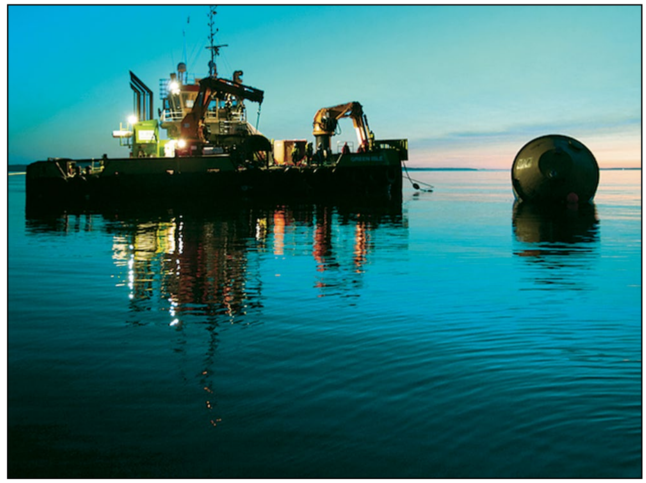

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Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices

Oceanographic processes define the marine environment: the flow of water determines the concentrations of dissolved gases and nutrients, transports sediments, and maintains the habitats and water quality that support marine organisms and healthy ecosystems. Important physical processes in the ocean include, but are not limited to, tidal circulation and basin flushing, wave action, local and basin-scale ocean currents, temperature and salinity gradients, sediment transport forming and shaping coastlines, and the exchange of heat and dissolved gases at the air-water interface. Harnessing energy with marine renewable energy (MRE) devices has the potential to affect these processes in both the nearfield (within a few device lengths) and the farfield (farther from the device, from the scale of multiple devices to the scale of an enclosed basin) by removing energy from the system, changing natural flow patterns around devices, and/or decreasing wave heights.

7.1.
IMPORTANCE OF THE ISSUE

MRE devices are most commonly sited in locations that feature high-energy densities where there is potential to extract energy. Channels that are constricted by depth and/or width increase water velocity and flow rates and may be well suited for harnessing tidal energy. The energy and configuration of waves are dependent on the fetch over which the wind can generate waves, the configuration of the continental slope and shelf, and in some cases, the geometry of the incident coastline. Ocean currents are formed along continental boundaries, driven by the rotation of the Earth, temperature gradients, and global winds, with narrower focused currents on the western side of ocean basins (western intensification). These are the regions where MRE devices may be able to most effectively harness energy from the ocean (Yang and Copping 2017). However, some areas may be too energetic for successful deployment and operation of devices, particularly in tidal areas characterized by high levels of turbulence (Chen and Lam 2015).

While the blockage of natural flow caused by tidal turbines is not as significant as hydropower dams and tidal barrages, tidal turbines will reduce the tidal range or the flushing of contaminants from an enclosed coastal system, but the effect will almost certainly be negligible until large arrays are deployed and operated (De Dominicis et al. 2017; Nash et al. 2014). Tides are a primary driver of sediment transport in enclosed basins, moving and suspending sediments that shape seabed morphology and support nearshore habitats. In addition, tidal currents play a role in water column mixing, changing the nutrient concentrations and plankton aggregations, and transporting fish and invertebrate larvae.

Wave energy converters (WECs) have the potential to alter wave propagation and under-currents, thereby affecting natural processes such as the transport of sediment in coastal waters and the shaping of coastlines. The transport of sediments supports the formation and protection of beaches and other coastal features (González-Santamaría et al. 2012), but can also lead to the erosion of shorelines and destruction of coastal infrastructure (Caldwell 1967). Waves are also responsible for vertical mixing of salinity, temperature, suspended sediments, dissolved nutrients in the water column, and plankton, further supporting marine life.

Ocean currents (e.g., the Gulf Stream current in the North Atlantic Ocean) are responsible for the transport of organisms and nutrients worldwide. Large arrays of ocean current turbines may have the potential to slow or alter the direction of ocean currents (e.g., Haas et al. 2014).

Large-scale MRE deployments have the potential to disrupt natural processes driven by tides, waves, and ocean currents. Yet these disruptions need to be viewed within the context of the ocean as a rapidly changing system, comparing the magnitude of potential disruptions caused by MRE development to the natural variation of key parameters in the marine systems.

7.2.
SUMMARY OF KNOWLEDGE THROUGH 2016

Changes in oceanographic systems caused by single MRE devices or small MRE arrays (~20 MW or less) are likely to be small compared to the natural variability of the system (Robins et al. 2014). In the absence of large-scale arrays, insight gained into the changes in the oceanographic system has relied on numerical model simulations to estimate potential farfield effects. These models need to be validated, but the scarcity of oceanographic data about these high-energy environments and the scarcity of device deployments worldwide make model validation impossible at this time (Copping et al. 2016).

