CHAPTER

19

Observing and monitoring the ocean

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19.1 Introduction

From time immemorial, humankind has looked to the ocean for food and other useful products, for warnings of impending danger (e.g., storms and invaders), for inspiration, wonder, and beauty, and as a broad avenue for exploration, adventure, and commerce (see Chapters 1 and 3). Today, we watch the ocean more closely and carefully than ever before. Globally, the ocean and its coasts affect human health and well-being in many ways, some positive, others negative (Sandifer et al., 2021a).

In this chapter, we explore some of the technologies and other means by which humans observe and monitor a variety of ocean characteristics and processes, and how they relate to human health and well-being. Included here are sections on observing and monitoring: (a) the physical environment, (b) the growing problem of plastic waste in the ocean, (c) marine biodiversity, (d) marine fisheries, (e) harmful algal blooms, (f) naturally occurring infectious microbes, and (g) marine mammals as indicators of potential ocean environmental effects on humans. The chapter concludes with a vision of the future where data from a broad range of ocean, coastal, community, and health surveillance efforts might be integrated into a coastal human health observing system.

While there will be some inevitable overlap with other chapters (see Chapters 11–14, and 20), this chapter primarily focuses on ocean observing and monitoring capabilities and technologies, and how these are used to develop predictions, warnings, and other tools to bolster and protect human health and well-being.

19.1.1 Key definitions/terms (note: Most technical terms are defined within the text)

Altimetry—measuring height or altitude.
Anthropogenic—of human origin or effect.
Antibiotic resistance—refers to situations where certain pathogenic bacteria become resistant to commonly used antibiotics.
Atmosphere—the envelope of gases surrounding the Earth.
Bacteriophage— viruses that infect and replicate only in bacterial cells.
Benthic—refers to the bottom of a water body.
Biodiversity—Earth's variety of life forms at all levels from the genetic to organism to ecosystem levels.
Biofilm—a thin, slimy film of bacteria on a surface.
Biogeochemical cycles—natural pathways by which essential elements of living matter are circulated.
Biosphere—all the parts of the Earth where living organisms occur.
Cryosphere—the part of the Earth characterized by frozen water.

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Cyanobacteria—microorganisms related to bacteria but capable of photosynthesis; earliest known form of life.
Eutrophication—refers to excessive amounts of nutrients in a water body.
Exposome—the measure of all the exposures of an individual in a lifetime and how those exposures relate to health.
Geosphere—rocks, minerals, and nonliving parts of soil.
Hepatotoxicity—causing damage to the liver.
Hydrosphere—the Earth's surface water.
Hyperspectral—a wide spectrum of light, not limited to the primary colors.
Mesoscale—intermediate scale.
Neurotoxicity—causing damage to the nervous system.
Omics—collectively refers to several areas of biological science that end with -omics, e.g., genomics, metabolomics, proteomics, transcriptomics.
One Health—an approach that recognizes and explores the interconnections of human, animal, and ecosystem health.
Parameterization—describe via parameters.
Phthalates—a particular type of plastic used in a broad range of consumer products.
Phytoplankton—small photosynthetic organisms in the ocean and other water bodies that produce approximately 50% of the Earth's oxygen. Harmful algae are often, but not always, planktonic.
Plasmid— a small, circular, double-stranded DNA molecule that is separate from a cell's chromosomal DNA.
Stoichiometry—the relationship between quantities of substances in a reaction or compound.
Syndromic surveillance—a public health early warning system that increasingly uses electronic health information to detect disease outbreaks.
Teratogenic— substances that may cause defects in the human embryo or fetus.
Thermohaline—combined effect of temperature and salinity.
Zoonotic—infectious disease transmitted from animals to humans.

19.2 Observing and monitoring physical characteristics of the ocean

Monitoring and understanding of the Earth's system (atmosphere, biosphere, cryosphere, geosphere, hydrosphere, and their interactions) is necessary if one is to comprehend how changes in our climate can affect human living conditions and health. The advent of new technologies, especially computers, has significantly expanded our ability to collect useful information about the oceans. Further, a variety of observational platforms now exists, and each provides a unique measure of ocean conditions. These include remotely sensed observations (e.g., satellites and high-frequency radars) and in situ measurements (e.g., moorings, floats, drifters, profilers).

Because of the wide range and turbulent nature of oceanic flows, not everything can be measured spatially and temporally, and it is necessary to prioritize the collection of observations that would enable us to develop a comprehensive picture of ocean conditions and variability. Since 1991, the Global Ocean Observing System (GOOS, 2022) has coordinated efforts to generate datasets that can be used to understand and sustainably manage the ocean's complex environment (Révelard et al., 2022).

An international effort, now called OceanPredict (https://oceanpredict.org; OceanPredict, 2023), was initiated in the late 1990s to demonstrate how ocean monitoring strategies could provide ocean forecasts on daily to weekly timescales (similar to atmospheric weather predictions) (Schiller et al., 2018). Over the past two decades, many nations have implemented functional, operational forecasting systems.

Several components are needed to assemble these systems: (1) routine real-time observations, (2) a numerical model, (3) data assimilation techniques, and (4) the ability to disseminate the products to stakeholders (Davidson et al., 2019). At present, most ocean prediction systems assimilate sea surface height anomalies and sea surface temperatures measured by satellites together with temperature and salinity profiles collected in situ, when available (Fig. 19.1).

For nearly 50 years, satellites have allowed a world view of the ocean [see Le Traon (2018) for a review]. Ocean variables currently measured from space are sea surface height (SSH), sea surface temperature (SST), sea surface salinity (SSS), significant wave height and wave spectra, ocean color, ocean mass, and continental and sea ice extent, flow, and deformation.

The first satellite dedicated to ocean observations (Seasat) was launched in 1977 and its mission marked the first time that altimetry (i.e., a technique for measuring heights of the Earth's surface) was used to observe the open ocean SSH. Since that time, altimetry measurements have been extended to other areas including coastal, cryosphere, and inland water hydrology (see International Altimetry Team, 2021 for a review).

A new satellite system capable of transmitting two-dimensional observations of the ocean's surface height was launched in Dec. 2022. The high-resolution Surface Water and Ocean Technology (SWOT) altimeter has a swath width of 120 km, which is comparable to having multiple traditional altimetry satellites orbiting at the same time. The SSH observations provided by SWOT will therefore be significantly more detailed than what was available as of 2022 when this was written.

SST and SSS determine the density at the surface of the ocean, which drives surface currents, water mass

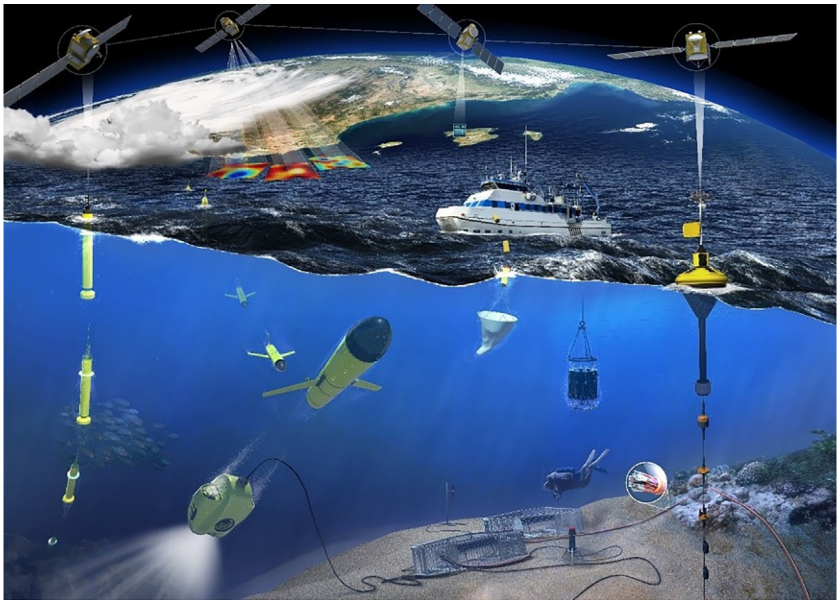

FIG. 19.1 Schematic representation of observations used in an operational ocean prediction system (satellites, shipboard, profiling floats, moorings, gliders, and autonomous vehicles). *Photo courtesy of SOCIB (Balearic Islands Coastal Ocean Observing and Forecasting System) and used with permission.*

formation, mixed layer depth, etc. Measurements of SST from satellites have been possible for decades, but it was the Advanced Very High-Resolution Radiometer (AVHRR) satellites introduced in the early 1980s that provided the basis for an observing system accurate enough to be used operationally.

High-resolution global SST datasets are now available via the Group for High-Resolution Sea Surface Temperature (GHRSST, 2022). Measurements of SSS from satellites are a much more recent development, beginning with the 2009 launch of the Soil Moisture and Ocean Salinity (SMOS) satellite. These measurements of SSS are less precise and with a coarser resolution than SST measurements (see Lee and Gentemann, 2018 for a review). Ocean color satellite measurements provide estimates of chlorophyll and have been used over the last decade to make significant contributions to ocean biogeochemistry, ecosystem, and fisheries. They are especially useful as tracers of mesoscale and submesoscale processes in coastal regions and can be used for model validation (Chassignet et al., 2005).

Essentially, the range of ocean parameters that can be measured from space is expanding as a consequence of continued advancements in satellite technology; and these new satellite measurements have the potential to significantly increase our capacity for better ocean prediction in the coming years. For example, a new instrument that uses a rotating radar beam to measure surface winds and waves, the Surface Waves Investigation and Monitoring (SWIM) instrument, was deployed in 2018, which provides much more accurate surface fluxes at the air-sea interface than traditional altimeters.

As expressed by Le Traon (2018), in situ data are necessary not only to complement satellite observations at and below the sea surface but also to calibrate and validate satellite observations. A key in situ observing system is the Argo program (Argo, 2023) (argo.ucsd.edu), a collection of approximately 4000 free-drifting profiling floats located throughout the global ocean. The Argo system generates ~14,000 temperature and salinity profiles from the upper 2000 m of the ocean each year. This in situ array is supplemented by ship-based observations such as Conductivity-Temperature-Depth profilers (CTDs), surface drifting buoys, autonomous underwater vehicles (AUVs), animal-deployed sensors, and moorings (Fig. 19.2).

Moorings are one of the oldest method used for collecting ocean data. Placed at fixed locations and depths, moorings can supply repeated measurements of currents, temperature, salinity, nutrients, carbon, and oxygen content. Some are equipped with cameras and networked for real-time measurement dissemination. Those having a surface buoy can also provide atmospheric measurements.

Most of the coastal moorings are maintained by national entities but, for the ocean interior, a collaboration of scientists from more than 20 countries built and maintain the surface and subsurface moorings that comprise the OceanSITES (2022) program. When compared to Argo, moorings offer higher quality data because the instruments are routinely calibrated. However, their main drawback is poor spatial sampling (i.e., a few spot measurements).

Since about 2010, autonomous vessels, such as gliders, have begun to make significant contributions to

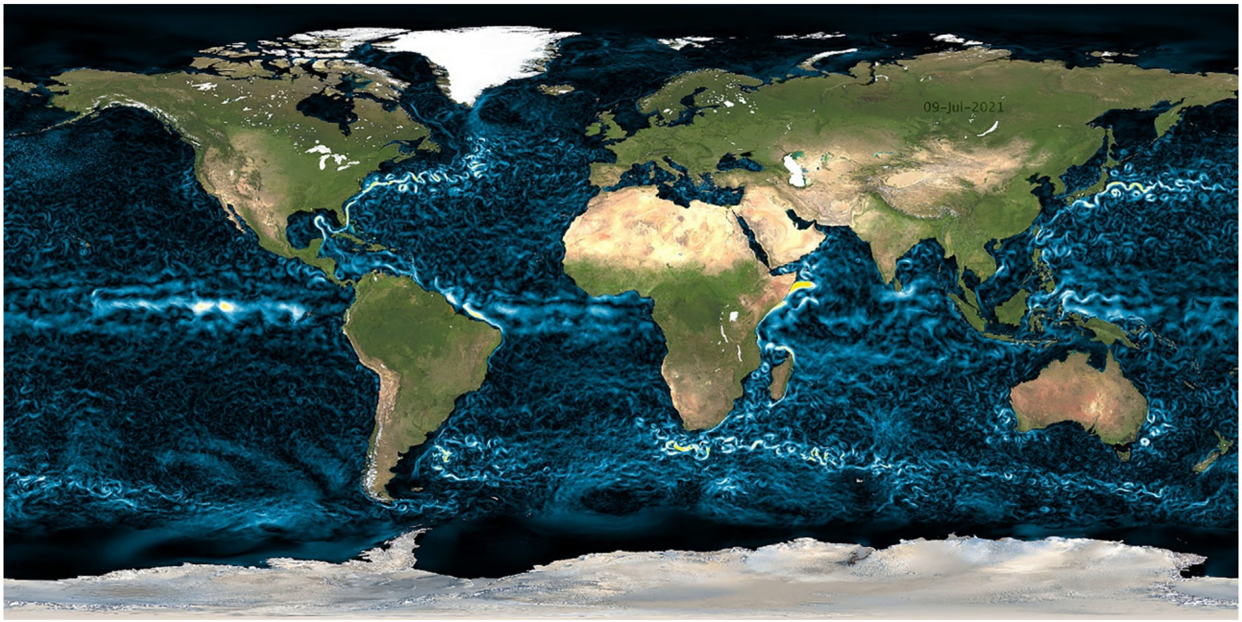

FIG. 19.2 Global snapshot of ocean velocity (1/12° horizontal resolution). Note the Gulf of Mexico Loop Current and Gulf Stream in the North Atlantic, the Kuroshio in the North Pacific, and the Agulhas current off South Africa. *Source: Eric Chassignet, original figure; used with permission, personal rights of use for any purpose retained.*

three-dimensional in situ observations in real time, especially in coastal regions. Another instrument that is fast becoming an important integrant of coastal ocean observation systems is the land-based high-frequency radar. The current network of these high-frequency radar instruments, having been widely adopted, provides essential, near-real-time surface currents to ocean observing systems in coastal regions around the world, from a few kilometers up to about 200 km offshore (Mantovani et al., 2020).

Careful management of all collected ocean data is essential, not only to increase our understanding of ocean dynamics, but also to ensure a timely distribution of data to operational centers. Furthermore, quality control needs to be an inherent part of data collection and sharing, because the usefulness of an ocean prediction system will only be as good as the data that are used to constrain the ocean models. Therefore, to be useful, data management systems must be capable of delivering real-time observations quickly with estimated uncertainties.

Finally, by comparing forecast and analysis system outputs together with observations, it is possible to evaluate their ability to meet specific user needs accurately and reliably. The resulting data and visual products can then be shared and made available to end users via the Web (OceanPredict, 2023).

Quality-controlled observations are combined with numerical models to perform routine ocean forecasts. An ocean circulation model (Chassignet et al., 2019) consists of governing equations for ocean current velocities, temperature, and salinity discretized to be solved numerically on computers. Ocean circulation models have evolved over the past decade through improved physical consistency of their numerical formulation, increased spatial discretization, better grid configurations, and more refined subgrid-scale parameterizations of unresolved processes (Fox-Kemper et al., 2019). Increased computational capabilities have enabled routine resolution of oceanic flows in current state-of-the-art ocean circulation models down to the mesoscale (eddies on the order of few tens of kilometers) globally (Fig. 19.2).

However, due to the turbulent nature of oceanic flows, ocean models cannot account explicitly for the entire range of scale interactions. In coastal regions where most of the world's population resides, very detailed regional coastal ocean models are needed to resolve the small-scale interactions (10–100 m) that occur between near-shore, estuarine, and shelf processes. Boundary conditions at the edge of the coastal domain are provided by coarser basin- or global-scale ocean forecasting systems (Kourafalou et al., 2015a, b).

The discrete ocean observations are then merged with the ocean numerical model via sophisticated data assimilation techniques [see Evensen et al. (2022) for a review] to build physically consistent estimates of the ocean's state. These ocean state estimates are used either to create reanalysis products that describe the past evolution of the ocean (Haines, 2018) or to forecast ocean conditions hours, days, or months into the future.

It is important to note that the quality of an ocean estimate, and subsequently of the forecast, is strongly reliant on the ocean numerical model's ability to accurately represent the resolved ocean dynamics as well as the unresolved physics (Hewitt et al., 2020).

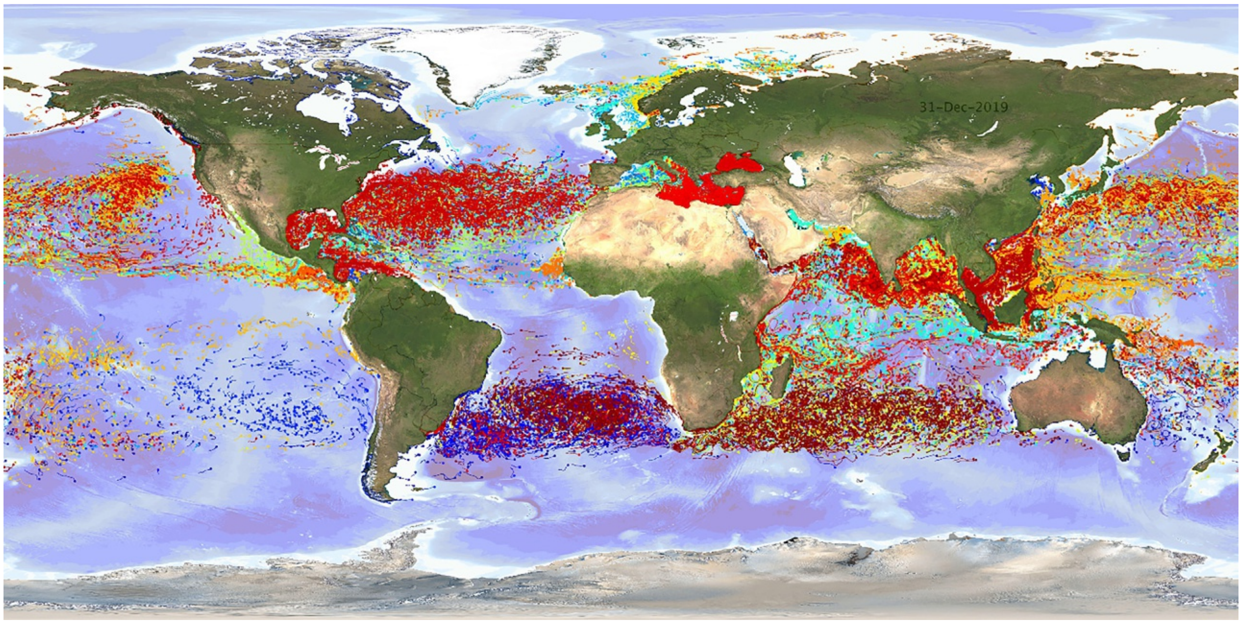

FIG. 19.3 Snapshot of marine plastic waste distribution. Note the accumulations in the center of ocean gyres and in the Great Pacific Garbage Patch. Colors correspond to the country of origin—multiple countries can have the same color—interactive viewing available at World's Ocean Litter (2022). *Source: Eric Chassignet, original figure, used with permission, personal rights of use for any purpose retained.*

Ocean dynamics are coupled with that of sea ice, waves, and atmospheric physics. Coupled ocean-waves-ice-atmosphere systems are needed to improve the representation of oceans' physical processes, especially on long-range seasonal to climate timescales, but also on short-range forecasts (Brassington et al., 2015; DeMott et al., 2021; Hewitt et al., 2017). In addition, while deterministic models are accurate enough for short-term weather time scales, longer subseasonal to seasonal scales require ensemble-based modeling systems capable of capturing uncertainty and predictability, or lack thereof (DeMott et al., 2021). Balancing the competing demands for an enhanced resolution to improve the fidelity of resolved flow features (Chassignet and Xu, 2021) and the additional ensemble members needed to extract a signal from the noise represents an ongoing challenge.

