENT IN AND ECOSYSTEM CONTEXT

DRAFT REPORT OF THE ECOSYSTEM SCIENCE AND MANAGEMENT WORKING GROUP (ESMWG) TO NOAA SCIENCE ADVISORY BOARD

NOVEMBER 18, 2016

SUBCOMMITTEE AUTHORS

JAMES YODER, LEAD

DAVID FLUHARTY

JO-ANN LEONG

Introduction

Robotics, 'omics (encompassing genomics, transcriptomics, and proteomics), advanced and miniaturized sensors, and informatics are becoming important technologies for mission agencies, especially NOAA, operating in the marine environment. The purpose of this document is to highlight emerging technologies that have been proven in research laboratories, are commercially available, do not require significant additional development costs and are relevant to NOAA's mission related to marine ecosystems, including ecosystem-based natural resource management and protecting endangered and threatened species. These technologies have potential advantages to NOAA for providing more coverage in time and space with less human intervention, making more efficient use of large infrastructure assets including ships and moorings, thus offering the potential for long-term cost savings. NOAA personnel are currently involved in the development, testing and evaluation of these systems. Thus much of the appropriate expertise resides within the agency to help broaden the use of these technologies within NOAA. We illustrate the potential of the technologies using current examples primarily drawn from research applications. The priority for broader implementation within NOAA will depend on the importance and priority accorded to the potential applications of these and other emerging technologies, as well as the transition challenges, including capitalization costs and understanding the relation between measurements from new technologies with instrumentation currently in use.

1. 'Omics and NOAA

This section is based on literature review, discussions with eDNA scientists and presentations to the ESMWG by invited speakers: Kelly Goodwin, R.P. Kelly, Amy Apprill, and Linda Rhodes as well as a White Paper to the NOAA SAB (Lodge et al. 2016).

The most promising area of 'omics for NOAA is likely genomics, because the technology has advanced to the point that genomic techniques can be used to scan the marine environment for species and habitat conditions in ways that dovetail with a set of NOAA's core missions. In recent years it has become possible to use genetic information from the cast-off cells of living organisms to identify their location and to describe the organismal community present at a time and place. Thus, by using these techniques, NOAA's line offices may adapt ecosystem management measures to address management needs using this more comprehensive view of the composition of ecological communities.

Metabarcoding is now common in microbial studies and is becoming more common for eukaryotes. NOAA is already using eDNA, with the promise of bypassing the need for tissue samples (i.e., monitoring viruses to vertebrates from a seawater sample). NOAA already has multiple activities developing and applying these emerging technologies in each region. The ESMWG encourages these activities and points to potential research that can assist NOAA with its management missions.

An important NOAA focus is on monitoring using eDNA which identifies the presence or absence of any particular organism. Examples of this suite of applications include:

- Monitoring for conservation and management of fish, coral and others organisms (Shafer et al. 2014).
- Using eDNA and genomic sensors to increase temporal coverage of target species and ecosystems and reduce ship reliance
- Assessing sea food safety e.g., understand pathogen dynamics and assess organism health.
- Examining human-ecosystem interactions (e.g., ecological diversity along an urbanization gradient; Kelly et al. 2016).

One obvious application with potential promise to NOAA is the use of metabarcoding in fisheries surveys, with the potential to improve ecosystem observations, increase efficiency, decrease sample backlog, increase temporal resolution and decrease ship time. Consistent with these goals, a pilot study (NOAA-CalCOFI Ocean Genomics Project) for applying metagenomics to NOAA needs is underway as part of the CalCOFI sampling program. The purpose is to better understand how the ecosystem will respond to large scale forcing caused by multiple stressors including warming and acidification and apply the knowledge to ecosystem and fisheries management. The challenge is to distill massive amounts of information into indices for utilization in ecosystem models.

A promising technology for monitoring the microbial component of marine ecosystems is the development of the Environmental Sample Processor (ESP) – robotic application of genomic sampling. Developed by the Monterey Bay Aquarium Research Institute and now built and marketed by McLane Research Laboratories (http://www.mclanelabs.com), the ESP can monitor ocean and coastal waters for harmful algal blooms with species identification using PCR and toxin detection using immunoassay. Reducing the energy requirements of the onboard technology, the refinement of techniques for nucleic acid detection, and further development of sensor communication are required. Also, equipment costs and the requirement for trained personnel limit ESP deployment by NOAA. Nevertheless, ESP has tremendous potential for biological sensing, both independently and in concert with other sensing technologies.