As of 2016, studies that attempted to measure oceanographic conditions before and after deployment and operation of MRE devices were limited (Copping et al. 2016). However, many numerical models had been developed to study energy removal and changes in flow around MRE devices. Modeling investigations of the effects of tidal energy generation saw considerable advances prior to 2016, with the placement of economically and socially reasonable numbers of turbines for an estuary or coastal embayment (Martin-Short et al. 2015; Yang et al. 2014), more accurate modeling of sediment transport processes (Fairley et al. 2015; Robins et al. 2014; Smith et al. 2013), and the inclusion of water-quality constituents (Wang et al. 2015; Yang and Wang 2015). Although the complexity of wave regimes and the number of different WEC designs under development posed challenges to wave modeling, numerical models have provided insight into beach erosion profiles (Abanades et al. 2014) and nearshore changes (Chang et al. 2014).

As of 2016, a small number of field and laboratory studies on the changes in oceanographic systems caused by MRE devices had been conducted. Research in the Bay of Fundy, Canada used natural variability as a proxy for the perturbations caused by tidal devices, to look at the changes in sediment dynamics and deposition in tidal creeks (O'Laughlin and van Proosdij 2013; O'Laughlin et al. 2014; van Proosdij et al. 2013). Experiments carried out in a flume, using a small-scale turbine and an artificial sediment bed, used simulated field conditions and identified the characteristics of erosion (Ramírez-Mendoza et al. 2015).

By 2016, significant progress had been made toward understanding and evaluating the potential effects of MRE devices on natural systems, yet five specific needs remained (Copping et al. 2016):

- validation of models with more field measurements around deployed devices
- reduction of model uncertainty with targeted research on turbulence
- variation of model inputs to account for differences in device designs
- creation of better linkages between the nearfield and farfield effects of MRE devices
- evaluation of the cumulative effects in relation to natural variability and anthropogenic activities.

7.3. KNOWLEDGE GENERATED SINCE 2016

Literature that advances the state of the science relative to changes in oceanographic systems is summarized here by field, laboratory, and modeling studies. Although a substantial body of literature focuses on power extraction potential and resource characterization for wave and tidal energy, only studies that explicitly address the environmental effects of MRE devices are included. Studies of the turbulence downstream of offshore wind turbines that have monopile foundations have been conducted (Baeye and Fettweis 2015; Miles et al. 2017; Rogan et al. 2016; Schultze 2018), but a structure spanning the full water column is not representative of MRE devices. Instead, future studies conducted around floating offshore wind foundations will be valid analogs to inform MRE deployments.

7.3.1. FIELD STUDIES

Field studies have focused on measuring changes in flow and turbulence near MRE development sites to provide for the calibration or validation of numerical models. As of 2020, few field studies have measured the effects of MRE devices, because potential changes are unlikely to be measurable within a system's natural variability for the current size of deployments (Petrie et al. 2014).

The greatest number of MRE devices worldwide has been deployed and tested at the European Marine Energy Centre (EMEC) in the United Kingdom (UK) but only a few projects have focused on measuring changes in oceanographic systems. Using the Flow, Water Column and Benthic Ecology (FLOWBEC) platform, Fraser et al. (2017) measured velocity in the wake of the bottom-mounted foundation for a tidal turbine to quantify turbulent interactions with the seabed. Compared to nearby control measurements, observations showed a 31 percent decrease in flow velocity and a 10–15 percent increase in turbulence intensity over two days of measurements. As part of the Reliable Data Acquisition Platform for Tidal (ReDAPT) project, two instrumentation platforms were deployed to characterize the EMEC Fall of Warness Tidal site and monitor flow and wave fields around a 1 MW Alstrom DEEPGEN IV tidal turbine (Sellar and Sutherland 2016; Sellar et al. 2017). Analyses of flow velocity and turbulence highlighted site-specific differences between ebb and flood tides, which can be used to optimize power production while minimizing likely environmental effects (Sellar et al. 2018). Wake recovery measurements around a deployed river turbine in Alaska, United States (U.S.), showed that the wake was persistent and did not show significant recovery downstream of the turbine (Guerra and Thomson 2019). Observations around deployments of three CETO5 point-absorber WECs off Perth, Australia, between November 2014 and December 2015, supported model predictions of reduced wave height leeward of the devices (Contardo et al. 2018). Key findings included that wave height reductions in the swell band were comparable to those in the wind-sea band, observations were greater than those simulated by the model, and some of the differences in the local wave climate were attributable to natural variability at the site. Turbulence was also measured at potential tidal extraction sites (Garcia Novo and Kyozuka 2019; Togneri et al. 2017). The results of these field studies inform numerical models that assist with device design and siting, but they also have implications for how MRE devices may affect the nearfield and farfield mixing of water and entrainment of sediment within the marine ecosystem.