Marine biogeochemistry models are increasingly being combined with existing physical forecasting systems to address important societal issues including environmental and human health concerns. This approach produces extremely valuable information that can be applied to support the maintenance of diverse and sustainable ecosystems and fisheries, or to predict the impact of an oil spill, a toxic algal bloom, or plastic pollution (see Ford et al., 2018 for a review).

Fig. 19.3 shows an example of mismanaged marine plastic waste distribution in the ocean obtained from particle tracking simulations using outputs from an ocean circulation model (Chassignet et al., 2021).

As part of the 2021–2030 United Nations Decade of Ocean Science for Sustainable Development (Ryabinin et al., 2019) (see Chapter 24), several efforts are underway (see Foresea, 2023) to advance the capacity, effectiveness, and application of ocean prediction systems. One of the goals is to build a seamless ocean information value chain that delivers products useful to end users seeking to address economic and societal issues. To achieve this goal, a challenge facing the ocean community is the exponential growth of ocean data generated by: (a) the rapid development of ocean observation technology; and, more so, (b) the size of model outputs due to the increased computing power and fidelity of ocean general circulation models.

Ocean science is entering the era of "big data" (Qian et al., 2021), and Haine et al. (2021) argue that a high-performance data science infrastructure should be built with open-source software and sufficient computing resources to facilitate access to observations and model outputs. Such technology is now under development (see the big data platform Pangeo, 2022, for example).

19.3 Observing and monitoring plastic waste in the ocean

This section addresses questions related to observing, monitoring, and predicting the distribution, abundance, and fates of plastic materials in the marine environment.

For information on the ecological and human effects of plastics on the environment, see Chapters 13 and 14.

Plastic is the most abundant form of litter in the world's ocean. Plastic pollution is a growing threat to the entire Earth's biosphere, with particles of various sizes and compositions ubiquitous in virtually all environments, including the land and soil, lakes and rivers, the atmosphere, the highest mountain ranges, the surface to depths of the world ocean, and even the Poles (Chassignet et al., 2021; Landrigan et al., 2020; Tekman et al., 2022; Zhao et al., 2022). Among all the forms of coastal and ocean pollution that can affect human health, plastic pollution is likely the most widely observed by the public at large, and there is growing concern about its known and especially unknown effects on ecosystem, organismal, and human health (McLeod et al., 2021; NASEM, 2022).

Not only is plastic pollution found in virtually all of Earth environments, but its occurrence has also been demonstrated in drinking water, various foods, and the air we breathe (Dybas, 2020). Some researchers even postulate that the amount of plastic is approaching that of natural organic carbon in certain ecosystems (Stubbins et al., 2021).

With the oceans covering 71% of the Earth's surface and effectively downstream from all other environments, the ocean is a major recipient of and sink for plastics of all kinds and sizes. Because of the global scale and rapidly growing scope of the ocean plastic problem, there is a critical need for comprehensive observing, monitoring, and tracking systems (e.g., NASEM, 2022; Vered and Shenkar, 2021). And, as demonstrated, plastic pollution is amenable to being observed with modern technology and its distribution and fate modeled.

19.3.1 How much plastic waste enters the ocean each year?

Plastics are typically described by size and type (e.g., fibers, fragments), although they can also be classified according to chemical composition. Commonly used size class designations are as follows: megaplastics—large pieces >1 m; macroplastics—easily recognizable pieces from 25 to 1000 mm; mesoplastics—pieces of 5–25 mm; microplastics—pieces <5 mm; and nanoplastics—pieces <1 μm (Fig. 19.4). Nanoplastics are not visible to the naked eye but are highly important because of the likelihood that they can be absorbed by organisms of all kinds up to and including humans.

Estimates of global plastic production vary widely, depending on the study and time frame considered, and range from 320 to 407 MMT (million metric tons) annually in recent years (Brahney et al., 2020; Chassignet et al., 2021; NASEM, 2022). The cumulative amount of plastic produced globally between 1950 and 2017 is estimated to be 8.3–10 BMT (billion metric tons), with about 75% of it eventually becoming waste. Regardless of the accuracy of specific estimates, the total amount of plastic waste generated, of which a portion accumulates in the environment, is enormous.

FIG. 19.4 Examples of size classes of plastic waste found in the ocean and along coastlines; note that there is no photograph of nano-sized particles as they are too small to be observed easily with the naked eye. *Photograph provided by Kunz: https://microplasticresearch.wordpress.com/what-is-microplastic/ (Accessed 26 May 2022), and used with permission.*

Plastic debris in the ocean has been reported for over 50 years, with continued accumulation assumed (Fig. 19.5). The United Nations Environment Program reports that 80% of marine litter comes from the land. Unfortunately, hard data on actual amounts of plastic that enter the ocean are few. Frameworks provided by Jambeck et al. (2015), Lebreton et al. (2017), Lebreton and Andrady (2019), and Schmidt et al. (2017) provide order of magnitude estimates of plastic reaching the ocean, but associated uncertainties are large.

The amount of plastic waste entering rivers, lakes, and the oceans is estimated to be 9–23 MMT annually (Borrelle et al., 2020; McLeod et al., 2021; Tekman et al., 2022), with substantial increases expected. However, only <0.3 MMT (1%–3%) is believed to remain on the ocean surface, with the other 97%–99% eventually going elsewhere in the oceans.

Rivers are thought to be the principal avenues by which plastic reaches the oceans, with rivers in South and East Asia the biggest sources; but, there are numerous avenues by which plastics find their way to the sea, with rivers certainly not the only contributor (Fig. 19.6). Weiss et al. (2021) reported that previous estimates of plastic transport via rivers were overestimated by 2–3 orders of magnitude. They concluded there was no "*compelling evidence for the rapid growth of the floating plastic stock in the ocean*."

Additionally, recent research suggests substantial transport by wind (with the ocean itself a major

FIG. 19.5 Examples of ocean-distributed plastic waste. Top: Plastic and natural debris on the shoreline of Kanapou Bay in Kaho'olawe, Hawai'i. Middle: Volunteers clean up plastic debris on a rocky Hawaiian shoreline. Bottom: Plastic debris at Hawaii Wildlife Fund beach clean-up. *Middle: Photograph credits: NOAA, used with permission. Bottom: Photograph credit: Megan Lamson, used with permission.*

contributor to the microplastic load in the atmosphere), and from the atmosphere to both marine and terrestrial environments (Brahney et al., 2020, 2022).

While it is impossible at present to derive an accurate estimate of the amount of plastic wastes that enter the global ocean annually, available data reveal the scale and significance of the ocean plastic problem and provide a robust foundation for new hypotheses. Much more research is needed to understand the overall "plastic cycle," including the participation of plastics in carbon and other biogeochemical cycles in terrestrial, marine, and atmospheric compartments (Rochman and Hoellein, 2020; Hoellein and Rochman, 2021; Stubbins et al., 2021).

As an early step toward understanding the "plastic cycle," Hoellein and Rochman (2021) developed a conceptual model of sources, pools, fluxes, and fates of plastic in a hypothetical watershed. They suggested that more work needs to be done to fill in this model with empirically derived quantity estimates such as those achieved for the global carbon cycle.

19.3.2 Where does the plastic go?

Because floating plastic is the most readily observed form of plastic debris, it is by far the best studied. Floating plastics are often concentrated in so-called ocean "hot spots" and "garbage patches" in the five large ocean gyres, especially in the North Pacific and South Atlantic, in heavily polluted rivers, on remote shorelines, and in some seafloor areas. The Great Pacific Garbage Patch (GPGP) is perhaps the best-known example of the oceans' plastic pollution problem.

Many numerical modeling studies of the distribution of plastics in the oceans have been conducted, predominantly dealing with transport by surface or near-surface currents and winds. A recent comprehensive study using a global ocean model addressed two of the questions we identify here: Where does the plastic come from? And where does it go (Chassignet et al., 2021)? Using previously reported estimates of amounts and sources of plastics, these authors employed a robust ocean circulation model to simulate the release and subsequent distribution of hypothetical plastic particles throughout the global ocean over a 10-year (2010–19) accumulation period.

Similar to observational studies, their results predicted high plastic concentrations in the subtropical areas of the North Pacific and South Atlantic Oceans and the Mediterranean Sea, and also the poorly observed Northern Indian Ocean and seas that connect the Indian and Pacific Oceans. The GPGP is a clearly identified feature (Fig. 19.7, see also Fig. 19.3 in the preceding section), although its actual position varies considerably with currents. Using Kenya as an example, their model predicted that 46 countries, particularly neighbors in the Indian Ocean, contributed to the

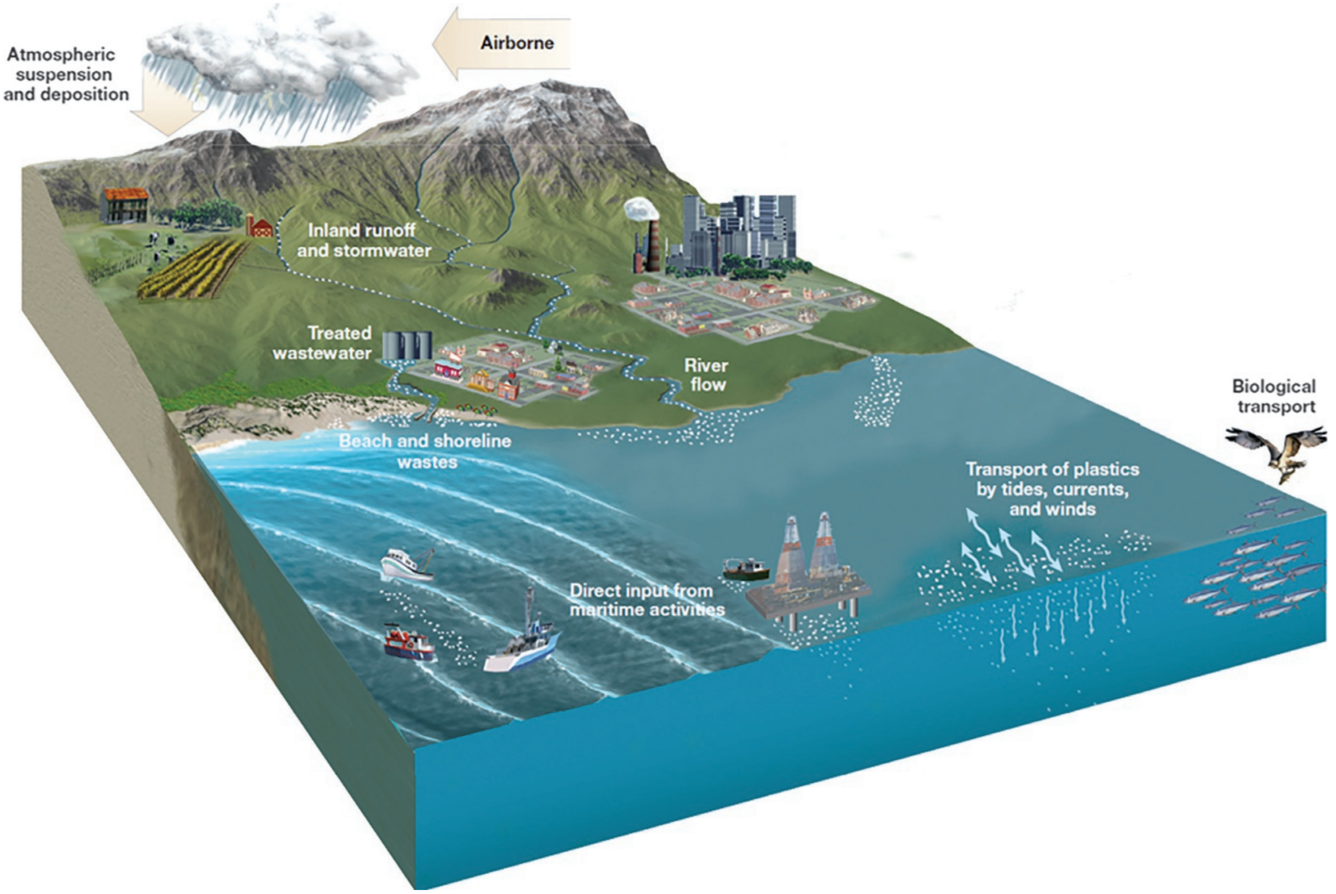

FIG. 19.6 Major transport pathways for plastics from the land to the ocean. *From NASEM (National Academies of Sciences, Engineering, and Medicine):* Reckoning with the U.S. role in global ocean plastic waste*, Washington, DC, 2022, The National Academies Press, reproduced with permission from the National Academy of Sciences, courtesy of the National Academies Press, Washington, DC.*

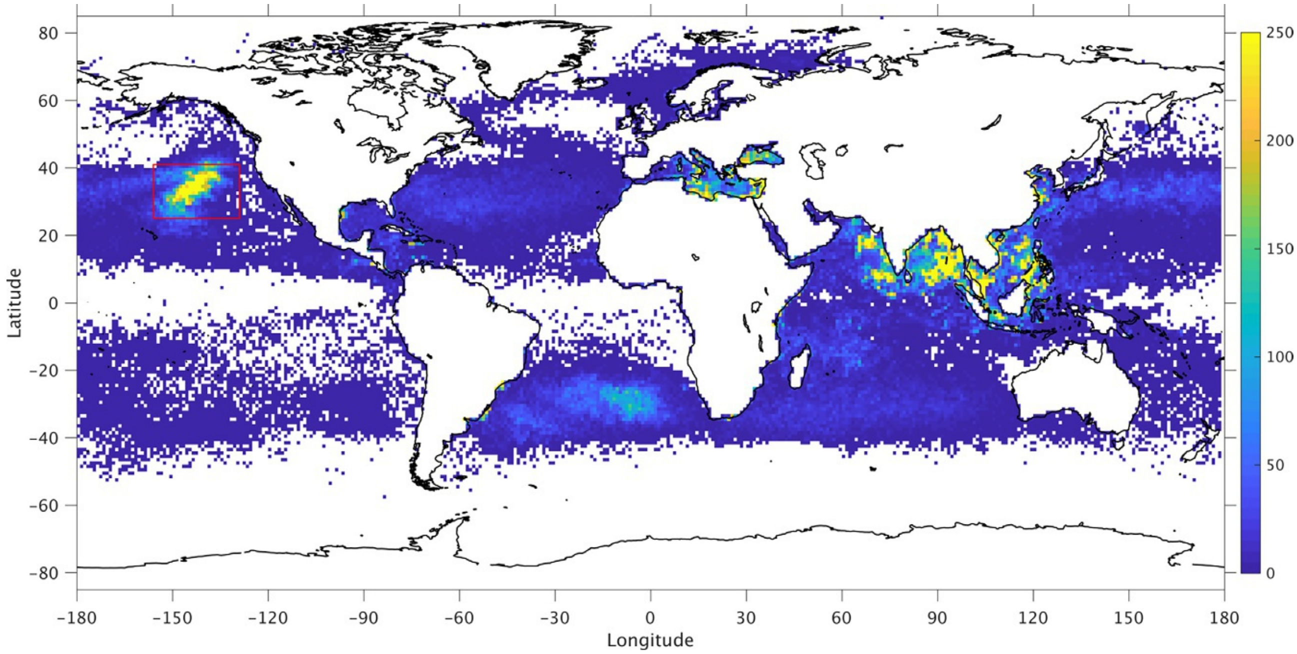

FIG. 19.7 The modeled mismanaged plastic waste concentration (in kg/km^2) showing 10 years of mismanaged plastic waste accumulation (2010–19) at the end of the integration. The red box denotes the Great Pacific Garbage Patch (GPGP, 129–156 W, 25–41 N). *From Chassignet EP, Xu X, Zavala-Romero O: Tracking marine litter with a global model: where does it go? Where does it come from?* Front Mar Sci *8:414, 2021. Copyright © 2021 Chassignet, Xu, and Zavala-Romero, used with permission of the first author.*

Kenyan plastic burden, while some also came from distant sources in South and Central America.

Hundreds of surveys of plastics have been conducted in surface waters, but assessments of subsurface concentrations have received much less attention. In a recent study, Zhao et al. (2022) used a combination of in situ pump filtration, plankton nets, and infrared imaging to sample microplastics from the surface to near the seabed in the South Atlantic Subtropical Gyre region. They reported high abundance (up to 244 pieces of small microplastics [<100 μm] per m^3) with substantial variation in horizontal and vertical abundances. Pump samples contained up to 2 orders of magnitude more microplastic particles than net samples. Smaller microplastics were distributed throughout the water column at all depths.

Much of the plastic that enters the ocean is believed to eventually reach the seafloor, with 40% estimated to sink rapidly while about 60% floats, at least initially; although much of the floating plastic is believed to eventually degrade, break up, and sink. As much as 99% of the plastic that does not wash up on shorelines ultimately ends up in the deep sea, where it may accumulate, or be redistributed by physical and biological processes. Benthic "hotspots" of high concentrations of plastic trash have been observed, some below major surface gyres that serve to concentrate floating plastic debris. However, reliable, quantitative information on plastics in the deep sea is sparse (Galgani et al., 2021; Stubbins et al., 2021).

Thermohaline-driven bottom currents (e.g., those observed in submarine canyons and trenches) are likely responsible for the transport of microplastic pollution to the seabed (Kane et al., 2020). These currents are believed to supply oxygen and nutrients that allow the development of deep-sea biodiversity hotspots, leading to concern that growing accumulations of microplastics will end up in the same places.

Detailed surveys in the Tyrrhenian Sea found microplastics in all benthic samples with concentrations as high as 191 pieces/50 g of sediment (extrapolated to 730,000 plastic pieces/square km) (Kane et al., 2020). There are currently no monitoring programs that regularly and systematically assess plastic transport by bottom currents.

19.3.3 How are plastics currently observed and monitored and what more needs to be done?

While many research projects and surveys contribute to knowledge of plastic pollution in the oceans, the largest and more continuous are a variety of community- and volunteer-based programs (e.g., "citizen science" or "community science;" see Chapter 22). All these efforts produce useful information, and likely engender positive environmental behaviors among participants, but none provide a comprehensive assessment.

Limitations include a primary focus on easily accessible coastal areas or other places known to concentrate plastics; lack of sampling designs that allow extrapolation and generalization of data; lack of inclusion of nonsurface ocean compartments; consideration of only one or a few particle sizes (usually the larger, more easily recognized and sampled materials); nonstandardization of methods, location, intensity, and regularity of sampling; and lack of continuity (some exceptions are noted below).

Some long-running institution- and community-based programs employ internally consistent methods and data reporting, but few are integrated with other such programs or support robust data harmonization and visualization. Perhaps the most significant limitation of the larger observing and monitoring efforts is their concentration on macro- to mega-plastics that are onshore or floating mostly in near-shore waters, plus in the major ocean gyres. As a result, as much as 95%–99% of the plastic actually in the ocean may be missed by many current surveys. And although ongoing poor management of waste plastic supports the assumption of increasing accumulation of plastics overall in the oceans, some research indicates an apparent "steady state situation" (Galgani et al., 2021).

Beaches and shorelines are the most commonly and extensively monitored areas for plastic litter, mostly as citizen- or community-science efforts involving many volunteers (see Table 19.1 for an example list of programs). Among the longest running and/or best known are the following:

The International Coastal Cleanup (ICC), coordinated by the Ocean Conservancy, was initiated in 1986 and is now underway in >100 countries. It is the largest of the volunteer and community science efforts to gather data about litter on beaches, coasts, rivers, and underwater dive areas. The ICC uses a standardized data card and has been collecting similar data since 1988; the data are comparable at local, regional, and national scales.

The Marine Debris and Assessment Project (MDMAP, 2022) is the US National Oceanic and Atmospheric Administration's (NOAA's) flagship community science shoreline marine litter tracking program. It has conducted >9000 surveys at 443 sites in 21 states and territories and 9 countries. Surveys are conducted monthly at or near low tide on sandy or pebbled shorelines that have neither regular debris removal activities nor structures that would affect local circulation. Volunteers focus on 100 m-long shore sections and on particles >2.5 cm, guided by an excellent user manual (Burgess et al., 2021). The data provide information on standing stock and accumulation.