2. Robotic Vehicles, Autonomy and Artificial Intelligence (RVAAI).

RVAII in the form of driverless cars and trucks promises to revolutionize the U.S. and global transportation industry. Similar changes are occurring in the way we sample and study the ocean in the form of gliders, various motorized (propelled) surface and underwater vehicles, and drones. In some cases, the vehicle and its autonomy are the new development, whereas in other cases the sensors are providing the new tool related to marine ecosystems.

Gliders, which are basically ARGO floats with wings, are in common use for slowly measuring sawtooth profiles of temperature and salinity to depths of up to 1000-m. Like ARGO floats, vertical glider movements are controlled by buoyancy changes, and thus require very little energy. As a result, gliders are excellent tools for extended missions (months). As an example, the Slocum G2 Glider marketed by Teledyne Webb Research has an endurance of up to 365 days operating to depths of 4-200m or as deep as 1000-m when equipped with the deep water buoyancy "engine".

The use of gliders for temperature and salinity measurements is well established. NSF, Navy and NASA are also developing the potential of gliders for ecological and biogeochemical measurements Applications are limited by the requirement that sensors need to be small and not require large amounts of power. There are many sensors, however, that do meet these requirements:

- phytoplankton concentration as determined from spectral backscatter and absorption, chlorophyll fluorescence and visual/holographic imagery;
- phytoplankton diversity from spectral backscatter, visual/holographic imagery and simple "omics" applications;
- phytoplankton rates from the kinetics of fluorescence, photoacoustic and stimulated oxygen kinetics;
- zooplankton abundance from acoustic backscatter and imagery;
- zooplankton and fish diversity from broadband acoustics, imagery and simple "omics";
- and acoustic receivers to track higher trophic levels that have been tagged with an acoustic tag.

As an example, passive acoustic measurements from a glider-based system were used to classify the calls of 4 species of baleen whales during a 3-week study in the Gulf of Maine and illustrate a NOAA-related application (Baumgartner et al. 2013). Sensors on board the gliders detected 25,000 fin, humpback, sei and right whale calls and correctly identified the correct whale species 86% of the time for the humpback, right and fin whales. The right whale sightings were reported to NOAA which took action to reduce the chance of a ship strike of this endangered species. The study demonstrated "that autonomous platforms can conduct real-time passive acoustic reconnaissance to improve the efficiency of aerial or shipboard visual surveys for either scientific or management applications." (Baumgartner et al. 2013). Passive acoustic recorders on gliders are part of the U.S. Northeast Passive Acoustic Sensing Network (NEPAN) which provides location data on acoustically active marine mammals and fish species. NEPAN covers the northwest Atlantic from the northern Gulf of Maine to the New York (Van Parijs and others 2015).

The ESMWG also heard a presentation by Dr. Whitlow Au who reported on results from Passive Acoustic Recorders/Monitors (PARs or PAMs) to monitor the environment for marine mammals. PAMs are in common use by offshore energy companies, particularly in European waters to ensure the safety of marine mammals during operations. Dr. Au described the results of a study at Station Aloha off Hawaii in which moored PAMs recorded the sounds of sei, blue, minke and fin whales. The observations indicate that

Hawaiian waters are a likely location for over-wintering of these species that spend the summer at higher latitudes (Oswald et al. 2016). The seasonal time series of recorded sounds suggests the possibility, that like humpbacks, these 4 species may breed and give birth during winter months in the comparatively warm waters off Hawaii. .