7.3.2. LABORATORY STUDIES

Studies conducted in flumes to understand wake recovery and turbulence due to tidal energy extraction can provide insight into the effects of MRE extraction (Mycek et al. 2014a, 2014b). Acoustic instrumentation was used to characterize flow and sediment transport in the wake of a scaled turbine, and the results indicated an increase in suspended sediment as far as 15 rotor diameters downstream, deposition along the centerline, and a horseshoe-shaped scour pit in the near wake region (Ramírez-Mendoza et al. 2018). Wake effects characterize the environment in the immediate area of turbines but might also have more distant effects with the development of large arrays. Close lateral spacing within an array causes significantly reduced velocity recovery, suggesting that spacing could be optimized for wake recovery (Nuernberg and Tao 2018). Three distinct wake regions were identified in a flume study (Ouro et al. 2019), which allowed for more detailed examination of changes that might affect the environment (Figure 7.1).

Experiments in wave tanks were also used to better understand the mechanics of reflected waves and the wave spectrum. Five cylindrical floating WECs were tested in a wave basin with different spacing, and it was determined that one wavelength distance apart reduced the changes in hydrodynamics (O'Boyle et al. 2017). Stereo-videogrammetry has been shown to demonstrate accuracy similar to wave gauges when measuring waves reflecting from walls (Winship et al. 2018).

7.3.3. MODELING STUDIES – TIDAL ENERGY

Until large arrays are deployed in the marine environment and field measurements are collected to determine whether MRE devices are affecting oceanographic processes, numerical models provide the best insight into what might occur as the MRE industry advances.

Literature addressing the effects of tidal energy extraction on the hydrodynamics of oceanographic systems has reported changes in velocity and residence times, without much elaboration about the environmental implications of such changes. Gallego et al. (2017) and Side et al. (2017) summarize a large collaborative modeling project, known as TeraWatt, that uses hydrodynamic, wave, and sediment transport models to examine the effects of tidal arrays in Pentland Firth and Orkney waters, UK, thereby demonstrating the application of numerical models to assessing the oceanographic changes in a system. Li et al. (2019) assessed the theoretical effects of a single tidal device on waves in shallow waters and showed a three percent reduction in wave

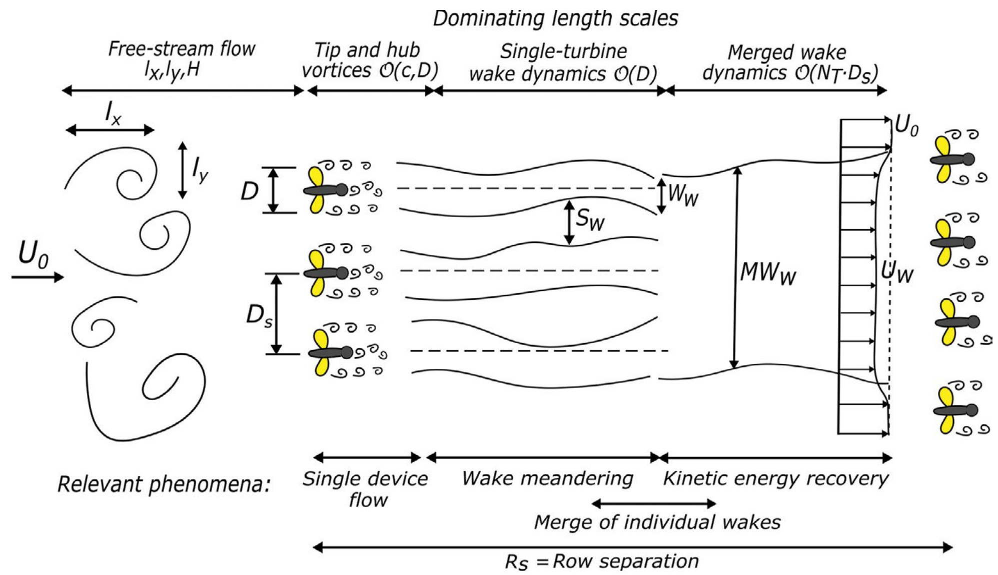

Figure 7.1. Schematic of the hydrodynamics of an array of tidal turbines. (From Ouro et al. 2019)

height and a slight increase in wavelength, where the magnitude of change was highly dependent on turbine size and water depth. Wang and Yang (2017) explored power extraction scenarios extracting 250 kW to 1.8 MW from tidal inlets in Puget Sound, Washington State, U.S., and showed that system-wide environmental effects were unlikely to be a concern for small arrays. A model of a large 480-device tidal array in northeast China showed reduced velocities as far as 10 km downstream (Liu et al. 2019). Guillou and Chapalain (2017) modeled a full-extraction scenario in the Passage du Fromveur, France that showed alterations to existing circulation patterns and displaced recirculation eddies near the tidal extraction site, determined using tracer experiments, and resulted in a 5 percent decrease in residence time across the Ouessant-Molène archipelago (Guillou et al. 2019).