The Marine Debris Tracker (2022), a mobile app originally developed by the University of Georgia in 2011, is now offered through a joint effort of NOAA and the University of Georgia. It can be used to record debris almost

TABLE 19.1 Examples of citizen science community monitoring programs for shoreline litter and their sampling objectives.

Organization	Scientific goals	Website
International Pellet Watch	Collection of pellets for chemical analysis	http://www.pelletwatch.org/
Korea Marine Litter Institute at OSEAN (Our Sea of East Asia Network)	Macro-litter abundance and composition	http://koreamarinelitter.blogspot.com/search/label/Introduction
Ocean Conservancy: International Coastal Cleanup	Macro-litter abundance and composition	http://www.oceanconservancy.org/our-work/international-coastal-cleanup/
Ocean Conservancy: Clean Swell	App for data collection	http://www.oceanconservancy.org/do-your-part/about-clean-swell.html
NOAA	Macro-litter abundance and composition	http://marinedebris.noaa.gov
COASST	Impact on biota	Coast.org
Marine Debris Tracker	Marine litter composition	https://marinedebris.noaa.gov/partnerships/marine-debris-tracker/ https://debristracker.org/
Cientificos de la Basura	Macro-litter abundance and composition	http://www.cientificosdelabasura.cl/en/
Following the Pathways of Plastic Litter	Macro-litter abundance and composition	http://www.save-ocean.org/
Marine Litter Watch	Macro-litter abundance and composition	http://www.eea.europa.eu/themes/water/europes-seas-and-coasts/assessments/marine-litterwatch
Plastic Tide	Macro-litter abundance and composition using drone technology and AI	http://www.zooniverse.org/projects/theplastictide/the-plastic-tide/about/results
Global Ghost Gear Initiative	Distribution of ALDFG	http://www.ghostgear.org/
Closing the Loop	Plastic pollution calculator and digital mapping tool used in SE Asia	https://www.unescap.org/projects/closing-the-loop/cities/da-nang

Reformatted from GESAMP: Guidelines or the monitoring and assessment of plastic litter and microplastics in the ocean. *In Kershaw PJ, Turra A, Galgani F, editors:* IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP/ISA joint group of experts on the scientific aspects of marine environmental protection, *Rep Stud GESAMP, vol. 99:130, 2019 and modified with additional information.*

anywhere. A major strength is the ability to generate a variety of comparisons and statistics.

The European Union also maintains a significant community-based Marine Litter Watch database (Marine Litter Watch, 2022) with an electronic app for recording litter (Marine Litter Watch app, 2022).

The UN's Economic and Social Commission for Asia and the Pacific's Closing the Loop program has developed a plastic pollution calculator and digital mapping tool using artificial intelligence (AI), remote sensing, and modeling tools to engage the public and support local plastic pollution action plans (Closing the Loop, 2022).

Research-based monitoring efforts such as in Japan for some rivers (Nihei et al., 2020), along with many others, provide a variety of survey, tracking, and modeling information; but, consistent integration of data resulting from these efforts is lacking (Closing the Loop, 2022).

Despite the widely recognized need for commonly accepted and utilized global standards and comparable methods for monitoring and tracking plastic litter in the ocean (e.g., NASEM, 2022; Vered and Shenkar, 2021), none are yet in sight. However, significant progress has been made in developing guidelines for what should be considered in marine plastic monitoring programs and how they should be conducted. Excellent examples include Fleet et al. (2021), Gago et al. (2018), GESAMP (2019), NASEM (2022), and NOAA (2015). Components of a future, comprehensive ocean plastic observing and tracking system are illustrated in Fig. 19.8.

The graphic illustrates: (1) documentation and cleanup of plastic litter on beaches and along rivers by human volunteers,; (2) use of satellites and manned and unmanned aircraft, and (3) volunteer vessels to discover and monitor concentrations of plastic waste in surface waters, (4) documentation of plastic waste by recreational fishers and others equipped with smartphone/tablet apps, (5) sampling of the water column and bottom with towed trawl and plankton nets, pumped water samples, sediment corers, (6) surface and subsurface vehicles, (7) autonomous and tethered bottom crawlers, (8) and moored sensor arrays, (9) ocean drifters to gather data for circulation models, and (10) biological "samplers" such as bivalve mollusks, and others.

Such a system should include the following 10 attributes:

(1) An a priori definition of the system's purpose and question(s) it is being designed to answer.
(2) Be scientifically and technically robust with widely accepted and standardized methods.

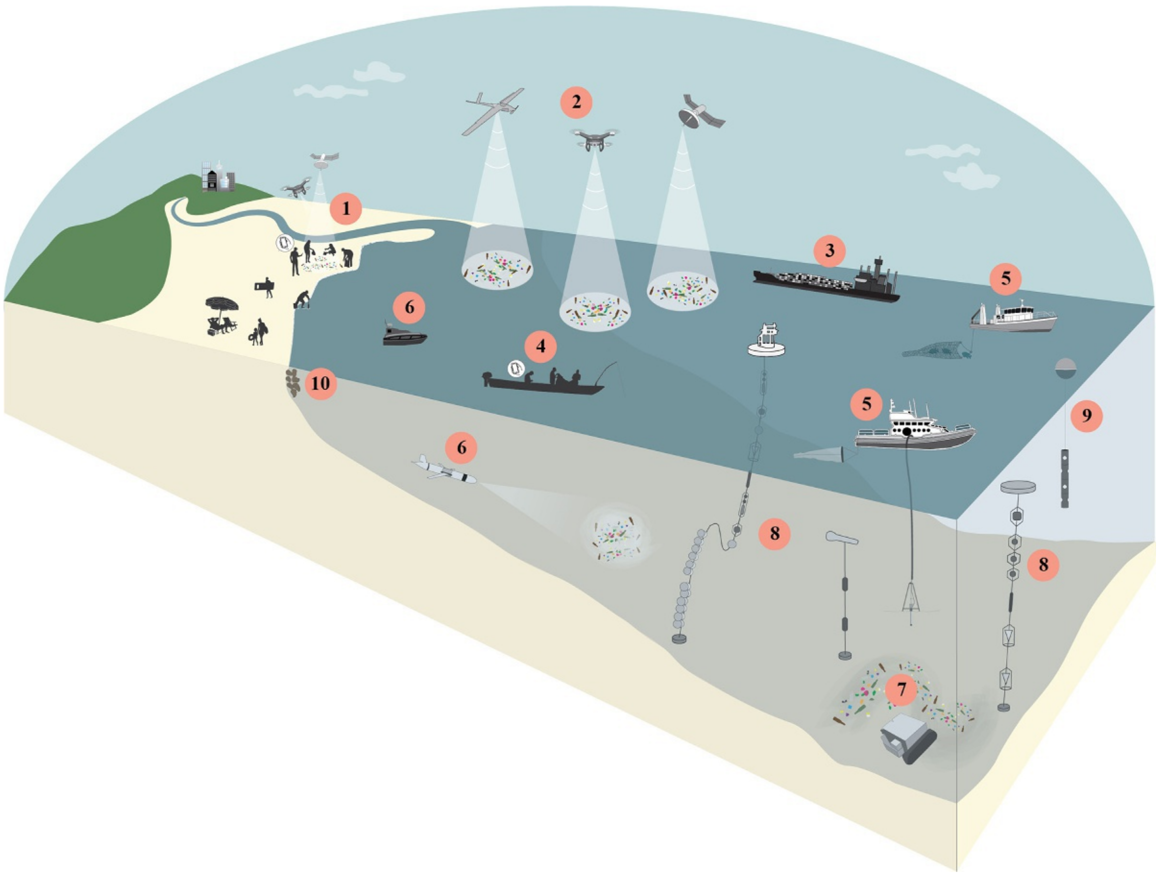

FIG. 19.8 Depiction of a network of monitoring platforms that can be utilized as part of a comprehensive marine debris observing system, collecting data at various scales. *©P. Sandifer, used with permission. Inspired by Fig. 6 in Maximenko N, Corradi P, Law KL, et al.: Toward the integrated marine debris observing system,* Front Mar Sci *6:447, 2019 and Fig. 6.4 in NASEM (National Academies of Sciences, Engineering, and Medicine):* Reckoning with the U.S. role in global ocean plastic waste, *Washington, DC, 2022, The National Academies Press.*

(3) Have sufficient resolution at spatial and temporal scales to address important questions.

(4) Have capacity to utilize and integrate data from a variety of observing, sensing, sampling, and monitoring technologies, including but not limited to remote, in situ, autonomous and others that will enable numerical modeling, prediction, and data visualization.

(5) Be able to coordinate and where possible integrate with prior and ongoing community- and research-based observing and monitoring efforts.

(6) Incorporate quantitative observations on contributions from land, watersheds, rivers, estuaries, the atmosphere, the ocean itself, and any other pathways that may be identified.

(7) Encompass systematic observations in all major ocean compartments (the atmosphere, the surface, the entire water column, the seafloor, benthic sediments, sea ice, estuaries, and shorelines) and include identification, characterization (size and chemical composition), and quantification of plastic inputs to the oceans.

(8) Consider the participation of plastics in biogeochemical cycles in terrestrial, marine, and atmospheric compartments (Hoellein and Rochman, 2021; Rochman and Hoellein, 2020; Stubbins et al., 2021).

(9) Incorporate the monitoring of marine organisms, such as filter-feeding bivalves and others that are known to pick up and perhaps concentrate or assimilate various plastic particles.

(10) Provide information and tools that can be used by policymakers, communities, and the public to better manage the use and disposal of plastics, remove them from the ocean and other environments, and significantly reduce animal and human exposure to potentially harmful plastic particles and the microbes and chemicals they may carry.

While there is much we do not know about the occurrence, transport, and fates of plastic in the oceans (Galgani et al., 2021), there is global recognition of the significance of the plastic problem and necessary commitments to solve it. A crucial missing element is the lack of a comprehensive ocean plastic monitoring program at a scale sufficient to answer basic questions about marine plastic litter.

An aspirational design for an Integrated Marine Debris Observing System (IMDOS) has been proposed by Maximenko et al. (2019). Similar to Fig. 19.8, such a system would have a global scope, with implementation at local to international levels. It would integrate data from a range of remote sensing technologies; gather observations from a variety of fixed and movable platforms and samplers, satellites, researchers, and volunteer citizen scientists; and employ and continuously advance state-of-the-art models to predict dispersion and accumulation of plastics, improve design and implementation of sampling efforts, and inform policy and management.

The IMDOS would include observations on all marine and coastal compartments (e.g., the air, rivers, water from the surface to the deep ocean, sediments, sea ice), and plastic debris of all sizes from the massive to the nano range. The IMDOS would also be linked to the Global Ocean Observing System (GOOS), perhaps with a similar (or the same) international governance construct. Development of some form of IMDOS or a comprehensive ocean plastic observing, and monitoring program should be a top priority of national and international governmental bodies and private partners.

19.4 Observing and monitoring marine biodiversity

Living resources in the sea are essential to the nutritional, recreational, economic, safety, and health needs of billions of people. Many human communities depend on fish as their primary source of protein and sustenance (see Chapters 1–3). Society is highly dependent on the oceans to support lives and livelihoods across the globe (OECD, 2016); to provide food, medicines, recreation, and cultural and aesthetic benefits; for protection against coastal hazards, harmful algal toxins, and pathogens; and even for long-term benefits from carbon sequestration and oxygen production. Access to wildlife is critical for human nutrition and sustenance; and the availability of medicines from the marine realm has already produced numerous pharmaceutical products although this is still a nearly untapped frontier (see Chapter 5).

However, our oceans and the life it supports (marine life as well as human life) are at risk from human activities and climate change. Our ability to manage healthy ecosystems, sustainably use living resources, and ensure these resources are available to meet human health needs in the future is dependent on our understanding of marine biodiversity—or the variation of life from within species (genetic variation) to across ecosystems.

Understanding and maintaining biodiversity is recognized as one strategy for sustaining the health of ecosystems and the services they provide and ensuring the resilience of human communities in the face of environmental change (Palumbi et al., 2009; Sandifer and Sutton-Grier, 2014). As Diaz et al. (2006) stated, "*Human societies have been built on biodiversity*."

The ocean is home to over 200,000 species with estimates suggesting that up to 1 million more are yet to be discovered (Appletans et al., 2012). Human health reliance on the ocean spans multiple taxa (from microbes to whales), all of which have the potential to be significantly impacted by anthropogenic pressures such as renewable energy development, offshore extraction, fishery interactions, chemical and biological pollution, climate change-associated temperature increases, ocean acidification, marine transportation and shipping, invasive species, and other economically driven coastal and offshore activities. The ocean is considered the greatest reservoir of biodiversity on the planet; yet, we really know little about its inhabitants. As a result, ocean biodiversity is endangered in both known and unknown ways and extents (see Chapter 9).

Marine species are expanding into new habitats and changing their behavior to avoid anthropogenic disturbances from a diverse array of impacts including climate change, shipping, fishing, and habitat loss. Understanding how marine species move or are otherwise impacted in the face of human activities and climate change is a necessity if we hope to manage and protect them and the services they provide for human health, well-being, and safety.

An observing system can provide critical information to support this understanding if it is designed in such a way as to enable users of the system to detect and predict the occurrence and distribution of animals and plants and their behaviors, track movements of species and populations, identify selection and use of habitat, and determine other patterns from local to global scales.

Existing data on marine species are insufficient; where they exist, they are fragmented, not well coordinated, and largely inaccessible. This is compounded by the reality that collection of species and living habitat observations lags behind that of physical and chemical observations and is underrepresented in global marine observing investments and activities (see Chapter 7). While the collection of marine life observations is currently inadequate to make global assessments of biodiversity health, there is reason for optimism: the technology exists to improve the situation and to enable us to share marine life information among local communities that need it and across the globe.

Since most marine species and ecosystems remain unstudied, management and global observing efforts typically rely on proxy observations like temperature, ocean color, and topography to locate and estimate populations of marine species, rather than relying on direct species observations to inform decisions. Yet, proxy observations are insufficient to understand and predict specific impacts of global climate change and human activities on marine life.

Globally, a number of groups are working to address the gaps in marine life information and understanding (Canonico et al., 2019). Members of the Marine Biodiversity Observation Network (MBON), the Global Ocean Observing System (GOOS), and the Ocean Biodiversity Information System (OBIS) are working with local communities and other stakeholders to expand efforts to monitor, detect, and predict life in our oceans. Through research and fieldwork, by sharing knowledge and technologies, and by engaging with information users and decision-makers on the ground, these groups are also establishing and promoting standard approaches for the collection and sharing of marine life information.

This includes building a community around data that are Findable, Accessible, Interoperable, Reusable (FAIR; Benson et al., 2018; Wilkinson et al., 2016), an approach that facilitates data reuse and sharing, and ensures data are available for cross-disciplinary science and decision-making. The collective success of these groups relies on effective coordination from the ground up: linking local communities to global science and observing, working across sectors and disciplines to connect scientific findings with communities that need the information (including the general public and health practitioners), and deepening their ability to explain marine life and ecosystem dynamics and the impacts changes in them will have on human health and well-being (see Chapter 24).

Expanding the use of existing or emerging technology, and supporting the development of new technology, is an important part of the solution. The sophistication of these technologies can range from very low-tech and low-cost nearshore tools to samples collected from ships to mooring-based approaches and the deployment of sensors from autonomous platforms such as gliders and other unmanned vehicles and analysis of eDNA (Fig. 19.9).

Another broad-based program is the 100 Island Challenge (https://100islandchallenge.org/) conducted by the Scripps Oceanographic Institute in California and focused on coral reefs around the world. Although coral reefs occupy only a very small portion of the ocean's surface area, they are estimated to house as much as 25% of marine biodiversity and provide a wide range of critically important ecosystem services for many people.

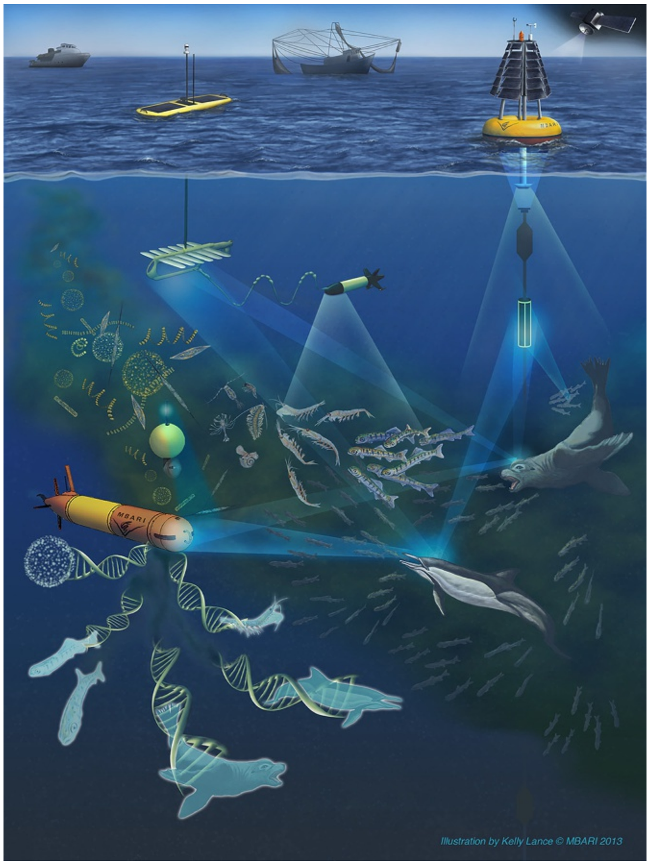

FIG. 19.9 Artist rendering of Monterey Bay Aquarium Research Institute technology used to collect samples for eDNA analyses. The "beams" emanating from the various instruments are an artistic rendering of data collection via sonar, passive microphones and digital cameras while the DNA helices indicate the capture of eDNA samples for genomic analysis. *Credit: Kelly Lance © 2013 MBARI; used with permission.*

19.4.1 "Omics"

Globally, researchers and resource managers are refining the collection and analysis of DNA, RNA, proteins, and small molecules to monitor life and life processes. This suite of techniques, often referred to as "omics," benefits fields ranging from public health to agriculture and fisheries and includes genomics, transcriptomics, proteomics, and metabolomics.

One omics approach that is expanding rapidly is the use of environmental DNA, or eDNA (see Chapter 6). Organisms release DNA material into the water and this eDNA can be collected in water samples, processed, and analyzed to identify specific organisms or describe communities as a whole. This method enables researchers and observing practitioners to look at life in the sea much in the same way as we look at "traditional" oceanographic parameters such as temperature, salinity, and oxygen—samples can be collected from moorings or ships and samplers are even being experimentally deployed on autonomous systems.

Research suggests these genomic approaches produce results that are comparable to traditional—and sometimes more invasive—survey methods and can be used to complement, if not ultimately replace, these methods. Global efforts to develop standards for sample collection, analysis, and data handling show promise for using eDNA to scale up to global observations at the level of other fields of ocean observing (Chavez et al., 2021), if informatics approaches are developed in concert with the monitoring and sampling approaches.

19.4.2 Animal movement

Movement data are foundational to understanding how species use habitats across multiple life stages and how these patterns and the species' ranges shift in the face of environmental change. Animal tracking using historical information or data collected via sound or satellite monitoring can be used to describe the movement and behavior of animals as they pass along our coasts and in our ocean; it is also useful in describing the habitats and areas of the ocean they occupy or transit through.

Rapid advances in transmitters, receivers, and data storage tags that can be attached to animals make it possible to collect high-quality observations on timescales varying from days to years and across different types of habitats. This information is useful across a range of resource management issues, including commercial and recreational fisheries and to predict potential wildlife interactions that might impact human health and safety.

The approach is not limited to pelagic and highly migratory species such as tuna, swordfish, or certain sharks, but can be used with coastal fishes such as giant seabass, rockfish, and certain sportfish, and for endangered and threatened species such as sea turtles (Fig. 19.10).

19.4.3 Passive acoustics

The marine environment is a noisy one. Whale sounds are familiar to many people, but the sounds of spawning fish, snapping shrimp, and dolphin clicks provide important cues for larval settlement, are important for social species and for mating and other aggregations, and influence predator-prey relationships. Efforts to collect marine sound information, including sounds produced by marine life, are growing quickly.