Vehicles propelled by motors, wave action or sails either on the surface or underwater are other examples of RVAAI technology. For example, the U.S. Navy has funded development and fleet deployment of REMUS vehicles. REMUS vehicles are torpedo-shaped propeller-driven autonomous submarines built by the Hydroid Division of Kongsberg Maritime (https://www.km.kongsberg.com/). The standard payload consists of an Acoustic Doppler Current Profiler (ADCP), side scan sonar and conductivity, temperature, depth sensor (CTD). For biological/ecological missions, REMUS vehicles can carry sensors to detect particles (optical backscatter), phytoplankton chlorophyll (fluorometer), bioluminescence, downwelling/upwelling spectral radiance (radiometer), various types of cameras, plankton pump, and video plankton recorder. Sensors to detect the ocean acoustical environment including the sounds of marine animals have also been deployed on REMUS vehicles. They have been used to track large marine animals, e.g. great white sharks (Skomal et al. 2015) that have been acoustically tagged.

Although highly capable for comparatively short-term missions (days), REMUS vehicles are also expensive. Smaller and less expensive motorized underwater vehicles are becoming commercially available. *Riptide Autonomous Solutions*, LLC markets a vehicle as small as 0.6-m in length weighing 5.5 kg. The small size currently limits the instrument payload options; although one assumes that the trend towards smaller instruments will soon provide suitable instruments to deploy on the smaller UUVs making them increasingly useful for ecosystem studies and management applications.

Saildrone, Inc. (http://saildrone.com/) manufactures robotic sailboats that can carry standard oceanographic sensors for surface measurements of physical and biogeochemical properties, and also has been used to carry a SIMRAD acoustic fish stock assessment device (wide band transceiver) for subsurface measurements of fish abundance. A Saildrone equipped with this acoustic device was recently successfully deployed by NOAA near the edge of the retreating Arctic ice cap to map the distribution of pollock (Markoff 2016). The Saildrone looks like a high-tech sailboat with a carbon fiber sail that catches the wind. The autonomous sailboat is controlled via satellite link to an operations center.

Liquid Robotics' Wave Gliders (http://www.liquid-robotics.com/) use the difference in motion between the ocean surface and a few meters below the surface to convert wave motion into propulsion. Wave Gliders are also equipped with solar panels to provide the energy needed to power oceanographic instrumentation and operate the vehicle. Wave Gliders can tow subsurface payloads weighing up to 500 kg. One mode of operations is for the Wave Gliders to relay data to ships or to shore via their satellite communication link from vehicles that remain below the surface, although with acoustical links to the Wave Glider. Liquid Robotics partners include Chelsea Technologies which specializes in optical, acoustic and physical sensors measuring temperature, conductivity, hydrocarbons, fluorescence, water clarity and primary productivity. *Jetyacks* (Sherwood, 2013), currently under development, are an example of a motorized surface autonomous vehicle (kayak) providing measurements in shallow water using down-looking sensors.

3. Imaging.

The applications of *in situ* digital imaging of marine organisms covers a wide range of spatial and temporal scales; from microbes to benthic macrofauna (Sieracki et al. 2009). Advanced data handling software (Informatics) are required to efficiently and effectively archive and analyze the imagery (Leow et al. 2015). Image analysis software is now available that can identify some phytoplankton, zooplankton and benthic organisms to genus and provide highly accurate and precise counts within the taxa. Systems currently in use are towed, moored or used in shipboard laboratories. Compared to many physical and chemical *in situ* sensors, imaging systems tend to be complicated, expensive, and have high power requirements. One assumes that as the technologies evolve (and technologies are comparatively young compared to standard oceanographic sensors for temperature, salinity, fluorescence, beam transmittance, etc.), the systems will become simpler and cheaper.

The *Imaging FlowCytobot* is an automated submersible imaging flow cytometer coupled to a digital camera for sustained and continuous observations of plankton species abundance (Olson et al. 2003, Sosik et al. 2003). Software for automated taxonomic classification of phytoplankton has been developed to process the time series of imagery providing a powerful tool for studying phytoplankton bloom dynamics (Sosik and Olson, 2007). The instrument is commercially marketed by McLane Research Laboratories, Inc.

An application of the *FlowCytobot* of particular relevance to NOAA's mission is the early detection of harmful algal blooms (HABs). In 2011, an I*maging FlowCytobot* deployed on the Texas Coast at Port Aransas provided early warning of 6 different blooms of *Karenia brevis*, a dinoflagellate known to cause human illness owing to neurotoxic shellfish poisoning (Campbell et al. 2013). An automated processing system was able to notify Texas State agencies within 4 hours of sample collection. In response, the state agencies closed oyster harvesting preventing any human illness.