The removal of energy or alterations to water circulation patterns have the potential to change sediment transport processes that result in shoreline erosion, replenishment of beaches and shorelines, scour around infrastructure installations, and sediment accumulation nearshore. Sediment bed-shear stress is quadratically related to changes in the amplitude of tidal currents, indicating that the extraction of tidal energy could strongly affect sediment transport (Neill et al. 2017). Several models have assessed changes in sediment transport under large tidal energy extraction scenarios, and highlighted morphological change in sandbanks, including long-term movement and alteration that may disturb the sensitive benthic ecology (Chatzirodou et al. 2019; Fairley et al. 2017, 2018). Localized sediment accumulation was predicted around a proposed 10 MW array in Ramsey Sound (UK) using a 2D hydrodynamic model (Haverson et al. 2018). Modeling of suspended sediments around two large idealized energy extraction scenarios of 770 MW and 5.6 GW in the upper Bay of Fundy indicated that suspended sediment may decrease by an average of 5.6 percent and 37 percent, respectively, across the basin because of increased sedimentation, which could affect habitat particularly on fine-grained intertidal areas of the basin (Ashall et al. 2016). A dampening of the flood-ebb asymmetry driven by tidal energy extraction was simulated in a channel, resulting in a reduction of the gross volume of sediment transported (Potter 2019). Finally, Nelson et al. (2018) developed a framework for optimizing tidal energy device siting while considering environmental effects such as sediment transport.

Changes in flow caused by the introduction of tidal turbines also has the potential to affect biogeochemical processes. A 2D model of a 1000 m idealized channel with 55 turbines indicated that the operation of the turbines increased the residence time of phytoplankton within a waterbody by five percent but resulted in a decrease of mean phytoplankton concentrations by 18 to 28 percent (Schuchert et al. 2018). Using the backdrop of Pentland Firth, coupled hydrodynamics and biogeochemical models were used to examine nutrient cycles and responses by microorganisms in the presence of large tidal extraction scenarios of 800 MW and 8 GW (van der Molen et al. 2016). The results showed an initial increase in particulate carbon content in the seabed as detrital material settled, although an equilibrium was reached after the first year.

Because of the natural variability in the movement and constituents of seawater, exacerbated by variability induced by climate change, oceanographic changes attributable to the presence of large arrays of MRE devices in the water may not be detectable at a level that is biologically important. A model of the two-way interaction between a 1 m sea level rise predicted for 2090 and tidal energy extraction at the entrance to the Bay of Fundy showed that the impact of sea level rise even exceeded that of a 3 GW tidal extraction scenario (Kresning et al. 2019). García-Oliva et al. (2017) modeled three large tidal extraction scenarios (240 MW to 2.2 GW) to assess changes in water level within the Solway Firth estuary (UK). Changes in low tide were most prominent within and around the farm, while changes in high tide were most prominent at the inner part of the estuary, potentially decreasing flood risk. Another study modeled a high-emissions 2050 climate change scenario to include a 3.8 GW tidal extraction across 10 arrays in Scotland (De Dominicis et al. 2017, 2018). This scenario indicated that tidal velocities were reduced by both climate change and tidal energy extraction locally, although the impact of climate change was an order of magnitude larger, resulting in reduced mixing and increased stratification. However, tidal energy extraction was shown to locally reduce extreme water levels, countering some impacts of sea level rise (Figure 7.2).

Most tidal energy extraction modeling studies explore farfield effects from large arrays on the order of 1 GW or more (Ashall et al. 2016; Chatzirodou et al. 2019; De Dominicis et al. 2017, 2018; Fairley et al. 2017; Gallego et al. 2017; García-Oliva et al. 2017; Guillou and Chapalain 2017; Guillou et al. 2019; Kresning et al. 2019; van der Molen et al. 2016), but some focus on nearfield effects from small arrays on the order of 20 MW or less (Haverson et al. 2018; Li et al. 2019; Wang and Yang 2017). There has been some technology convergence for tidal devices; the greatest number of tidal deployments to date have been horizontal-axis turbines, either mounted on the seabed or suspended in the water column (floating).

7.3.4. MODELING STUDIES – WAVE ENERGY

As with tidal energy extraction, wave energy effects in the farfield physical environment cannot be measured until large arrays are deployed, but numerical models may provide estimates of potential future effects.

Array configurations significantly vary the impact on the nearshore wave climate. Three array configurations of 12 WECs—a single row, two rows, and three rows—were modeled to determine the potential effects of the Westwave array on the west coast of Ireland (Atan et al. 2019). The three-row configuration produced the least power extraction per device and led to a greater change in significant wave height, implying that array configuration can be modified to reduce impacts. Work summarized by Gallego et al. (2017) demonstrated the utility of numerical models to investigate wave arrays in Pentland Firth and Orkney waters, and showed localized effects on coastal morphology that decreased with distance. Several array designs and incident wave conditions were modeled for two hypothetical 60-device wave arrays at a test site off Newport, Oregon, U.S., to determine the threshold for wave-induced longshore force that may affect beaches and nearshore features (O'Dea et al. 2018). This study showed that wave arrays located close to shore and spaced close together will have greater effects, especially as wave heights and periods increase. Using a probabilistic framework, Jones et al. (2018) modeled the changes in shear stress and bed elevation caused by the introduction of a hypothetical 18-device wave farm consisting of oscillating water column WECs off Newport, Oregon. From this study, a Spatial Environmental Assessment Tool risk analysis was developed to visualize the potential impacts on different habitat types along the coast.