Sound information is of increasing interest for marine biological diversity and climate change indicator projects and is being used to support diverse natural resource management decisions and applications, including to assess ecosystem conditions, evaluate enforcement of ecosystem and species protections, and track restoration efficacy in marine protected areas.

Passive acoustic recording devices can be deployed from mobile and fixed platforms and in a range of environments to sample the "soundscape" in whatever way is most appropriate for the types of sounds that are of interest or to the monitoring objectives. Soundscape monitoring might be targeted to tracking human and animal activity within a marine protected area, or it can be entirely focused on documenting biological sound for biodiversity research. Also of interest is the integration of acoustic detections with other data (including other types of data about or the habitat itself) to describe status and change in an ecosystem.

19.4.4 Imagery

Imagery is an important tool for exploration and biodiversity discovery and to support ecosystem-based approaches that require understanding beyond a single species focus. Imagery can be collected from moored or benthic cameras, diver-operated or autonomous video, baited remote underwater video systems (BRUVs), imaging microscopes such as the Imaging Flow Cytobot (IFCB) (see also Harmful Algal Bloom section in this chapter), and even from large marine organisms

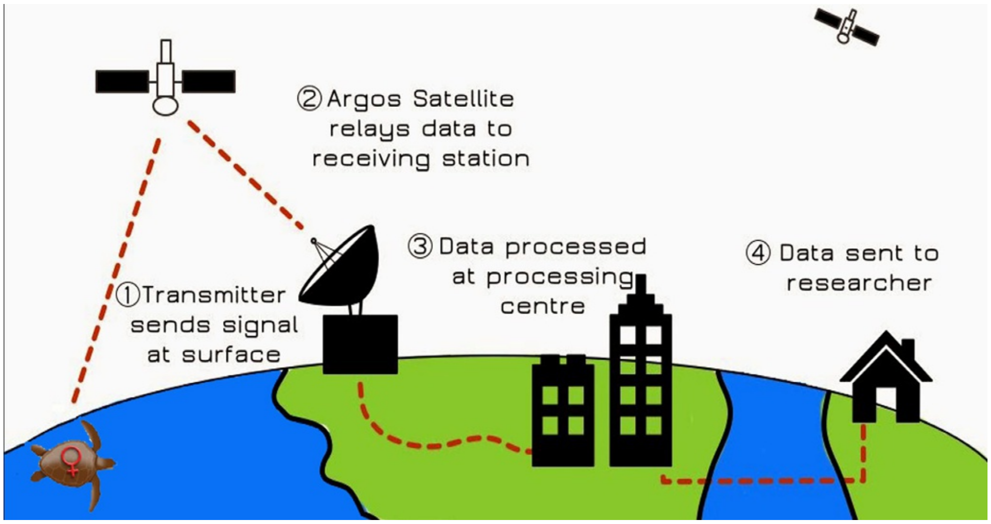

FIG. 19.10 Tracking sea turtle movements via a satellite. *Source: Sea Turtle Conservancy, 2022. (conserveturtles.org) Used with permission.*

FIG. 19.11 Elephant seal equipped with digital camera. *Photograph by Dan Costa, University of California, Santa Cruz; NMFS permit #87-1743-06, used with permission.*

equipped with cameras (Fig. 19.11), to offer just a few examples. These approaches can be used to document species found in remote areas of the ocean, provide insights into their behavior, and visualize community change over time. Imaging systems are essential for recording biodiversity from autonomous vehicles.

However, most imagery is presently analyzed manually, which is time-consuming and expensive; but, image analysis techniques targeted at underwater image classification are under development (see also the Fisheries section in this chapter).

19.4.5 Remote sensing

The above are primarily examples of sensors or platforms to collect in situ observations, or direct measurements of species or phenomena. Remote sensing, or the collection of information from a distance such as from aircraft, drones, or satellites, allows observers to see much more than they might on the ground or in the water.

While field surveys cover small areas and can be used to identify specific elements of biodiversity, remote sensing allows for an understanding of larger scale patterns, influences of land on the oceans, and other ecosystem dynamics. Remote sensing from satellites, in particular, ensures collection of these observations repeatedly and over long periods of time. Alone or when combined with in situ observations, remote sensing represents an important suite of tools for marine biodiversity science and management.

19.4.6 Data management

Many of the approaches described here generate large volumes of data. For the observations to be most useful, data management practices and availability of cloud-based data storage must be considered as part of any monitoring plan. Real-time data are often preferred; and can be critical for monitoring events such as harmful algal blooms or white shark proximity to beaches, but it is not always feasible for biological data collections. Regardless, the information must be openly accessible to support timely assessments that are useful for decision-makers.

Public health applications will likely require that marine species data be integrated with other data types (e.g., environmental data, social science, or human behavior information) and compared among geographic regions (see the section on human health observing in this chapter). Ideally, data on marine species of interest should be managed consistent with global best practices and data standards, which can ease the integration of biological data with other data types for richer assessments of species-environment-human interactions. Adherence to globally agreed upon standards for data and metadata should be considered to ensure this is possible.

In particular, the Darwin Core data standard is widely used to share and integrate biodiversity data (Wieczorek et al., 2012). Originally designed for natural history collections, Darwin Core has grown in use and applicability and has been adopted by global biodiversity data repositories such as the Ocean Biodiversity Information System (OBIS) and the Global Biodiversity Information Facility (GBIF).

Once data are standardized, they can be integrated into data aggregation systems for reuse by data analysts for science and the development of decision tools and products.

The Marine Biodiversity Observation Network is creating an international "community of practice" that will enable sustained observations of marine biodiversity at various levels from genes to species, communities, and ecosystems. This effort builds on already established physical and biological observing systems operating under global entities such as the Group on Earth Observations and the Global Ocean Observing System and will contribute new observations via existing and developing technologies.

The concept of the Marine Biodiversity Observation Network is to support sustained ecosystem resources by integrating data leveraged from a variety of long-term sources. Thus, a major emphasis will be on assimilating data from disparate observational and monitoring systems to provide a more comprehensive picture of life in the sea in all its myriad forms and to increase our understanding of how human activities and our changing climate are affecting ocean life and how ocean life affects us.

19.5 Observing and monitoring marine fisheries

The world's marine fisheries help feed billions of people, provide livelihoods for tens of millions, and are important elements of local and national economies (see Chapters 3, 9, and 18). Despite the need for greater amounts of seafood, world fisheries may be reaching limits of sustainable production. Globally, there are an estimated 10,000 fisheries including all types. The United States alone actively manages nearly 500 marine fisheries, with some of the most extensive and effective management programs anywhere (Boemish et al., 2020).

However, at the global level, only about 70% of fisheries have some (often small) degree of catch monitoring and only about 6% (600) are "scientifically assessed and managed" (Fujita et al., 2018). Enhancing sustainable fishery outputs will require much better science-based monitoring, assessment, and management of fisheries and fishery stocks, hence the substantial interest in enhancing fisheries observations and monitoring.

Most marine fisheries can be separated into several categories:

(1) Large-scale industrial fisheries that usually involve many vessels, some of which can be quite large, and typically target one to a few species (e.g., pollock, king crabs, cod, tuna);
(2) Small-scale fisheries are often prosecuted by many individual fishers using a variety of small craft and focusing on many different species, frequently in an opportunistic way (catching and using what is there). Small-scale fisheries are common in the Global South and may make up as much of 50% of the world's reported seafood landings and 95% of the overall number of fisheries (DeJean, 2020);
(3) Subsistence fisheries are those prosecuted primarily to put food on the table and can be considered a subdivision of small-scale fisheries and/or of recreational fisheries;
(4) Recreational fisheries are those pursued primarily for pleasure and sport, although a portion of the catch is often consumed and, depending on area rules, some may even be sold. However, the primary purpose is generally recreation, although in many cultures there is little, if any, distinction between recreational and subsistence fishing;

In general, recreational and subsistence fisheries are subjected to much less monitoring and regulation than large commercial fisheries, although in some regions (e.g., the United States) and some fisheries, they may be responsible for a substantial portion of the overall catch. However, on a global basis, marine recreational fisheries landings are estimated to be only ~1% of total landings (Friere et al., 2020), although this estimate is associated with a high level of uncertainty due to the lack of formal reporting of recreational catches in many areas of the world.

(5) Illegal, unreported, and unregulated (IUU) fisheries occur predominantly in areas outside national jurisdiction and/or with poor natural resource governance and management. As the name implies, they are carried out by outlaws and may account for 20% of the world's catch overall (Widaja et al., 2019), with estimates reaching as high as 65% for West Africa (Doumbouya et al., 2017) and 70% in Chile (Donlan et al., 2020). IUU fishing threatens ocean sustainability and hugely impacts poor people, who depend on the pirated resources for daily sustenance. Because the US imports >90% of its seafood from other countries, it has undertaken an International Monitoring, Control, and Surveillance program (IMCS, 2022) to improve surveillance of IUU fishing and to assist other countries in building fishery management capacity and in managing protected species and reducing by-catch.

Some important definitions related to fisheries observing and monitoring are given in Box 19.1, and basic information needs for science-based fisheries management are listed in Box 19.2. Activities required to produce these information elements include research, observation, monitoring, modeling, prediction, management, regulation, and enforcement.

These activities are essential to maintain sustainable harvests in fisheries of all kinds and require active participation by many players, including fishers, resource management agencies at all levels from the local to the international, a cadre of dedicated fisheries and other natural and social scientists, legislative bodies, enforcement agents, people involved in processing, marketing, and consuming of fishery products, and the general public to whom most fisheries actually belong (typically, they are "public goods"). They also require the development and implementation of new technologies for observing, monitoring, and managing fisheries and effective governance that includes the active participation of fishers.

Because the kinds, scope, and scales of fisheries differ substantially, there is no one-size-fits-all or universal way for observing and monitoring them, although similar approaches are often used, and comparable kinds of data may be collected. However, these must be tailored to the fishery. For example, what may work well for large industrial fisheries may not work at all in small-scale fisheries carried out by less sophisticated and resourced fishers.

BOX 19.1

Fisheries observing, monitoring, surveillance, control, and management.

Observing fishing activities at sea; can be limited to a single vessel, place, time, event, or multiple subjects. Includes data collection via a variety of active and passive means.

Monitoring of fishing activities at sea; includes the ongoing collection of observational data, analysis, and reporting.

Surveillance of fishing and associated vessels and their activities to ensure compliance with laws and regulations, often using aerial imaging and electronic means, usually without the express cooperation of fishers.

Control of fishing activities through licensing, permitting, laws, regulations, and areas.

Management using the best available scientific and other information, including fishers' experiential knowledge to develop management plans and regulatory requirements that are updated regularly with new information and technology.

Encouraging compliance with fishing regulations through engagement and transparency in rule making, robust and even-handed enforcement, open two-way communication, sanctions, fines, peer-pressure, and market forces (e.g., sustainability certification requirements).

Modified substantially from Box 2 in Cremers K, Wright G, Rochette J: *Strengthening monitoring, control and surveillance beyond national jurisdictions*, STRONG High Seas Project (website). https://www.prog-ocean.org/wp-content/uploads/2020/01/Cremers-Wright-and-Rochette-2019.-Strengthening-Monitoring-Control-and-Surveillance-in-Areas-Beyond-National-Jurisdiction.pdf, 2020 and focused solely on fisheries.

To be effective, fisheries monitoring has to include nontarget species (those caught incidentally, termed "by-catch"), as well as targeted species and ecosystem considerations. These latter encompass the ecological roles played by both target and nontarget species within the ocean ecosystem: how the ecosystem affects target species and how fishing activities affect the ecosystem; and how well fishers comply with management regulations.

Fisheries monitoring requires observations on the biological populations of organisms extracted and impacted, the fishing operations themselves, and the socioeconomic and cultural characteristics of fishers and purveyors of fishery products. It also requires the development, implementation, and regular improvement of population modeling and predictive capabilities that can be used to establish management regimes and compliance requirements.

As Chang et al. (2020) noted, while there are many environmental challenges to ocean fishery populations including pollution and climate change, the "*most direct and age-old impact we exert on the ocean and its ecosystems is overfishing*." And overfishing can lead not only to the decline of fish stocks but also to loss of marine biodiversity, impairment of ecosystem functioning and provision of ecosystem services, and jeopardize food security and livelihoods for many (Bradley et al., 2019).

BOX 19.2

Basic information needs for modern fisheries management.

- Species or group of species that make up the fishery stock(s)
- Fishing areas and methods, including gear types and characteristics
- Depths, types, and importance of habitats in the fishing area
- Population dynamics of the target species, including age and growth, reproduction, recruitment, sex, and size composition of stock and catch, estimated natural and fishing mortality rates
- Other key life history characteristics of the targeted species and any nontarget species that may be regularly impacted
- Catch amount (landings)
- Discard amount (by-catch) and interaction with protected species (e.g., sea turtles, sea birds, marine mammals)
- Ecosystem interactions, including dependence on critical habitats (e.g., nursery areas, spawning grounds), potential interaction with and damage to sensitive habitats from fishing activities (e.g., coral reefs, biodiverse benthic areas), effects on nontarget species populations
- Socioeconomic and cultural factors including characteristics of fishers, their communities, numbers, and types of vessels in the fishing fleet, markets, scale and economics of the fisheries, geographic areas, competition from other users (e.g., other fishers, shipping, recreation, energy) for space, political jurisdictions, and responsible management authorities
- Regulatory compliance levels and effectiveness of regulation and enforcement
- Governance constructs and supporting legal mandates

Ecosystem-based fishery management (EBFM) is a concept that began to become widely accepted during the late 1990s and early 2000s (Pikitch et al., 2004; USCOP, 2004) and is now being undertaken in numerous areas of the world. It involves the integration of ocean ecosystem observations with human activities, including fishing, to produce integrated ecosystem assessments and drive dynamic ocean models (Schmidt et al., 2019). Recent evidence indicates that ecological factors may play dominant roles in determining the abundance of fish stocks (Hilborn et al., 2020), underscoring the need for an ecosystem approach to fisheries management.

The only established approach to reduce and prevent overfishing is scientifically based and enforced fisheries management that embraces continuous and comprehensive monitoring of fishing activities and fishery stocks as well as factors that affect them.

In general, fisheries data can be divided into two main categories: fishery-dependent (i.e., data derived from a given fishery or fisheries, its participants, and its associated economic and other activities) and fishery-independent (i.e., data derived from scientifically designed and implemented surveys and other research typically conducted by fisheries scientists separate from fishing activities).

Regardless of how collected or what stock assessment models are employed, the most important element for successful fisheries management is the quality of the data (NAS, 2000; Schmidt et al., 2019). Observing and monitoring systems provide much of the basic information needed for effective fisheries management.

19.5.1 Summary of fisheries observing and monitoring systems, sensors, and technologies

Currently, fisheries data are recorded by a variety of means from fishers and other stakeholders, including seafood processors and dealers using:

(1) Log books—paper logs with vessel identification, date/time/location, fishing gear, catch, by-catch, and any related information and electronic versions of logbooks with digital records of fishing data via computer, phone, or tablet; depending on connectivity, electronic logbooks can send data ashore prior to landing.

(2) Vessel trip reports—written reports documenting fishing trip participants, catches, landings, and discards.

(3) Reports from on-board human observers—because of cost and other considerations observers are only used in relatively few fisheries, typically in developed countries with significant fishery management programs. Observer programs employ trained observers, who are not part of the regular vessel crew, to document and report vessel locations, onboard fishing activities, catch composition and sizes, discards, and interactions with protected species.

(4) Landing records—records of all seafood products landed at a particular dock, fish processor, or other location.

(5) Port sampling and dockside surveys—sampling of randomly or otherwise selected catches by fisheries authorities, usually at the dockside.

(6) Point-of-first sale and dealer reports—records of the first sale when seafood is landed from a vessel and subsequent sales by seafood dealers.

(7) Telephone or mail surveys about fishing participation, catch and effort, most frequently used to collect information on recreational and small-scale fisheries (e.g., the Marine Recreational Information Program (MRIP) in the United States).

(8) Experiential knowledge of fishers and others—may be imparted via stakeholder advisory bodies and used to augment information on fishing practices and ecosystem integrity.

While all these methods will likely continue to be used for a long time, more technologically advanced approaches are rapidly being adapted and adopted for fisheries monitoring purposes (although many are still in the proof-of-concept stage in terms of broad utility in fishery management decision-making).

However, it is worth noting that some or most of the more sophisticated technologies and extensive human oversight explored below may, in some cases, be more costly than a given fishery is worth. Thus, these are typically reserved for large, monetarily valuable fisheries. A paradox is that many local and small-scale fisheries may be overfished due to lack of the kinds of monitoring and control possible in larger ones.

The information presented below about fisheries observation and monitoring methods and technologies was derived in large part but not exclusively from Blaha (2014), Boemish et al. (2020), Bradley et al. (2019), Camus et al. (2021), Cremers et al. (2020), Donlan et al. (2020), Fujita et al. (2018), Kritzer (2020), Rourke et al. (2022), Tseng and Kuo (2020), and Van Helmond et al. (2020).

19.5.2 Vessel/fishing activity monitoring, observations, and surveillance

Fisheries observing and monitoring employ a variety of technologies and approaches, with many of these used in tandem to provide a more comprehensive view of fishing operations, catch, discards, and interactions.

Components of a comprehensive monitoring system are illustrated in Fig. 19.12, with each explained briefly below.