HabCam is a towed system to take digital images of the seafloor that are transmitted back to a ship-based system that processes and stores the imagery. It is based on 16 bit color machine vision digital cameras and high speed strobes. It includes a machine vision interpretation of the imagery to classify both the organisms in the field of view, as well as the seafloor habitat in which they are living (Gallager et al. 2014). The instrument can be towed and can now be deployed on a REMUS 600 AUV. The towed version is flown 1-3 m above the bottom (http://www.whoi.edu/oceanus/feature/habcam).

Results have been compared and calibrated using joint tows of a NOAA survey dredge and HabCam primarily on the Georges Bank scallop fishing grounds. The HabCamV4 project is developing an operational system for NOAA to routinely assess the abundance of scallop stocks and demersal fish in relation to their type of habitat.

Other Technologies.

New NASA and ESA satellite missions recently launched or in development will significantly augment current capabilities. ESA's Sentinel-2 and Sentinel-3 missions provide higher spatial and spectral resolution than SeaWiFS, MODIS and VIIRS. The new capabilities and algorithms will significantly improve, in particular, the ability to image coastal environments, including benthic habitats such as sea grass beds and coral reefs. Space-borne LIDARS offer an approach to generate profiles of particle scattering (which is related to phytoplankton density) and thus resolve vertical structure. They also offer the capability to look through light cloud cover and to estimate phytoplankton abundance at high latitudes during seasons of low or no incident solar irradiance. CubeSats or other small satellites offer the potential for comparatively inexpensive space platforms for ocean remote sensing. A sensor to measure ocean color radiometry and deployed on a CubeSat is under development (https://www.clyde.space/our-missions/11-seahawk) . Small drones launched from ships are now being used to observe and study marine mammals. Highly capable small drones are anticipated for the future and should provide a significant new platform to observe many large marine organisms, including those that spend part of their life on sea ice.

Conclusion and Recommendations

In conclusion, new sampling platforms, instrumentation and data handling techniques are rapidly changing how ocean scientists study and manage marine ecosystems and natural living resources. NOAA laboratories and scientists are involved with many of the emerging technologies, although the emerging technologies described here are not fully implemented within the agency. The priority for broader implementation will depend in part on the transition challenges, including capitalization costs and understanding the relation between measurements from new technologies with instrumentation currently in use.

NOAA is developing the capacity to utilize the multiple applications of 'omics relative to its multiple missions. NOAA should continue to invest in these technologies and their applications. However, in so doing NOAA should take advantage of commercial / private development of sensors, because this area is rapidly advancing and costs are decreasing and quality is increasing. For example, it is not necessary for NOAA to invest in its own databank of eDNA as long as it can benefit from other efforts in this regard. NOAA should continue its investment and look to develop new applications for eDNA monitoring and analysis. ADOPT NOW.

The number of types and applications for unmanned robotic vehicles are exploding and include subsurface floats, gliders and propelled vehicles, as well as vehicles that make observations from the surface of the ocean and the air above it. Sensors for these vehicles are also developing rapidly and now include different instrument approaches for determining the presence, types and abundance of some marine organisms ranging from microbes to marine mammals. Many believe the future of ocean measurements will rely heavily on robotic vehicles and new sensor technologies, including measurements related to living marine resources. ADOPT NOW.

Sophisticated imaging systems, including microscopes and digital cameras, for the laboratory and for use on board oceanographic ships have been in use for many years. These same systems are now being deployed *in situ* on moorings or towed behind oceanographic ships providing much more capability. They offer the potential to fill time and space measurement gaps of important species. IMPORTANT, WATCH FOR FUTURE APPLICATIONS.

Automated measurement systems are capable of collecting data at rates far greater than can be efficiently analyzed using traditional methods that depend heavily on human involvement. Sophisticated data analysis techniques and personnel trained to use them are required to effectively utilize the high data volume of new sensing systems ADOPT NOW.

Passive acoustic sensors on moorings and mobile platforms, as well as new sensors for new orbital and suborbital platforms including ship-launched drones, aircraft and satellites are coming on line and are adding to our ocean observation capabilities. IMPORTANT, WATCH FOR FUTURE APPLICATIONS.

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