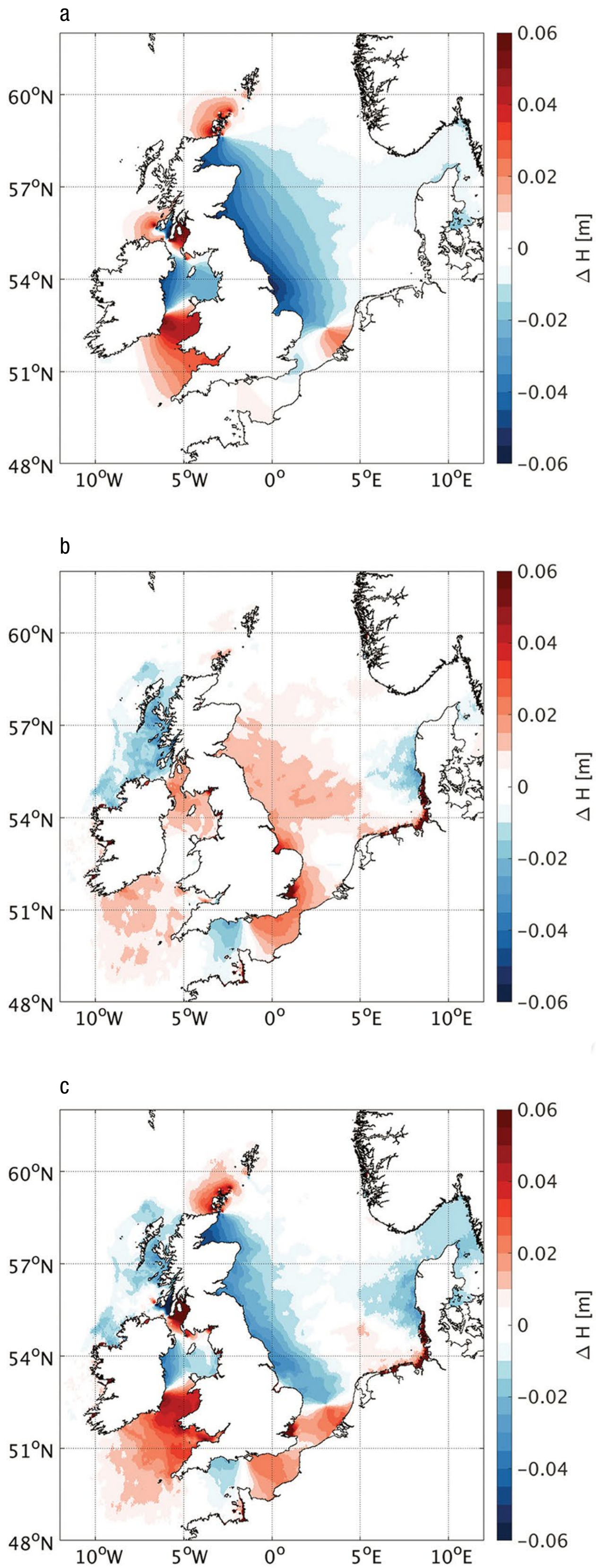

Figure 7.2. Change in spring peak tidal range, shown as the change in tidal height in meters, due to (a) tidal stream energy extraction during present conditions, (b) future climate conditions, and (c) tidal-stream energy extraction and future climate conditions. (Adapted from De Dominicis et al. 2018)

Because wave devices are often located in coastal waters, modeling studies have explored their effects on beach erosion, often analyzing the potential use of WECs for coastal protection. A staggered two-row array of overtopping devices at eight locations along an eroding gravel-dominated deltaic beach in Guidalfeo, Spain, was found to decrease the average significant wave heights by 18.3 percent, wave run-up by 10.6 percent, and beach erosion by 23.3 percent along the coast and by 44.5 percent at the central stretch of beach (Bergillos et al. 2018). In addition, a 44.6 percent decrease in longshore sediment transport and an increased amount of dry beach surface at the optimal array location were shown—significant because the array was located close to shore (Rodriguez-Delgado et al. 2018). Declines in the wave climate, caused by a floating wave array near an eroding beach-dune system in Asturias, Spain, were modeled to alleviate erosion of the dune front and support the dual use of WECs for coastal protection and energy generation (Abanades et al. 2018). However, for most open coastlines, WECs are unlikely to assist with coastal protection because the devices would be locked down during large storms that cause the most significant erosion.

Most wave models assess small arrays of 20 or fewer devices and the resulting nearfield effects (Abanades et al. 2018; Atan et al. 2019; Bergillos et al. 2018; Jones et al. 2018; Rodriguez-Delgado et al. 2018), likely because of the complexity of modeling diffracted and radiated waves around multiple devices or arrays. However, two studies looked at farfield effects around large wave arrays (O'Dea et al. 2018; Venugopal et al. 2017). There has been little technology convergence for wave devices; a plethora of WEC designs are under consideration, including attenuators, oscillating water columns, overtopping devices, and point absorbers. Each WEC design captures different aspects of wave energy and may affect the wave climate in different ways. Representing these different device designs accurately in numerical models adds a layer of complexity to the models, but several methods for parameterizations have emerged, including geometry solvers (Gallego et al. 2017; Venugopal et al. 2017) and idealized power matrices (Chang et al. 2016; Smith et al. 2012).