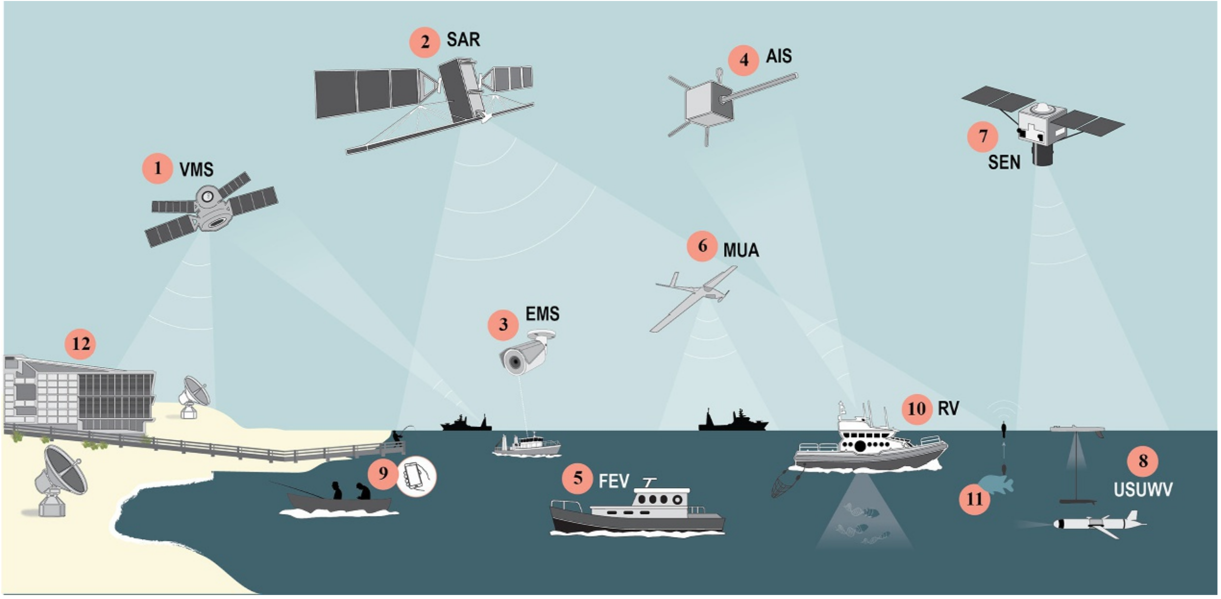

FIG. 19.12 Technological components of a comprehensive monitoring system for marine fisheries. (1) Vessel monitoring system (VMS): system onboard a fishing vessel that transmits location and other data. (2) Synthetic aperture radar (SAR): satellite-based radar that can detect vessels virtually anywhere and anytime but does not acquire vessel identity. (3) Electronic monitoring system (EMS): system onboard a fishing vessel that collects video and/or still imagery of fishing activity and associated location, effort, and other data and stores it in a computer hard drive for later analysis. (4) Automatic identification system (AIS): onboard system for larger vessels—broadcasts vessel identity via a satellite as a routine safety measure for many ships. Can be turned off by the vessel operator. (5) Fisheries enforcement vessel (FEV): patrol boats/ships providing human observations by enforcement personnel. (6) Manned and unmanned aircraft (MUA): unmanned aircraft are usually remotely controlled (e.g., drones). They collect data by both human and instrument observations, including imagery. (7) Satellite-based optical and other sensors (SEN): provide imagery, environmental and other information, not necessarily specific to fishing. (8) Unmanned surface and underwater vehicles (USUWV): remote control or autonomous and equipped with sensors, GPS, cameras, etc. (9) Mobile computing apps for smartphones and tablets. (10) Research vessels (RV): conduct routine and experimental forms of fishery-independent data collection, including samples, eDNA, use of passive sound recorders and active and passive sonar, and others. (11) Pop-up archiving satellite tags: collect and store location and other data and then transmit it when the tag is released from the fish and floats to the surface. (12) Ground/earth station and/or fisheries authority: Receives, stores, analyzes, and assimilates data. *Copyright P. Sandifer, inspired by a figure in Blaha, 2018, used with permission.*

- Vessel monitoring systems (VMS): These are rapidly maturing systems that have been adopted in a number of fisheries. VMS employ on-vessel equipment that broadcasts vessel GPS coordinates, speed, and other information, although not fishing activity, via satellite to a shoreside monitoring center and provides for direct communication to and from vessels, allowing authorities to alert vessels that appear not to be in compliance with regulations. VMS are considered to be secure, and the data are difficult to fake; but, data sharing is often limited by legal restrictions.
- Automatic identification systems (AIS): Many vessels, not just those used in fishing, utilize AIS for safety and other reasons. AIS uses VHF (very high frequency) radio (limited range) or satellite (essentially unlimited range) to broadcast vessel identity, position, course, and speed. These broadcasts can be received by nearby ships and fishing authorities on shore. While they can detect vessel movement patterns that are indicative of fishing, they do not collect actual fishing data and can be turned off or tampered with. Vessels involved in IUU fishing and other illegal activities often turn off or disable the AIS.
- Electronic monitoring systems (EMS): These are comprehensive electronic systems for fisheries monitoring that not only collect and report vessel location but also much detail of fishing activities. EM systems were developed as alternatives to or extensions of on-board observer programs to increase coverage of catches, discards, and fishing practices and are mainly used in large, industrial-type fisheries in developed countries (e.g., the United States, Canada, Australia, some EU countries) where the levels of catch and investment make sense. They employ closed-circuit TV and/or still cameras, GPS recorders, hydraulic pressure and other fishing gear sensors, and a data management/control center (on-board computer with a dedicated hard drive) (Fig. 19.13). Next-generation EM systems are likely to include mobile computing, artificial intelligence (AI), and machine learning to gather additional data on catches, discards, and interactions with protected species (see iFIMS below). While EMS are relatively easy to install and operate, they are vulnerable to tampering and to delays between data collection and assessment. EMS are likely to be adapted for

FIG. 19.13 Examples of camera views from electronic monitoring (EM) fishery trials. Camera views show different angles of the catch sorting process and the net hauling area. The lower resolution of this panel of photos is due to the fact that they are actual photos taken by an on-board electronic monitoring system. *From Van Helmond ATM, Mortensen LO, Plet-Hansen KS, et al.: Electronic monitoring in fisheries: lessons from global experiences and future opportunities,* Fish Fish *21:162–189, 2020, used with the permission of the first author.*

different fisheries and gain further acceptance over time but are of less utility in most small-scale and subsistence fisheries.

- Manned aircraft and at-sea patrol vessels: These are employed for surveillance for enforcement purposes and to deter illegal fishing and other activities (e.g., drug smuggling and human trafficking).
- Unmanned aerial vehicles (UAVs): These include remote controlled or autonomous drones and other aircraft that carry imaging equipment and sometimes additional sensors. Imagery can be transmitted for immediate use and the UAVs can be used to monitor remote areas or IUU fishing due to their relatively stealthy nature. However, they are limited by weather conditions and flight duration and range.
- Mobile computing (apps for smartphones and tables): The development and use of mobile apps are exploding, especially in recreational fishing, with literally tens to hundreds of apps being available to record fishery-dependent data such as catch, size, discards and releases, by-catch or nontarget species interactions, and related spatial and temporal observations. While data transmission is often limited by the availability of cell service or Wi-Fi (typically close to shore), the mobile devices typically have robust storage capacity to allow accumulation of data for later analysis onshore. Use of such apps, along with peer pressure, can increase regulatory compliance. Bradley et al. (2019) and Fujita et al. (2018) list numerous examples of mobile apps, but they are being developed (and disappearing) rapidly; so, such lists quickly become outdated. In addition to growing utilization by recreational fishers, mobile apps may become an important low-cost method for gathering fisher-dependent information for small-scale, subsistence, and other data-poor fisheries, including those in some remote areas.
- Integrated fishery information management systems (iFIMS): These are proposed as “next generation” types of systems that will be internet-based, integrate fishery data of multiple types and sources, including vessel information, crew, location, catch, landings, surveillance, and tracking, etc. and able to provide a near real-time picture of fishing activity and harvest to fishery managers (Bradley et al., 2019). Such systems also are likely to incorporate automated identification and measuring of captured fish using artificial intelligence and machine learning applications applied to video feeds from electronic monitoring systems. This technology is currently being tested and refined but is not yet being used in fishery management (Tseng and Kuo, 2020).

19.5.3 Other technologies and sensors

- Synthetic aperture radar (SAR): SAR is a relatively low-resolution, satellite-based sensor that is on 24/7, not dependent on cooperation from vessels, and able to detect vessels under all weather conditions and in remote areas that are otherwise difficult to monitor. However, they are unable to identify vessels.
- Unmanned and autonomous or remote-controlled surface and underwater vehicles: They encompass a variety of equipment types (Fig. 19.14). Wave gliders are examples of unmanned surface vehicles that can be useful for collecting oceanographic and near-ocean surface meteorological data for use with fisheries and other ecosystem information. They utilize wave energy for propulsion and solar panels to generate power for satellite communication devices, AIS units, and sensors (e.g., acoustic recorders). Advantages include endurance, low maintenance, and ability to operate in remote areas; but they are slow and, at present, can carry a very limited instrument load.

  Unmanned underwater vehicles are typically torpedo-shaped devices that can be equipped with various instrument packages including cameras, sonar, and other sensors to collect data, for example, on fishery populations, oceanographic conditions, ecosystem status, or impacts of fishing gear on habitat.
- eDNA (i.e., environmental DNA) is DNA shed by organisms into water that can be filtered from water samples, analyzed, and used to assess distribution and, sometimes, abundance and biomass of target fishery species. Its use requires knowledge of DNA signatures of species of interest, comparison to DNA libraries, understanding of degradation processes and time frames (eDNA usually degrades within 1 week to 1 month), and requires specialized equipment and personnel with appropriate training. While eDNA currently is useful only as an ancillary tool for assessing fishery populations, it holds considerable potential for future cost-effective fisheries' independent monitoring of fishery populations and biodiversity (Curry and Ausubel, 2021; Li et al., 2020; Rourke et al., 2022).
- Sound sensors, including both passive listening/recording of anthropogenic and biological (e.g., whale songs) sounds and active sonar to assess abundance and biomass, are used in fisheries and ecosystem research, but the data derived are only occasionally used in management.
- Standard and electronic (satellite) tagging of animals allows scientists to follow migratory, feeding, and other behaviors and equipping animals with oceanographic sensors and cameras enables the gathering of species-specific ecological data. Tagging data are routinely used in the development of stock assessments and fishery

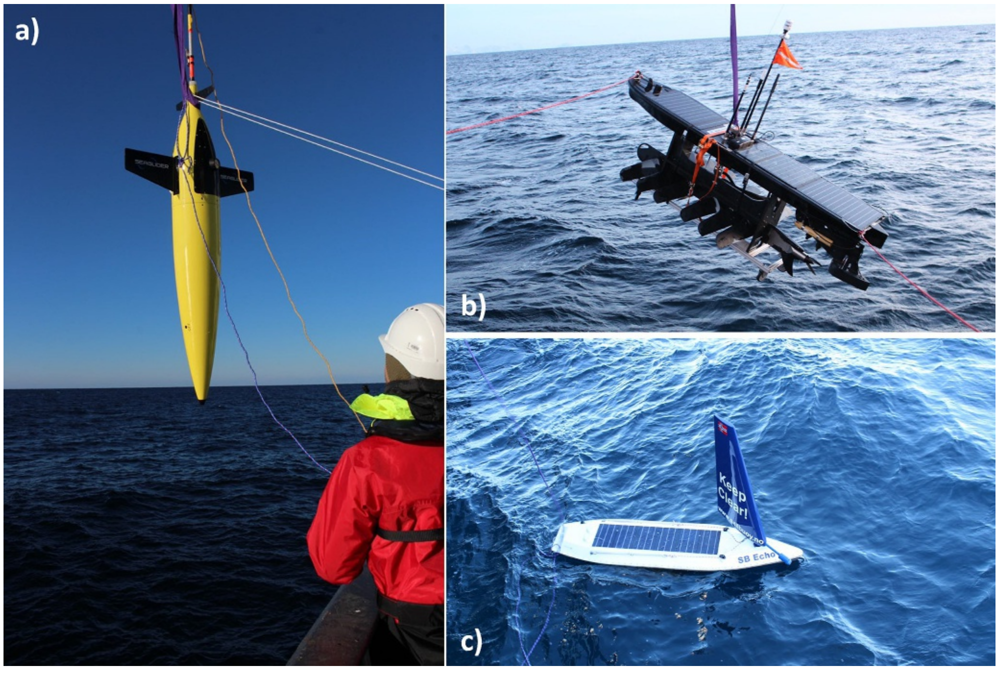

FIG. 19.14 Examples of autonomous surface and underwater vehicles that can be used to gather data on ocean ecosystems and fisheries. (a) Seaglider (Huntington Ingalls Industries; formerly Kongsberg Maritime), (b) Wave Glider SV3 (Liquid Robotics), and (c) Sailbuoy (Offshore Sensing). *From Camus C, Andrade H, Aniceto AS, et al: Autonomous surface and underwater vehicles as effective ecosystem monitoring and research platforms in the Arctic,* Sensors *21:6752, 2021, used with the permission of the first author.*

management plans, and tagging programs are frequently employed in recreational fisheries for both data collection and to increase interest in conservation and management of the resources. Pop-up archiving satellite tags collect and store data and then transmit it when the tag is released from the fish and floats to the surface. Data from such tags have been used with an observation-assimilating ocean model to provide improved understanding of swordfish movements and ecology (Braun et al., 2019).

In addition to technological advances in observing and monitoring, more people- and market-centered efforts are also being applied. These include independent third-party certification programs such as the Marine Stewardship Council (MSC, 2022), a global nonprofit organization that ensures that seafood marketed with its certification has been caught sustainably. Increasingly, markets are requesting or requiring such certification. Similarly, the Monterey Bay Aquarium's Seafood Watch (https://www.seafoodwatch.org; Seafood Watch, 2022) program, and others like it, educate consumers on how to choose sustainable seafood.

While these technologies and market-based measures are being applied and others developed for use in fisheries around the world, especially in developed countries, there is no "magic bullet" for effective fisheries management, including the enforcement of fishery regulations (Fujita et al., 2018). Technology must be implemented by people who have high levels of integrity, technical knowledge, capacity, and resources to use the technology properly. Also required are enabling legal and governance constructs, and the active cooperation of fishers and other stakeholders.

All of these require robust communication among resource managers, scientists, and stakeholders; and transparency and fairness in data collection; its use in the development of management plans and regulations, and in the enforcement of compliance requirements.

19.6 Observing and monitoring harmful algal blooms

Harmful algal blooms (HABs) are both natural and human-induced/exacerbated phenomena where marine and freshwater algae and cyanobacteria proliferate much beyond usual concentrations, resulting in large assemblages that may foul and/or color the water, and may produce compounds that are highly toxic to humans and many aquatic and terrestrial animals (Backer et al., 2015) (see Chapters 11 and 20). In some cases, blooms are so dense that they may impact recreational and other uses of certain water bodies.

The distribution, frequency of occurrence, number of species involved, and health and economic impacts of HABs are reported to be intensifying in association with climate change-related increases in temperature, alterations of hydrologic cycles, and growing numbers of extreme weather events (Berdalet et al., 2016; Paerl and Otten, 2013; Gobler et al., 2017; Wells et al., 2020), although some studies now question this link (Anderson et al., 2021; Hallegraeff et al., 2021). Many HABs appear to be further enhanced by the increased use and subsequent runoff to the coasts of nutrients from fertilizer and industrial, human, and animal wastes (Bullerjahn et al., 2016; Paerl et al., 2016).

Together, marine and freshwater HABs are known to produce well over 100 toxic substances, and human exposure to these toxins can occur via a multitude of routes, including by ingesting contaminated water or seafood, direct contact via recreation (e.g., swimming or boating in HAB-impacted water), or by inhalation of aerosolized toxins (Berdalet et al., 2016). Different HABs and their toxins can have a wide range of negative health effects in humans and even cause death.

HABs are well known in coastal ocean waters and estuaries around the world, and are rapidly becoming significant problems in large bodies of freshwater, where they threaten potable water supplies as well as recreational resources. Increasingly freshwater HABs are being pushed into brackish water areas of estuaries by heavy rainfall events or water management actions, where their toxins can co-occur with those from coastal marine blooms (Heil and Muni-Morgan, 2021; Metcalf et al., 2021; Zepernick et al., 2022).

HABs pose a growing threat globally, with a diverse and seemingly ever-increasing number of species involved. For example, agencies of the US State of Florida monitor >75 species of harmful and potentially harmful algae and cyanobacteria (Heil and Muni-Morgan, 2021). And although hard data on the true number of HAB-associated illnesses are hard to come by, the CDC recently reported 321 HAB-related emergency department visits between 2017 and 2019 in the United States (Lavery et al., 2021).

Because HABs can be a major threat to human health and coastal economies, there is growing interest in improving our ability to predict both their occurrence and toxicity to provide timely public health warnings and forecasts and to understand bloom dynamics so that blooms and their impacts can be prevented or diminished. Development of predictive models and forecasts requires robust observational and monitoring systems, similar to those described elsewhere in this chapter for ocean physical characteristics, plastic distribution, and biodiversity, and involves similar technologies plus monitoring of nitrogen and phosphorus, and where possible, bloom toxin concentrations in water.

One may wonder why freshwater HABs are included in an oceans and human health textbook. The reason is quite simple. As noted for plastic pollutions, water flows downhill, ultimately ending up in the marine environment bringing plastic waste with it. So it is with freshwater HABs, which are occurring more frequently and intensely and washing downstream into estuarine and coastal waters where their toxins are released (Zepernick et al., 2022). Freshwater HABs are also major problems in inland seas such as the Great Lakes in the US. Therefore, in this section, we provide some examples of the technologies and processes currently used to observe and monitor HABs in both marine and fresh waters.

19.6.1 Coastal and marine HABs

As discussed in Chapter 11, not all HABs are alike. This significantly adds to the challenge for observing and monitoring HABS and, unfortunately, there is not a "one size fits all" solution (Bresnan et al., 2021).

Some HABs cause shellfish toxicity at a very low number of cells in the water and some HABs species have huge biomasses associated with them; yet, each of these conditions are referred to as a "bloom." To add to the challenge of monitoring these different HAB species, some are benthic dwellers, some live throughout the water column, and some live near the surface and their place in the water column may change based on their life-cycle stage. Therefore, there is not one observation or monitoring strategy that can be used across all HABs.

For example, the Gulf of Mexico organism, *Karenia brevis*, is always toxic; therefore, observing cells can be a surrogate for toxicity. Other microalgae, such as several species from the genus *Pseudo-nitzschia*, can be either toxic or nontoxic, and thus require toxin measurements as well as identification and counts of algal cells. Due to the different levels of toxicity associated with different HABs, regulatory standards for closing shellfish beds to harvesting and then reopening them following a bloom event, and for posting warnings or closing and reopening recreational beaches, differ across regions and countries.

For the purpose of this discussion, we draw a distinction between monitoring or measuring a HAB species and/or its toxicity for public health reasons and observing HABs. For human health protection from fish and shellfish poisonings, there are very rigid protocols and methods; and again, these protocols and methods vary by species, toxicity, and national standards. Doucette et al. (2018) provide a detailed review of the various laboratory methods and tools available.

Observing HABs refers to in situ real-time or near real-time measurement of cells, toxins, or an established proxy. These observations can provide early warning to a resource manager that a bloom is approaching; and adaptive sampling strategies can be implemented in a timely manner to optimize mitigation efforts. These mitigation efforts may be to inform shellfishers (shellfish harvesters) that a bloom may be imminent and allow them to harvest ahead of the bloom (and therefore, ahead of the shellfish bed closure); or if massive fish kills are expected, a resource manager may implement emergency workers for beach clean-up. Animal health resource managers may alert community observers to be aware of odd animal behavior in hopes of removing the animal from the toxic environments and treating for toxicosis.

Many emerging technologies are being developed to observe both algal cells and toxins in the water in real time or near real time. This approach presents unique challenges. Problems for many real-time water sensors (not just HAB sensors) include power consumption and availability (i.e., battery power vs. cabled arrays), data telemetry capability (near shore vs offshore), biofouling, vandalism, and significant annual operations, and maintenance costs. Most platforms/sensors begin as benchtop units that allow the processing of samples in the laboratory. The challenge is to then take these units into the field, or in this case, the marine environment.

19.6.2 Observing HAB cells

Due to the complexity mentioned above, there are few instruments that can be deployed and maintained for an extended period for HAB cell observing.

The Imaging Flow Cytobot (IFCB) (Fig. 19.15) has a sophisticated cytometer and video technology maintained

FIG. 19.15 The Imaging Flow Cytobot, an imaging microscope that can provide real-time sensing of harmful algal blooms. *IFCB, McLane Research Laboratories, 2022a. Photograph used with permission.*

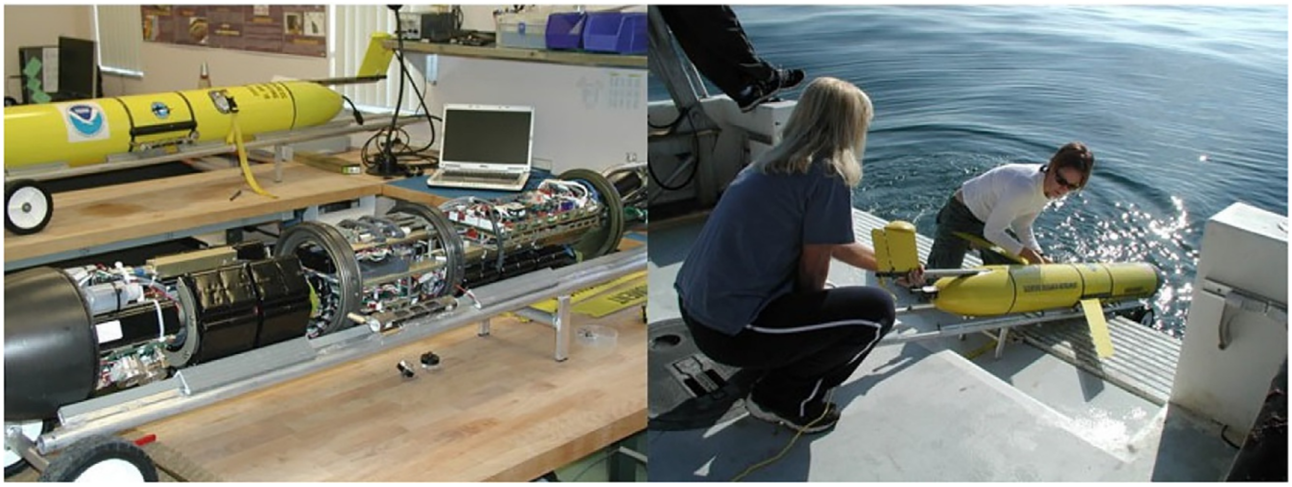

FIG. 19.16 The Programmable Hyperspectral Seawater System (PHYSS), previously referred to as the Optical Phytoplankton Discriminator (OPD), for harmful algal bloom detection. Developed by Mote Marine Laboratory. *Photograph used with the permission of Barbara Kirkpatrick.*

in water-tight housing. The IFCB is able to continuously assess the plankton community structure in situ and, through the application of developed "classifiers," identify HAB species of interest (Sosik and Olson, 2007). With concerns of climate change shifting plankton community structure and potentially creating conditions for HAB species to occur in new environments, the IFCB can be a powerful tool to monitor changes in plankton communities. The disadvantages of the IFCB are primarily the complexity and cost of the instrument and the accompanying requirement for dedicated, trained staff to deploy and maintain it. Efforts to decrease power consumption and data processing time are underway.

The second in situ device is the Programmable Hyperspectral Seawater System (PHYSS) previously referred to as the Optical Phytoplankton Discriminator (OPD) developed by Mote Marine Laboratory (Fig. 19.16).

The PHYSS uses the unique optical properties of the pigments in a water sample and is able to estimate the likelihood of a phytoplankton species presence. Regarding HAB detection, the PHYSS has accurately identified the likelihood of gyroxanthin diester, the unique pigment found in *Karenia* species found in the Gulf of Mexico (Kirkpatrick et al., 2000). Although not commercially available at this time, a complete description of the unit and the numerous deployments are discussed in Shapiro et al. (2015). The previous version, the OPD, was engineered for the payload of an underwater Slocum glider. Unfortunately, the upgrade of the glider from the G1 to G2 changed the size of the glider's science instrument bay and virtually made this capability defunct.

Another approach is the CytoBuoy, an instrument that was a bench flow cytometer model (CytoSense) and which is placed in a pressure-tight housing configured to be an "add on" sensor to a surface buoy. This instrument combines classic flow cytometry with two lasers to provide information about particle size and pigment signatures. The unit has demonstrated the ability to identify HAB species and has been integrated into moored platforms (Dugenne et al., 2015; Pereira et al., 2016).

19.6.3 Molecular methods

The Environmental Sample Processor (Fig. 19.17) is a fully automated system designed to collect discrete water samples in situ, concentrate particles, and automate

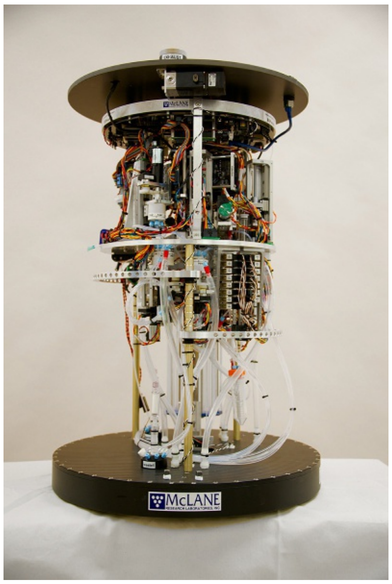

FIG. 19.17 The Environmental Sample Processor capable of automated molecular analysis. *McLane Research Laboratories: https://mclanelabs.com/environmental-sample-processor/ (Accessed 26 May 2022b). Photograph used with permission.*

molecular analytical technologies within the unit. Detection chemistries employ membrane-based and protein-based DNA probes.

Data generated by the instrument are transmitted in real time via a variety of communication strategies including cell phone, modem, or satellite. The current models require a fixed mooring and/or have the unit placed in the water as a drifter which inhibits the adaptive sampling strategies needed in HAB bloom surveillance. The unit is currently being engineered to fit in the payload of a long-range autonomous vehicle to address this need.

As discussed earlier, few in situ, real-time instruments are currently available. To address the spatial and temporal challenges HAB observing requires two very different strategies. The first is the use of satellites or remote sensing. This approach is extremely appealing due to the very large geographic area a HAB can cover (Heil and Steidinger, 2009). However, the application of satellite imagery is highly variable for different HAB species and a given bloom's location to the near surface at any point in its life cycle. Remote sensing has been shown to be a powerful tool in many areas where HABs occur including the Gulf of Mexico (Stumpf et al., 2003), the Gulf of Maine (Anderson et al., 2005), and the Baltic Sea (Graneli et al., 2008), and for some important freshwater cyanobacteria blooms, as described in the Cyanobacteria section.

In many situations such as remote sensing from satellites, HAB species do not exhibit characteristics that distinguish them from other phytoplankton (Berdalet et al., 2016). Additionally, as Graneli et al. (2008) reported, the resolution of the imagery is often not fine enough to identify daily variations and variations from one location to the next. Observations must be incorporated into the analysis of remote sensing imagery to accurately identify a HAB species out of all the other species that may occur in the upper water column.

19.6.4 Volunteer community science networks

Although not an "instrument" in the true sense of the word, to address the spatial and temporal observation needs for HABs, many community science (a.k.a. citizen science) networks have been created (see Chapter 22). These range from commercial and recreational boaters and fisherman acting as "eyes" on the water and reporting unusual and/or specific events, to beach reporters submitting real-time beach conditions, to community scientists collecting water samples and either analyzing the samples themselves with designated equipment and training or by sending samples to a central laboratory for analysis (Nierenberg et al., 2009; Graneli et al., 2008; Heil and Steidinger, 2009).

In some cases, native American tribes, for whom shellfish are important culturally and for livelihoods, have established their own community science HAB monitoring programs. One example is the Southeast Alaska Tribal Ocean Research (SEATOR) partnership (Harley et al., 2020). Although these are not true in situ observations, they make a substantial contribution to information regarding bloom location and impacts.

As cell phone technology and applications improve, continuing to engage community scientists in HAB observing is essential. An example is the National Phytoplankton Monitoring Network (PMN) operated by NOAA in the United States. For over 20 years, the PMN has engaged volunteers including school children in a community/citizen science and educational project to monitor phytoplankton, with a specific focus on HABs, across the country. Volunteers are trained to collect samples and identify numerous species of harmful algae using digital microscopy and a smartphone app, with results reported to NOAA's HAB program.

The program involves more than 600 volunteers who sample nearly 70 sites in 36 states and territories, and the phone app is used in many other countries as well. Although the data do not drive models or forecasts, PMN volunteers have discovered 500 blooms and their data are used as direct inputs for HAB monitoring programs in at least four states and reported to numerous others (Morton and Gano, 2015; NOAA, 2022).

Another example is the Gulf of Mexico-based HABscope project. HABscope is a combination of a low-cost commercial microscope, a 3D-printed adapter, and an iPod. Community scientists are trained and given their own unit. During *Karenia brevis* blooms, they are asked to collect water samples from nearby beaches and place a few water drops under the microscope. Instead of manually identifying and counting the cells, which takes a very high level of training and time, the volunteers take a 30-s video of the sample. The video is uploaded to a site supported by the Gulf of Mexico Coastal Ocean Observing System (GCOOS) and image analysis software then examines the video for cells and estimates a cell count.

The increased number of observations provided by this project allows greatly improved estimations of the spatial, temporal, and intensity characteristics of a bloom (Hardison et al., 2019). In 2021, the project provided over 5000 videos (or cell counts). When compared with the observations produced by the State agency in Florida using traditional methods, this is almost 50% more observations.

To continue to protect public health, the laboratory-based analysis of HAB species and toxins for shellfish and finfish industries will remain the gold standard. However, in situ observations can provide early warning of a HAB event and, therefore, protect public health (Campbell et al., 2010). The scientific community needs to continue to move the many laboratory-based approaches to in-water, real-time observations to better protect public health.

19.6.5 Cyanobacteria and other freshwater HABs

Although cyanobacteria occur in saline as well as in freshwaters and some marine cyanobacteria also produce toxins (Chorus and Welker, 2021), cyanobacterial blooms and the toxins they produce are major water quality concerns for inland surface freshwater lakes and reservoirs (Watson et al., 2015). While freshwater HABs are frequently overlooked and substantially understudied phenomena, they may have huge impacts on human, animal, and ecosystem health and well-being.

Although the responsible algae and cyanobacteria occur naturally, their presence in massive blooms is often a result of both direct and indirect human influences. Examples of direct effects are point source discharges and nonpoint source runoff of nutrients that result in eutrophication (Glibert, 2017) and salinization of freshwaters (Cañedo-Argüelles et al., 2016). Indirect influences from climate change can further stimulate HABs and interact with nutrient pollution to further exacerbate HAB events (Paerl et al., 2016).

Impacts of inland HABs can be severe (Fig. 19.18), as evidenced by high-profile events. For example, a bloom of the cyanobacteria, *Cylindrospermopsis raciborskii*, in a drinking water reservoir on Palm Island (Australia) poisoned people due to hepatotoxicity (Hawkins et al., 1985), and cyanobacterial blooms in Lake Erie, USA, shut down the drinking water supply for Toledo, Ohio, a city of ~400,000 people (Bullerjahn et al., 2016).

In addition, HABs associated with the haptophyte, *Prymnesium parvum*, have severely impacted aquaculture operations and fisheries in inland waters, such that fisheries managers no longer stock some systems because of annual fish kills resulting from HAB events (Brooks et al., 2011). HAB impacts routinely occur across the freshwater-to-marine continuum.

For example, in the case of *P. parvum*, which is a euryhaline species typically studied in coastal and marine systems (Graneli and Solomon, 2009), it has moved inland, resulting in severe impacts in moderately saline waters (Roelke et al., 2011) that are particularly influenced by climate change (Roelke et al., 2012) and salinization of freshwater bodies by natural resource extraction (Renner, 2009) (see Chapter 1).

Other high-profile examples across the freshwater-to-marine continuum include inland cyanobacteria blooms that impact coastal systems. For example, *Microcystis* sp. that blooms in Pinto Lake were transported to Monterey Bay, California, USA, which resulted in intoxication of southern sea otters (Miller et al., 2010); and releases from Lake Okeechobee, Florida, USA, impacted water quality and organisms residing in downstream estuaries (Phlips et al., 2020; Metcalf et al., 2021).

It is thus not surprising that HABs are considered a classic One Health issue, which requires embracing systems-based thinking to advance an understanding of the inherent connections among HAB-forming species,

FIG. 19.18 A large cyanobacterial bloom in Lake Erie. *Photograph by Skypics.com, used with permission.*

environmental factors influencing HAB formation, and subsequent adverse outcomes to human health (CDC, 2022a) (see Chapter 1).

19.6.6 Water quality assessment, observing, and monitoring

Freshwater HABs have been reported from more than 50 countries including most of the states in the United States (Heil and Muni-Morgan, 2021). Inland HABs and associated risks resulting from their toxins are increasingly recognized as major challenges for contemporary water quality assessment and management paradigms (Brooks et al., 2016).

For example, a number of priority research questions aimed at advancing more sustainable environmental quality recently identified HABs as key research needs around the world (Furley et al., 2018; Van den Brink et al., 2018; Fairbrother et al., 2019; Gaw et al., 2019; Leung et al., 2020). Exposure to HAB toxins in recreational waters and source waterbodies for potable water supplies were similarly identified as important issues for environmental public health practice (Brooks et al., 2019). Such observations have been made by diverse professionals working across disciplines in government, academia, and business because severe inland HABs can present the greatest relative water-quality risks to public health and the environment (Brooks et al., 2017).

Just as for HABs in coastal and marine waters, detecting and monitoring harmful blooms of cyanobacteria (CHABs) require both direct surveillance of blooms and their toxins via sampling and indirect observations by remote sensing via a satellite and manned and unmanned aircraft, along with observations of physicochemical factors that may drive or affect bloom formation and toxin production (Bullerjahn et al., 2016). Biochemical testing methods including ELISA (enzyme-linked immunosorbent assay), HPLC-UV (high-performance liquid chromatography with UV), LC-MSMS (liquid chromatography and tandem mass spectroscopy), along with molecular methods [polymerase chain reaction (PCR) and quantitative PCR (PCR/QPCR)] to detect genes involved in toxin synthesis are routinely used and are being deployed on in-water and portable devices and buoys, along with sensors that can detect cyanobacterial pigments.

Other sensors regularly used in limnology and oceanographic studies are employed to collect data on temperature, pH, dissolved oxygen, conductance, and other parameters as needed. A variety of water sampling devices and multispectral sensors for algal pigments can be deployed via boats and ships including the Environmental Sample Processor (ESP) of McLane Research Laboratories, which is being adapted for use with CHABs as well as marine HABs as noted in the marine HAB section. Finally, inexpensive HAB field kits are being developed that can provide rapid indications of whether a putative bloom is in fact a CHAB.

Concomitant with data collection is the use of statistical and process models to explore the mechanics and dynamics of bloom development and toxin production and to forecast the likelihood of CHAB events. While important progress has been made in the development and use of models, much remains to be done, in particular to further understand bloom formation and to accurately forecast blooms and, especially, toxin levels.

In the United States, NOAA's PMN program now includes freshwater HABs in the Great Lakes and other regions. The US EPA provides a well-developed program that could be expanded to support more robust monitoring efforts for cyanobacterial and other HABs (EPA National Aquatic Resource Surveys, 2022); however, the scope of this program presently does not allow for frequent monitoring of algal toxins in inland surface waters.

Satellite imagery has been developed to identify surface cyanobacteria events in near real-time in order to monitor large lakes (>100 ha) (Lunetta et al., 2015). Lakes $>100\,km^2$ in area have shown increases in blooms' magnitude and severity in recent years (Ho et al., 2019; Wilkinson et al., 2022). The high value of satellite monitoring of CHABs has been demonstrated clearly for the Great Lakes and other large freshwater bodies (Bullerjahn et al., 2016; Iiames et al., 2020; Whitman et al., 2022).

Similar to the situation for many anthropogenic chemicals, surface water monitoring and assessment of HABs are not consistently occurring in many countries. When this essential environmental public health service (CDC, 2022b) is occurring, it is most commonly delivered by field collection and examination of algae and cyanobacteria by microscopic methods, or using remotely sensed imagery, often from satellites. Such information is important because microscopic identification of species of concern and observation of algal blooms with remote sensing can serve in a triage function to prioritize additional studies in specific locations.

However, this practice represents a key consideration for water quality assessment and management because the presence of a HAB-forming species does not necessarily translate to the magnitude of the toxins present, or the subsequent risks that specific toxins present to public health and the environment.

Field assessments of cyanotoxins have often used ELISA techniques, which are less expensive and relatively simple to perform. However, ELISA approaches are not as analytically robust as liquid chromatography–tandem mass spectrometry methods, particularly when isotope dilution is employed (Haddad et al., 2019) and commonly cannot distinguish among specific co-occurring congeners or quantify other cyanotoxins of increasing concern (Lovin and Brooks, 2020; Scarlett et al., 2020).

Cyanotoxins have received increased study in recent years and are characterized by diverse biological activities in humans and other organisms, e.g., neurotoxicity, hepatotoxicity, and reproductive and developmental toxicity (Bláha et al., 2009).

It is important to note that these common surveillance methods rely on the preselection of targeted toxins for determination; yet, diverse compounds are produced during HAB events, and their biological activity profiles are largely undefined. Nontargeted analytical chemistry approaches are advancing for diverse organic environmental contaminants (Charbonnet et al., 2022), and present much promise to accelerate HABs research within an ocean and human health context, particularly as efforts to define and predict exposome linkages with adverse human health outcomes progress (Zhang et al., 2021).

Other substances can also be produced by cyanobacteria, including retinoids, which are teratogenic, and endocrine-disrupting contaminants of emerging concern (Pipal et al., 2022). Unfortunately, inadequate availability and quality of existing aquatic toxicology information for microcystins, anatoxins, and cylindrospermopsin currently limit the development of water quality criteria to support freshwater and marine HAB assessment and management activities (Lovin and Brooks, 2020; Mehinto et al., 2021; Scarlett et al., 2020).

Assessing the risks of inland HABs to public health and the environment is further challenged by differential production of toxins across the surface water gradients of nutrients. For example, N:P (nitrogen:phosphorus) stoichiometry and salinity influence the growth, toxin production, and aquatic toxicity associated with *P. parvum* (Baker et al., 2007, 2009; Hill et al., 2020; Taylor et al., 2021), and N:P stoichiometry can similarly influence the production of cyanotoxins by common CHAB-forming species (Osburn et al., 2023; Wagner et al., 2019, 2021). Such information has important implications for developing predictive models of cyanotoxin production during CHAB events (Grover et al., 2022), and thus supporting public health decision-making, particularly as an understanding of N:P, and not just P, and nitrogen fixation progress across the freshwater-to-marine continuum are needed (Marcarelli et al., 2022; Wurtsbaugh et al., 2019).

Fortunately, the new subdiscipline of stoichiometric ecotoxicology is interfacing ecological stoichiometry with environmental toxicology and chemistry by advancing the understanding of nutrient interactions with chemical stressors and nutrient stoichiometric conditions that lead to toxin production (Peace et al., 2021). However, it will be important for future water quality assessment and management efforts for HABs to consider the freshwater-to-marine continuum (Fig. 19.19), given that traditional reductionistic approaches can lead to the development of multiple entities involved with freshwater and marine resource management, including fractured public health responsibilities along the continuum.

Next-generation assessment and management of HABs will require systems-based approaches to understand conditions leading to bloom formation, predict locations where impacts likely will be pronounced, support monitoring and surveillance efforts using robust technologies, and improve the coordination of interventions among natural resource management and public health professionals, particularly as efforts to manage exposures to anthropogenic contaminants progress in the face of climate change.

While some previous studies postulated increased frequency and intensity of HAB events as a result of climate change, more recent analyses suggest that there has been no overall global increase in occurrences of marine HABS over the 30-year period 1990–2019 for which adequate data were available for analysis (Anderson et al., 2021; Hallegraeff et al., 2021). In contrast, global rises in water temperatures and nutrient loading have resulted in increased freshwater cyanobacterial blooms (Zepernick et al., 2022), and the interactions of these blooms with estuarine and coastal waters pose significant and growing health threats.

As the world population continues to increase and more people move to the coast, the demands for water-based recreation, protein-rich foods such as fish and shellfish, and potable water will also continue to increase, making protection from HAB toxins a continued public health and oceanography challenge that will require greater HAB observation and monitoring capacity and increased coordination and collaboration between scientists studying marine and freshwater HABs.