7.4. GUIDANCE ON MEASURING CHANGES IN OCEANOGRAPHIC SYSTEMS CAUSED BY MRE

The study of physical oceanographic processes is essential for assessing and ultimately quantifying the potential effects of MRE development on the physical environment, as well as for characterizing the tidal or wave resources available for extraction (Bergillos et al. 2019; González-Santamaría et al. 2013; Jones et al. 2018; Palha et al. 2010; Rusu and Guedes Soares 2009, 2013). Accurate measurements of the physical oceanographic environment before and after the deployment and operation of MRE devices can help understand potential effects on processes and resources such as water quality, sediment transport, and ecosystem processes.

7.4.1. ACOUSTIC DOPPLER TECHNOLOGIES

Measurements of subsurface current velocity are typically obtained using acoustic methods. Transducers transmit and receive sound signals at specific frequencies and ocean current velocities are computed based on sound travel time and the frequency shift (Doppler shift) of the echo (e.g., Simpson 2001). Multiple transducers enable resolution of 3D current velocity and direction. Because the principles of operation for the acoustic Doppler current profilers (ADCPs) rely on sound scattering, these instruments can also provide information about particle concentrations, including total suspended sediment (Gartner 2004; Wall et al. 2006), plankton biomass (Cisewski et al. 2010; Jiang et al. 2007), and fish school swimming speeds (Lee et al. 2014; Patro et al. 2000).

ADCPs (Figure 7.3a) are available in a wide range of acoustic frequencies, enabling measurement distances of up to hundreds of meters and at various spatial resolutions (from centimeters to meters). Acoustic Doppler velocimeters (ADVs; Figure 7.3a), which operate based on Doppler-based measurement principles similar to those of ADCPs, sample a small volume of water at a single point in the water column. Many ADVs are capable of sampling at a high rate of frequency (>8 Hz) to quantify forcing parameters such as shear stress, vertical sediment flux, dissipation rate of the kinetic energy of turbulence, and particle settling velocity (e.g., Fong

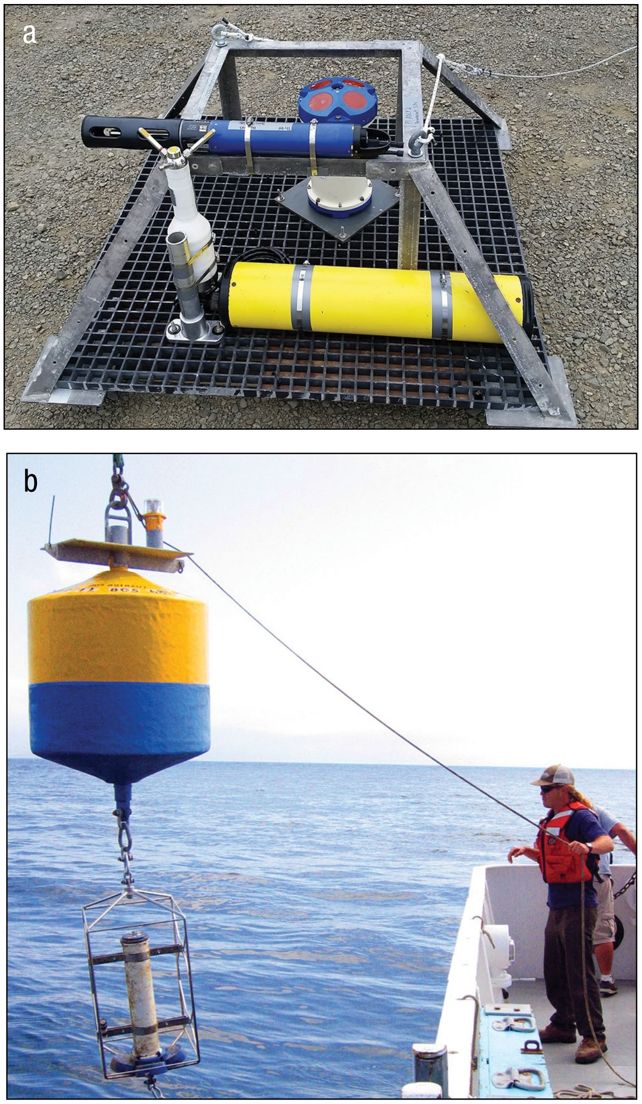

Figure 7.3. (a) An ADCP (background), ADV (foreground), and water-quality sensor (middle) mounted on a bottom platform, upward looking; and (b) a downward-looking ADCP mounted in-line on a coastal mooring. (Photos courtesy of Frank Spada [a] and Grace Chang [b])

et al. 2009; Fugate and Friedrichs 2002; Kim et al. 2000; Thorne and Hay 2012; Voulgaris and Throwbridge 1997). These types of measurements are critical for sediment transport monitoring and model parameterization (i.e., choosing appropriate parameters and values of parameters in models such as erosion rate) in the vicinity of MRE devices and may be useful for determining MRE design criteria and operational controls. A recent study demonstrated the utility of ADVs for evaluating the geomorphic effects of tidal turbine arrays under a variety of array designs and different environmental conditions (Musa et al. 2019). Laboratory results quantified local and non-local hydrodynamic and morphodynamic changes in response to different tidal turbine siting strategies to inform future turbine deployments for optimizing power production while minimizing environmental effects.