19.7 Observing and monitoring naturally occurring infectious microbes (*Vibrios*)

19.7.1 Major *Vibrio* bacterial illnesses

Of the millions of bacterial species in the world today, there are only 1415 known to cause disease in humans (Scott et al., 2019). The oceans alone harbor about two million bacterial species (Curtis et al., 2002). These include a variety of *Vibrio* species that are common in salt and brackish waters globally. Because of their natural occurrence and ubiquity in many coastal and marine waters and their ability to cause significant illness and

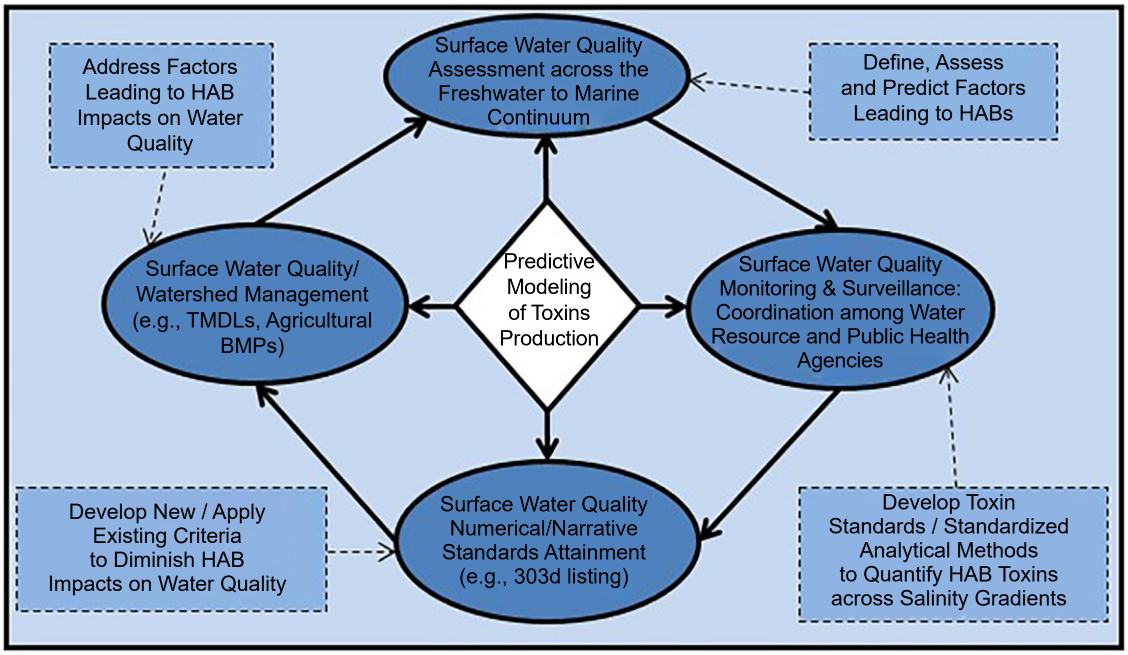

FIG. 19.19 A conceptual model of research (dashed rectangles) and management (solid ellipses) of harmful algal blooms across the freshwater-to-marine continuum exemplified within an existing regulatory framework of the US Clean Water Act. HAB = harmful algal bloom; TMDL = total maximum daily load; BMP = best management practice. *Figure modified from Brooks BW, Lazorchak JM, Howard MDA, et al.: Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems?* Environ Toxicol Chem *35:6–13, 2016, and used with the permission of the first author.*

death in humans, we include them here as a primary example of naturally occurring infectious disease agents in the oceans (see Chapter 12).

*Vibrio*s are rod-shaped, Gram-negative bacilli that may inhabit estuarine and marine environments, where they persist in both culturable and nonculturable states and tolerate a wide range of salinities and temperatures (Ramalingam and Ramarani, 2006; Alam et al., 2009; Osunla and Okoh, 2017).

Vibrio cholerae, the causative agent of cholera, is by far the best known for its ability to cause illness via the consumption of contaminated potable water and seafood. Two other species, *Vibrio parahaemolyticus* and *Vibrio vulnificus*, occur naturally in recreational waters and may cause major gastrointestinal illness, serious wound infections, and death via consumption of contaminated seafood and recreational contact (Sanderson and Tapp, 1998).

*Vibrio*s are often highly virulent due to their extremely short life cycle (around 13 min), and abilities to reproduce by binary fusion (splitting their DNA in half quickly) and to incorporate new genes from mutations, plasmids, or bacteriophages. These attributes result in a genetic process which permits the addition of new genes into the chromosome quickly (Crawford, 2007), enabling *Vibrio*s to be very adaptive to the environment and possibly enhancing their virulence and/or antibiotic resistance (Baker-Austin et al., 2010).

V. cholerae is a free-living marine bacterium that occurs in marine and brackish waters and has limited mobility by lashing its whip-like flagellum (Crawford, 2007). It can live independently of human or animal reservoirs in estuarine waters where it clings to chitinous surfaces of arthropods such as copepods or other shellfish and to diatoms (Crawford, 2007; Lutz et al., 2013).

During algal blooms, *Vibrio*s are also capable of concomitantly increasing their abundance and as a result infect humans (Crawford, 2007; Faruque et al., 2005). Annually, approximately 120,000 deaths are estimated to be caused by cholera worldwide, with most associated with contaminated drinking water and poor sanitation. Illnesses from the consumption of molluscan shellfish also occur. Illnesses associated with cholera typically last 4–6 days (Howard-Jones, 1984) and can have a high mortality rate, if untreated.

Cholera outbreaks often occur after natural disasters due to contaminated drinking water and poor sanitary conditions (Scott et al., 2019). For example, following a large earthquake in Haiti in 2010, there was a significant cholera outbreak, which infected >790,000 Haitians, resulting in >9000 deaths. This was the worst cholera epidemic in recent history, according to the US Centers for Disease Control and Prevention (Centers for Disease Control and Prevention (CDC, 2016). The Haiti cholera outbreak later spread to neighboring countries including the Dominican Republic (31,070 cases), Cuba (678 cases), and Mexico (171 cases) with additional cases reported in Venezuela and in Florida in the United States.

In addition to *V. cholerae*, both *V. vulnificus* and *V. parahaemolyticus*, occur widely in coastal waters, are taken up by molluscan shellfish and other seafood and may also pose a significant disease risk via ingestion and wound infections in exposed coastal populations (Fig. 19.20).

Environmental factors associated with the occurrence of *Vibrio*s include temperature, salinity, and pH and shifts in these parameters associated with climate change, and exposure to nutrients and trace metals can affect gene expression (Baker-Austin et al., 2006, 2013; Correa Velez and Norman, 2021). These climate change and environmental factors often cause *V. vulnificus* to overexpress genes involved in biofilm formation, which in turn results in highly virulent and antibiotic-resistant strains, which cause severe illness and death (Correa Velez and Norman, 2021) (see Chapter 10).

For *V. vulnificus*, note that only 13% of all illnesses with this organism in the United States were associated with foodborne exposure, primarily seafood. Approximately 60% of the illnesses are nonfoodborne and primarily wound infections. Dechet et al. (2008) reported the recorded cases of nonfoodborne *Vibrio* Illnesses (NFVIs) in the United States from 1997 to 2006, with 1210 out of a total of 4754 *Vibrio* illnesses (25%) being NFVIs. Recreational activities (e.g., swimming, wading, and boating) accounted for 70% of exposures for patients with NFVIs associated with all *Vibrio* species.

Conversely, the majority of illnesses associated with *V. cholerae* and *V. parahaemolyticus* were foodborne, associated with the consumption of seafood. Globally, Trinanes and Martinez-Urtaz (2021) estimated a half million *Vibrio* illness cases in 2020. *Vibrio*s are predicted to significantly expand in the future due to climate change, in terms of both temporal and spatial coverage, which is expected to lead to increased disease burden.

Trinanes and Martinez-Urtaz (2021) predict that, by 2100, an additional 38,000 km of coastline will experience incidences of *Vibrio* illness under the most unfavorable climate change modeling scenario. Temporally, these authors projected that the seasonal periods suitable for these pathogens would also increase, with an expansion rate of around one additional month of illness/year every 30 years.

19.7.2 Environmental factors affecting *Vibrio* illnesses

Other environment-related factors that may be associated with the increased virulence and highly antibiotic resistance nature of *Vibrio* infections today include rapid growth of coastal populations, urbanization, and industrialization along with attendant increases in coastal pollution (Baker-Austin et al., 2006, 2013; Correa Velez and Norman, 2021; Vernberg et al., 1997).

Baker-Austin et al. (2008, 2009) reported that >98% of *V. parahaemolyticus* and *V. vulnificus* in southeastern US coastal waters are resistant to as many as 13 (average 8) mainline antibiotics. Correa Velez and Norman (2021) stated that increased nutrient levels associated with sewage effluent caused genetic changes in *V. vulnificus* which led to increased downregulation of genes involved in motility and more upregulation of genes involved in biofilm formation.

Increased biofilm formation may result in greater adherence of *Vibrios* to particles, including cyanobacteria (Faruque et al., 2005; Greenfield et al., 2017) and

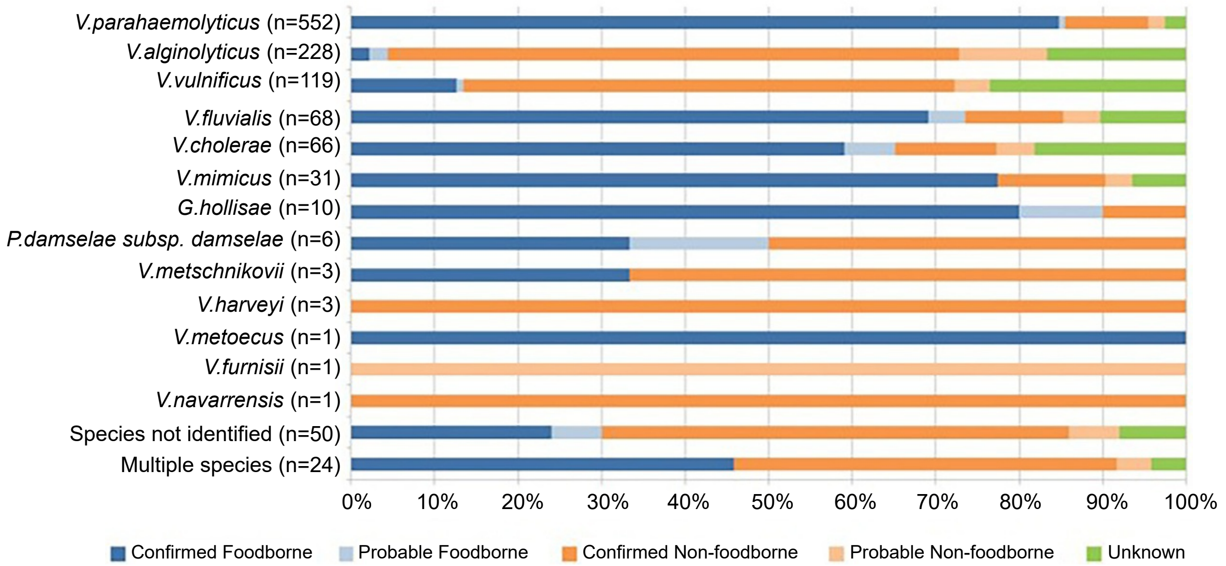

FIG. 19.20 Major causes of *Vibrio* illness in the United States in 2014, by species and by foodborne versus nonfoodborne routes (CDC, 2016).

microplastics (Amaral-Zettler et al., 2020), which may be bioaccumulated by nonspecific particle-feeding molluscan shellfish. These factors could increase *Vibrio* levels in molluscan shellfish consumed by the public [e.g., a serving of oysters may contain as many as 335 microplastic particles (Weinstein et al., 2022)]. In addition, increased biofilm formation has often been associated with increased antibiotic resistance (Gupta et al., 2018) and virulence (Castillo et al., 2018) in *Vibrio*s (Fig. 19.21).

Eutrophication is increasing in estuaries in the United States and around the world (Bricker et al., 1999, 2007; Malone and Newton, 2020) and may be stimulating the upregulation of biofilm genes in *V. vulnificus*, as observed in response to increased nutrient exposure. This may be a "tipping point change" that is helping to drive surges in *Vibrio* disease, along with increased human host risk factors such as higher levels of obesity and underlying liver disease.

These and related climate change influences likely have played significant roles in the increased occurrence of *Vibrio* illnesses in the United States from >4000 estimated cases in 2004 to >80,000 estimated cases in 2022 (CDC, 2022a). The combination of environmental and climate change, and increased host susceptibility factors may, in part, contribute to these recent increased levels of *Vibrio*-related seafood and wound infections noted globally (Harrison et al., 2022; Trinanes and Martinez-Urtaz, 2021; Vezulli et al., 2016).

19.7.3 *Vibrio* forecasts: Reducing exposure to these risk factors

In 1854, Dr. John Snow recognized that part of treating cholera required viewing patients not as individual cases but as a representative sample of the whole population and in relation to their responses to stressors from their surrounding environment. Viewing the patient temporally and spatially within the environment in which they live revealed important information (Ruths, 2009).

Snow's use of geographic maps and correlations of the outbreak with drinking water sources served as the logic to support the development of public health interventions needed to control London's cholera epidemic in the 1800s. This approach helped provide the foundation for modern epidemiologists who, today, view the strength, severity, and propagation of infectious diseases as a product of humans and their bio-physicochemical environment (see Chapter 20).

Today, epidemiology underpins our understanding of large-scale, rapid-onset infections around the globe such as the COVID-19 pandemic caused by the SARS-CoV-2 virus, and recent epidemics of SARS (Severe Acute Respiratory Syndrome), MERS (Middle East Respiratory Syndrome), and the H1N1 virus (swine flu). Epidemiologists track cases, monitor the threat of global pandemics, and develop predictive models based on important environmental and human risk factors in order to warn and inform the public and prevent/minimize exposure.

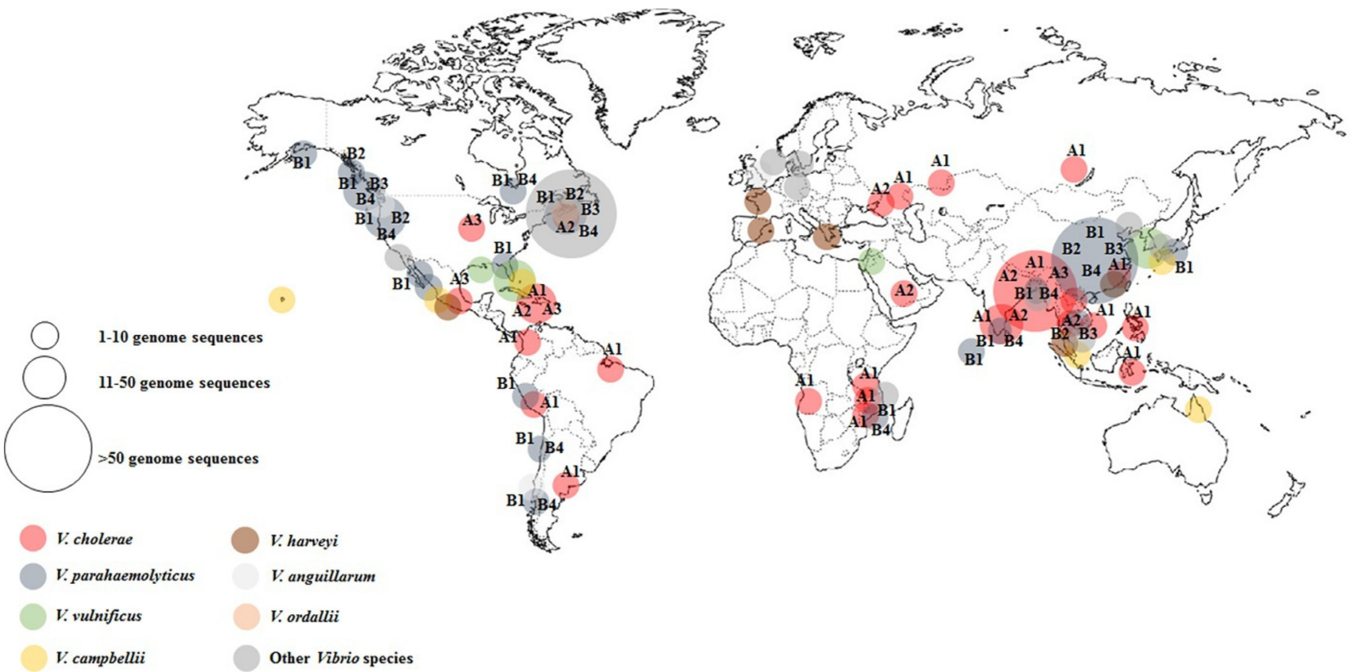

FIG. 19.21 Global geographical distribution of zot-encoding prophages, which cause virulence in *Vibrio* species. Zot refers to the zonula occludens toxin and prophages are genetic material from viruses that infect bacteria. Color blocks represent different *Vibrio* species most abundant in databases. Circle size is proportional to the number of *Vibrio* genome sequences carrying a zot-encoding prophage in a specific geographic location. The main phylogenetic groups identified are for *V. cholerae* (A1–A3) and V. parahaemolyticus (B1–B4) are included in the figure to facilitate comparison. *From Castillo D, Kauffman K, Hussain F, et al.: Widespread distribution of prophage-encoded virulence factors in marine Vibrio communities,* Sci Rep *8(1):1–9, 2018, used with the permission of the corresponding author.*

Using environmental forecasts to alert the public and prevent exposure is the 21st-century approach to preventing, managing, and controlling infectious disease, along with the development of vaccines and therapeutics. That is precisely what international, regional, and local health agencies do as was apparent during the COVID-19 outbreak. Public health warnings provided via a variety of media, including social media, inform and caution the public about health risks.

Expanding this approach with *Vibrio*s will include enhanced interactions with health practitioners including physicians, epidemiologists, environmental scientists, and microbiologists, all of whom play critical roles in rapidly diagnosing illnesses and reporting cases to public health databases. This will increase the ability of epidemiologists to view disease cases within the context of communities and the surrounding environment, just as Dr. Snow viewed patients in London >165 years ago.

Better reporting of *Vibrio* occurrence and illness cases, sequencing, and the use of remote sensing have supported modeling that clearly indicate that *Vibrio* illnesses are being reported at higher latitudes and throughout longer periods of time each year throughout the globe (Baker-Austin et al., 2020). These changes in the spatial distributions of *Vibrio* illness to higher latitudes appear to be due to rising ocean temperatures globally and increased salinities in areas upriver from estuaries due to sea level rise and flooding. This trend underscores the role climate change may play today, just as the transition to urbanization and problems of poor sanitation played in London's cholera outbreaks in the 1850s.

The integration of remote sensing, risk mapping of optimal growth conditions, genomic sequencing, and microbial ecology has led to enhanced data visualization techniques, which better inform the public and provide a far more cohesive understanding of the risk posed by pathogenic *Vibrio*s (Baker-Austin et al., 2020).

Today, global climate change and environment scientists are developing more complex remote sensing, epidemiological mapping, and molecular sequencing tools, which have led to the development of ecological forecast models to better inform the public and prevent illnesses caused by *Vibrio* bacteria (Baker-Austin et al., 2020; Deeb et al., 2018; Muhling et al., 2017; Paranjpye et al., 2015).

As an example, NOAA has developed a *Vibrio* forecast model for the Chesapeake Bay to warn people of the increased abundance of *Vibrio*s, so that individuals at high risk from infections may avoid exposure (Muhling et al., 2017). This forecast is based upon an algorithm that uses temperature, salinity, and other variables to predict "hotspots" or locations of high *Vibrio* bacterial abundance (Fig. 19.22).

Muhling et al. (2017) forecast model predictions using a high-emissions climate scenario and greatest increased temperature model indicated that by 2100, *V. parahaemolyticus* occurrences could increase by 150%–300% in Chesapeake Bay. Similarly, the probability of *V. vulnificus* occurrence increased markedly across the Bay during the peak summer season, and the overall area of high probability expanded across most of the Bay (Fig. 19.22).

Conversely, future forecast projections for *V. cholerae* did not indicate substantial changes as the observed salinity association of *V. cholerae* restricted its distribution to the upper Chesapeake Bay and major rivers, with little expansion of habitat under future climate change scenarios. These findings underscore the significant differences in response to climate change among these three *Vibrio*s of public health significance; and how complex eco-forecasting can be, as risk will vary not only with occurrence and distribution but also with human exposure via seafood consumption and wound contact.

A similar climate change forecast model to predict current and future changes in optimal growth conditions for *V. vulnificus* with different sea level rise conditions was developed by Deeb (2013) and Deeb et al. (2018) (Fig. 19.23). Initially, an algorithm was developed to predict *V. vulnificus* abundance using temperature and salinity as the primary predictive variables along with sea level rise. Next, an integrated neural network model was constructed using climate models to forecast long-term changes in temperature and precipitation. Both a land surface runoff model [e.g., Parameter elevation Regression on Independent Slopes Model (PRISM)] associated with increasing or decreasing predicted precipitation and a sea level rise model affected salinity.

This neural network model made it possible to forecast future changes in salinity and temperature, which could then be applied to the *V. vulnificus* algorithm to predict increases or decreases in optimal growth conditions. The results of this modeling indicated that sea level rise-associated changes in salinity have greater impact than temperature per se on increased *Vibrio* exposure risk, particularly in brackish watersheds located upstream of many estuaries. The model demonstrated that continued sea level rise will result in increases in optimal growth conditions for *V. vulnificus*, with exposure risk increased by 2070 compared to current conditions.