Acoustic Doppler current meters are self-contained (internal power and data storage) and can be deployed on a variety of sensing platforms, including real-time systems, from fixed and profiling moorings to manned and unmanned surface and underwater vehicles. They can be oriented with transducers pointed upward, downward (Figure 7.3b), or horizontally in the water column. Further, acoustic measurements are largely immune to the effects of biofouling (biological growth is generally acoustically transparent), making ADCPs and ADVs ideal systems for long-term (months), near-continuous measurements of 3D current velocities and particle concentrations. These types of sensors have been widely used for MRE environmental monitoring. Jones et al. (2014) employed ADCPs in combination with conductivity-temperature-depth (CTD) profiles and marine mammal observations to investigate the distribution of harbor porpoises (*Phocoena phocoeana*) in relation to fine-scale hydrodynamics in support of MRE development in Europe. Fine-scale features were identified in ADCP and CTD data and related to harbor porpoise density and distribution.

Some ADCPs are equipped with surface tracking and/or pressure transducers to enable co-located measurements of water elevation and spectral wave parameters (e.g., height, period, and direction) when mounted with transducers pointed upward. Wave measurements can also be obtained from bottom-mounted pressure gauges and wave staffs (e.g., Grogg 1986), or surface wave measurement buoys whose measurement principles are based on inertial measurement units (Earle 1996) or global positioning systems (Herbers et al. 2012). Although wave staffs and pressure gauges are depth-limited and more commonly used in wave tanks for MRE applications, wave buoys may be moored or allowed to passively drift in virtually any body of water (Raghukumar et al. 2019) (Figure 7.4).

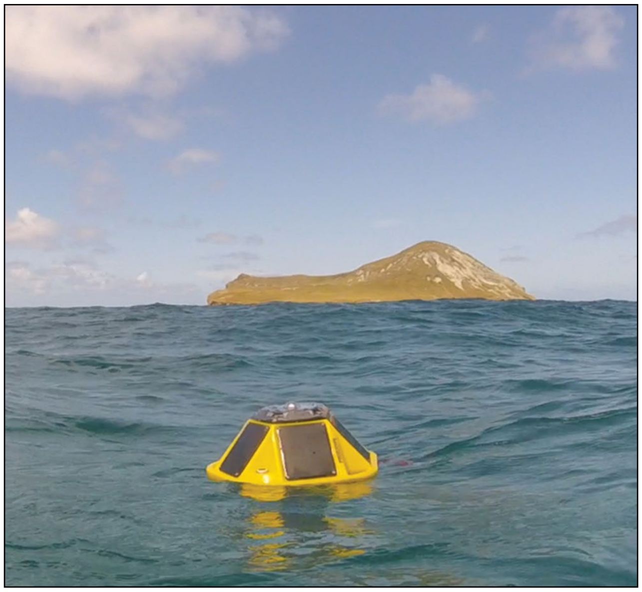

Figure 7.4. Spotter (Sofar Ocean) real-time wave measurement buoy. (Photo courtesy of Grace Chang)

7.4.2. REMOTE SENSING TECHNIQUES

Surface waves and currents can also be measured using remote-sensing techniques (e.g., radar altimetry, high-frequency radar, synthetic aperture radar, light detection and ranging [LiDAR]), or stereo photogrammetry. The primary advantage of remote-sensing technologies is that they provide synoptic measurements over relatively large spatial extents. The disadvantages may include poor spatial resolution, accuracy, range of detection, and/or limitations in measurement parameters (e.g., some technologies provide wave height but not direction or period).

Marine radar techniques are increasingly being employed for assessment, evaluation, and environmental monitoring in support of MRE projects (Bourdier et al. 2014). In The Crown Estate lease areas for MeyGen Ltd. and Scottish Power Renewables in Scotland, marine radar was used to obtain maps of surface currents in support of tidal turbine array deployments (Bell et al. 2014). This technique provided synoptic and accurate, high spatial resolution measurements of tidal currents for resource characterization and array design. Marine radar can also provide information about the potential downstream effects of tidal turbines, such as sea surface roughness modulations (turbulent wakes) in relation to tidal turbine foundation structures (Bell et al. 2015).

Remotely sensed optical technologies such as LiDAR show great promise for near-continuous observations of oceanographic processes in support of MRE environmental monitoring. While LiDAR techniques are more traditionally used for measurement of bathymetry (used as inputs in numerical models), they can also provide accurate assessment of waves, currents, and coastal morphology. Automated terrestrial LiDAR devices are effective tools for analyzing coastal processes at a wide range of spatial and temporal scales, from detailed investigation of individual wave propagation to long-term evaluation of hydrodynamic and morphodynamic variability in coastal zones (O'Dea et al. 2019). When deployed in the vicinity of WEC or tidal turbine arrays, LiDAR systems can satisfy the ocean parameter measurement criteria for high relevance and impact, feasibility, and cost.

7.5. RESEARCH AND MONITORING NEEDS TO RESOLVE THE ISSUE

Most regulators accept the fact that single MRE devices are unlikely to disrupt the oceanographic system into which they are deployed, and that we cannot expect to gather conclusive data about the potential effects of arrays until commercial MRE development progresses (Jones et al. 2016). In the meantime, improvements in numerical modeling capabilities and the validation of those models can help set the stage for evaluating future monitoring and research needs for larger arrays. Although progress has been made, key research and monitoring needs identified in the *2016 State of the Science* report (Copping et al. 2016) remain relevant. Recommendations for research and monitoring to advance the knowledge of MRE effects on oceanographic systems and move the industry forward are listed in the following sections.

7.5.1. IMPROVING MODEL VALIDATION

Given the general lack of commercial-scale MRE deployments, few field data are being collected with which to validate model simulations. Oceanographic measurements collected for the purpose of characterizing the power potential at MRE sites are being used to verify model assumptions and outcomes from the UK and other regions where tidal turbines and WECs have been deployed (e.g., Sellar et al. 2017, 2018). Comprehensive monitoring was performed, mostly in the nearfield, at the sites of several single devices or small arrays located at EMEC, UK (Fraser et al. 2017; Sellar and Sutherland 2016; Sellar et al. 2017) and Perth, Australia (Contardo et al. 2018). As large arrays are deployed in the future, pre- and post-deployment farfield measurements will be needed to provide data for model validation.

Numerical models are steadily improving in resolution and realism, yet these improvements increase their dependency on high-quality measurements. Many geographic locations lack high-resolution bathymetry data that drive model realism. Models often use basic bottom drag or momentum sinks for tidal turbines or basic parameterizations for WECs, so fine-tuned device parameterizations are needed to accurately represent energy removal and changes in water flow (e.g., Apsley et al. 2018). To address the need for datasets, research should target the enhanced accuracy and resolution of sensors and remote technology, more consistent methodologies for data collection, and better sharing of existing datasets.

7.5.2. ASSESSING CUMULATIVE EFFECTS: NATURAL VARIABILITY AND ANTHROPOGENIC ACTIVITIES

Assessing energy removal in the context of natural variability and other anthropogenic activities is particularly challenging and hampers estimation of the potential effects of MRE on the environment. Ocean circulation and sediment transport patterns naturally shift seasonally and over multi-year patterns such as the North Atlantic Oscillation, Pacific Decadal Oscillation, and El Niño Southern Oscillation. Extreme events like hurricanes or winter storms are also capable of causing significant acute change. Other anthropogenic activities such as the placement of offshore structures or dredging may also directly affect localized physical processes. Other anthropogenic pressures may be more indirect, such as a dam reducing coastal sediment supply from rivers and increasing coastal erosion. Similarly, MRE arrays may cumulatively interact with one another (Waldman et al. 2019). And all these local changes exist against the backdrop of a changing climate experiencing warming oceans and rising sea levels.

Cumulative effects studies will reduce uncertainty by isolating the effects of MRE extraction from natural and anthropogenic pressures. The effects of MRE extraction must also be compared to the impact of non-renewable energy sources that are being offset. A methodology for carrying out effective cumulative impact assessment is elusive but is sorely needed as additional use of ocean spaces come online. The MRE community needs to be a partner in developing and implementing methods that address cumulative impacts.

7.5.3. UNDERSTANDING ENVIRONMENTAL IMPLICATIONS

Models predict changes in physical parameters, which may cascade into changes in the environment. To be meaningful, these predictions must be linked to potential impacts on specific organisms and ecosystem processes. These types of linkages are elusive but some insight can be gathered using proxies such as changes in sediment deposition rates to indicate changes in habitat structures (e.g., O'Laughlin et al. 2014), by comparing potential changes to natural variability (e.g., Kregting et al. 2016), or by coupling physical models to biogeochemical models (e.g., van der Molen et al. 2016). Learning from industry analogs may provide some early insights about the environmental effects of arrays. Environmental implications are often site-specific, but trends may be identified that apply across multiple bodies of water, different MRE device designs, and specific organisms. Studies that explore these trends can provide valuable guidance for the interpretation of model results and for device developers to minimize the potential effects of MRE devices on the oceanographic system.

7.6.
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NOTES

Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices

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REPORT AND MORE INFORMATION

OES-Environmental 2020 State of the Science full report and executive summary available at:
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