The largest temporal increase was observed at the most upriver sites where, currently, *Vibrio* exposure risk is low. This suggests that many current brackish water areas at the upper end of estuaries will be most affected as salinity as well as temperature change under future climate conditions. Identifying these areas as *Vibrio* Vulnerable Areas now provides opportunity for their expanded monitoring as early warning indicators of risk and thus to deliver public warnings to reduce exposure.

Current forecast models predict the abundance of *Vibrio*s, which would generally have the potential for greater genetic diversity including risk factors such as virulence and antibiotic resistance. These risk factors have

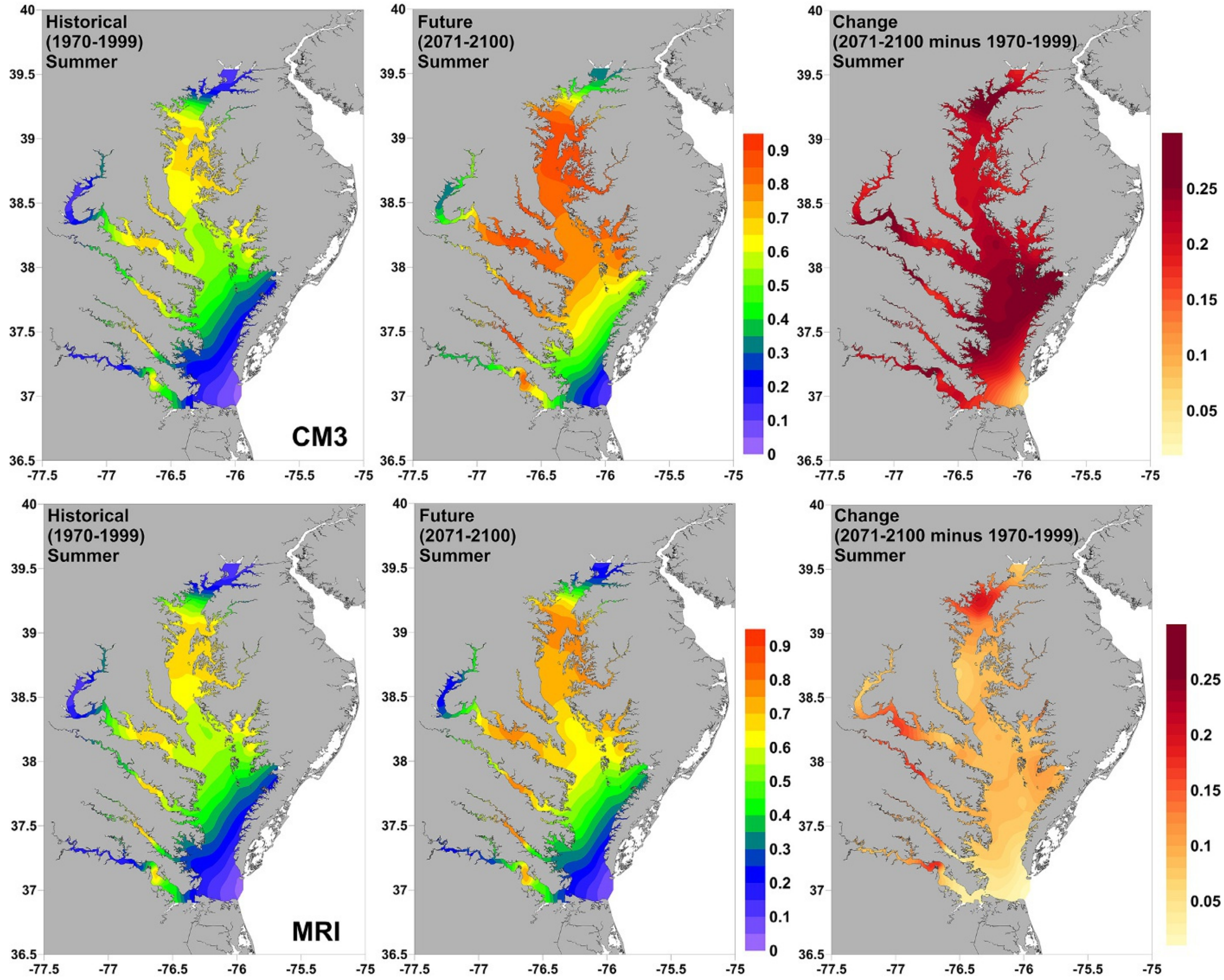

FIG. 19.22 Projections of increased *Vibrio vulnificus* abundances in the Chesapeake Bay due to increased temperatures associated with climate change. Color codes represent the past (1970–1999) and projected future (2071–2100) increases in *V. vulnificus* abundances throughout the Chesapeake Bay as a result of increased global temperatures associated with climate change. Also, the percent difference between the past and future is indicated (third graph of each model). Two global climate change scenario models were used including the CM3 (climate scenario with the greatest increased temperature) (top 3 graphs) and the MRI (climate scenario, which had the least amount of future increased temperature) (bottom 3 graphs). Note the significant differences between both models in past and future *V. vulnificus* abundance projections as indicated by color code changes (i.e., more orange and red tones), particularly the increased abundance in the mid- and upper-bay regions with both models (e.g., 15%–25% increases throughout most of the Chesapeake Bay during the 21st century in the CM3 model). *From Muhling BA, Jacobs J, Stock CA, et al.: Projections of the future occurrence, distribution, and seasonality of three Vibrio species in the Chesapeake Bay under a high-emission climate change scenario,* GeoHealth *1:278–296, 2017, used with the permission of the first author.*

been highly correlated with human *Vibrio* illness (Scott et al., 2019).

Resistance of *Vibrio*s to a wide range of antibiotics commonly used to treat infections is an area of growing concern (see Chapter 12). For example, Baker-Austin et al. (2008, 2009) showed that 99% of the *V. vulnificus* and *V. parahaemolyticus* along the South Atlantic coast of the United States were resistant to as many as 13 antibiotics, with most strains resistant to multiple antibiotics.

Other environmental factors besides climate change may be very important in future forecast models including concentrations of nutrients, antibiotics and other pharmaceuticals, personal care products, and microplastics from wastewater treatment plants and other pollution sources (e.g., urban nonpoint source runoff) (Uyaguari et al., 2011; Scott et al., 2012; Muraya et al., 2013).

Increased nutrient pollution associated with agricultural runoff, discharges of treated and untreated sewage, pet waste, runoff from lawns and roadways, and industrial processes may result in eutrophication and significant ecological changes in the microbial community, including increased abundances of cyanobacteria and other HAB species and hypoxia (Brooks et al., 2016). Higher nutrient levels also may boost virulence in *Vibrio*s.

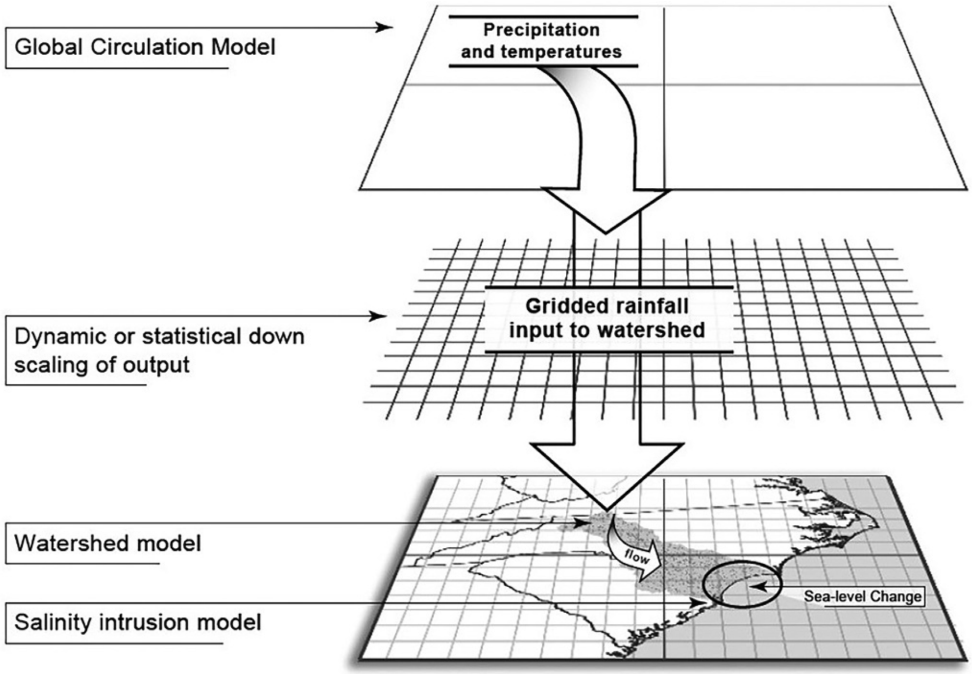

FIG. 19.23 Neural network model developed by Conrads et al. (2013) and applied to *Vibrio* by Deeb (2013) and Deeb et al. (2018). *This figure is from a US Government publication.*

Burgeoning human populations in coastal areas will produce more sewage effluent, which may ultimately impact nutrient levels and water quality. Conrad and Harwood (2022) reported that the addition of 1% sewage to estuarine water caused the density of both a pure culture of *V. vulnificus* and a natural *V. vulnificus* population to increase by two to three orders of magnitude (100–1000-fold). Correa Velez and Norman (2021) similarly reported that exposure of *V. vulnificus* to sewage effluent decreased the expression of genes involved in motility while increasing the gene expression of biofilm formation. Thus, human exposure to estuarine waters containing *Vibrio* bacteria and filter-feeding shellfish that concentrate *Vibrio*s could lead to greater health impacts in the future.

Increased biofilm formation would result in *Vibrio*s adhering to more particles and surfaces and may also possibly increase antibiotic resistance. *Vibrio*s also are known to grow on microplastic detritus, and Amaral-Zettler et al. (2020) found that *Vibrio*s were the dominant bacterial colonizers in North Sea sediments and North Atlantic Ocean waters. Microplastic waste can be consumed by bivalve mollusks, potentially leading to higher *Vibrio* levels in the shellfish consumed by the public.

Preventing exposure of high-risk individuals to pathogenic *Vibrio* bacteria is the key to reducing *Vibrio* illnesses in the future. Current *Vibrio* forecast models provide the visualization tools needed to better alert and inform the public. These, along with future improvements in the monitoring of *Vibrio* populations and predictive modeling, coupled with enhanced community engagement tools, will provide robust public health warnings, and advance our understanding of *Vibrio* ecology and associated illnesses.

The inclusion of antibiotic resistance and virulence factors into future *Vibrio* occurrence/abundance forecasts will improve the accuracy and precision of these forecast models to better protect public health and prevent exposure and development of the disease.

19.8 Observing and monitoring marine mammals

Sentinel organisms can provide indications of environmental stress and potential health threats to humans and other organisms (Sandifer et al., 2007) (see Chapters 7 and 20). Because of their many similarities to humans, marine mammals are excellent examples of such sentinels (Bossart, 2011).

As air-breathing mammals, they are susceptible to chemical pollutants, biological toxins, and infectious pathogens through inhalation exposure pathways, as are humans. Many marine mammals, including Mustelidae (sea otter and chungungo), Odontoceti (toothed whale), Ursidae (polar bear), and all Pinnipedia (seals), are carnivorous. They feed on fish, cephalopods, crustaceans, bivalves, or even other marine mammals, making them susceptible through ingestion exposure routes similar to those for humans.

Many marine mammals fill an upper trophic position in marine food webs and are thus highly exposed to persistent organochlorine pollutants (POPs) that are biomagnified through the food chain (see Chapter 13). The similar physiology to humans as compared to other marine species, the potential for high exposure to biomagnified pollutants, and susceptibility to chemicals, toxins, and pathogens in the air make marine mammals important and valuable indicators of hazards to humans in coastal and open ocean environments.

19.8.1 Chemical hazards

People living in coastal communities represent more than 34%–45% of the global population (UN Atlas of the Oceans, 2022). Many coastal residents consume local seafood, which can be an important route of exposure to chemical contaminants (see Chapter 4 and 13).

Marine mammal species that inhabit coastal waters, and particularly populations that have limited or regional movements, often consume seafood from the same local sources as coastal residents. In fact, a human-dolphin cooperative fishery has been described in Southern Brazil, where bottlenose dolphins or "botos" (Tursiops truncatus) assist local fishermen in locating and herding fish (Pryor and Lindbergh, 1990; Zappes et al., 2011).

Because marine mammals ingest whole fish rather than fillets, and in greater quantities than their human counterparts, their exposure to chemical contaminants from the fish can be much higher. Lipophilic contaminants in seafood can accumulate in the lipid-rich blubber of marine mammals, reaching extremely high concentrations. For this reason, some researchers monitor marine mammal tissues, including blubber, skin, blood, or organs to provide an early warning of chemical contaminants to which humans may be exposed.

Since marine mammals are protected species in the United States, organs are sampled from dead animals (e.g., those that get stranded on the shore), are by-caught in fisheries, or hunted for subsistence purposes as provided under the Marine Mammal Protection Act (16 U.S.C. §§1361 et seq.). However, stranded animals often die as a result of disease and may have depleted lipid stores; thus their contaminant concentrations may not be representative of the population from which they came. Decomposition may further limit the usefulness of samples.

In contrast, fresh samples of blubber and skin can be obtained readily using remote biopsy sampling techniques (Weller et al., 1997; Krahn et al., 2007; Sinclair et al., 2015). Remote samples can be obtained, for example, by using a crossbow or rifle to shoot a small hollow-ended dart at a marine mammal. As the dart bounces off the animal, it pulls out a small plug of skin and blubber and then floats in the water for ease of collection by scientists.

Remote biopsy allows researchers to collect relatively large sample sizes and to have greater control in sample selection. Smaller and more logistically tractable species such as some delphinids (dolphins), phoeconids (porpoises), and pinnipeds (seals, sea lions, walruses), can also be temporarily caught for the sampling of blubber, skin, blood, urine, and feces (see Barratclough et al., 2019 for a review of bottlenose dolphin catch-release health assessment studies). New methods are also rapidly evolving to expand remote sampling options for species such as large whales for which hands-on sampling is not possible (Marangi et al., 2021; Pasamontes et al., 2017).

Measures of POPs, dioxin, metals (e.g., mercury), polybrominated biphenyls, per- and polyfluoroalkyl chemicals, and other emerging chemical contaminants of concern have been reported from marine mammal studies across geographically diverse areas, providing information on spatial and, in some cases, temporal, trends. A meta-analysis of polychlorinated biphenyls (PCBs) and other POPs in killer whales and multiple dolphin species from across the European coast identified global PCB "hotspots"; and concluded that despite regulations to reduce PCB contamination, persistent chemicals in the marine environment continue to be of concern (Jepson et al., 2016).

In the US, some of the highest POP concentrations have been reported in bottlenose dolphins from the Turtle/Brunswick River Estuary and near Sapelo Island on the Georgia coast (Kucklick et al., 2011). A study that compared bottlenose dolphin POP concentrations to those measured from adjacent human communities, one of which was a community on Sapelo Island, found that the dolphin contaminant concentrations reflect the patterns and levels of pollutants in the people, but with dolphin blubber concentrations being up to three orders of magnitude higher (Backer et al., 2019).

Recent research also suggests that marine mammals can be good indicators of plastic pollution. Due to their feeding ecology and widespread distribution, two cetacean species, sperm whales (*Physeter microcephalus*) and fin whales (*Balaenoptera physalus*), have been suggested as global indicators of macro- and microdebris, respectively (Fossi et al., 2020). A more regional analysis concluded that river dolphins (*Pontoporia blainvillei*), South American fur seals (*Arctocephalus australis*), and South American sea lions (*Otaria flavescens*) have key attributes important for the selection of indicator species in the Southwest Atlantic and specifically in the Rio de la Plata estuary (González Carman et al., 2021), with localized movements, documentation of plastic interaction, ease of sampling, and high public profile contributing to their selection.

While analysis of the gastrointestinal tract is the standard approach for assessing the occurrence of ingested plastic in stranded or by-caught animals, methodological approaches are emerging for measuring the concentration of plastic additives or assessing biomarkers of toxicological effects from remote biopsy samples of live marine mammals (Fossi et al., 2020).

In addition, for bottlenose dolphins that are amenable to hands-on sampling, concentrations of urinary metabolites of phthalates (chemicals added to plastics, personal care products, and other common goods) have been measured and compared with concentrations reported for humans from the National Health and Nutrition Examination Survey (NHANES) (Hart et al., 2020). While the significance of phthalate exposures is still not well understood, initial research in dolphins indicates that the exposure may be impacting thyroid hormone homeostasis, offering insight into potential mechanisms for adverse health effects (Dziobak et al., 2022).

Some biomonitoring programs include the sampling of marine mammals either as indicators of contaminants in the food web or to directly assess exposure risk for indigenous people that consume marine mammals. For example, the Arctic Monitoring and Assessment Programme (AMAP) includes monitoring of marine mammal tissues to understand health risks for Arctic communities, and this information is particularly important now as the scientific community as well as indigenous communities strive to understand how climate-related changes may affect contaminant accumulation, movement, and future human health and ecological risks in the Arctic (AMAP, 2021).

Marine mammals not only provide an indication of potential exposure for people but also may provide insight into possible health effects and adverse outcome pathways. Long-term studies of California sea lions (*Zalophus californianus*) have not only provided insight into temporal trends of POP exposure along the US west coast (Randhawa et al., 2015), but also demonstrate that POP exposure increases the odds of developing urogenital cancer in sea lions that are also infected with herpes virus (Gulland et al., 2020). As virally associated cancers also occur in people, this link with exposure to marine contaminants may have significance for human health.

In addition, studies following the Deepwater Horizon oil spill in the Gulf of Mexico found consistency in the types of oil-associated toxic responses observed across vertebrate species, including respiratory system abnormalities in both humans and bottlenose dolphins (Takeshita et al., 2021).

19.8.2 Harmful algal toxins

Similar to chemical contaminants, marine mammals can be exposed to harmful algal toxins as described earlier in Section 19.4, through inhalation or ingestion, and can provide an early warning of toxin vectors, and insight into adverse outcome pathways. Since the late 1990s, observed neurotoxic effects in California sea lions from domoic acid (DA) exposure have contributed to the understanding of adverse outcome pathways that lead from the ingestion of DA through fish, binding of receptors in the brain, cell death in portions of the hippocampus, neurological effects including disorientation, ataxia, and seizures, and ultimately to reduced survival and reproductive failure (Bejarano et al., 2008; Goldstein et al., 2009; Gulland et al., 2002).

The regular occurrence of *Pseudo-nitzschia* blooms along the US west coast and the high number of animals exposed have made California sea lions a model system for understanding DA toxicity (Anderson et al., 2021).

Similarly, studies of stranded manatees during *Karenia brevis* blooms along the Florida coast have helped scientists to understand acute respiratory effects as well as longer term immune effects related to brevetoxin exposure in marine mammals as well as in humans (Bossart et al., 1998; Fleming et al., 2005; Walsh et al., 2015). Studies of bottlenose dolphins and manatees in the northern Gulf of Mexico led to the initial discovery that brevetoxin can accumulate in the marine food web and be a vector for toxin exposure even after the dissipation of a bloom (Flewelling et al., 2005). More recent strandings of rough-toothed dolphins (*Steno berdanensis*) provide the first account of brevetoxicosis in the eastern Atlantic Ocean and suggest a potential link to climate change (Fernández et al., 2022).

The decline of Scottish harbor seal (*Phoca vitulina*) populations led to the discovery of chronic exposure of the seals to both DA and saxitoxins through the consumption of contaminated fish, and a link to immunomodulatory effects including lymphocytopenia and monocytosis (Jensen et al., 2015).

19.8.3 Infectious disease

Prior OHH research suggests that marine mammals are not only useful sentinels of infectious disease in the marine environment, but, in some cases, may also be vectors for disease transmission (Bogomolni et al., 2008; Bossart, 2011) (see Chapter 12).

The potential for marine mammals to be pathogen vectors is supported by findings of zoonotic pathogens such as *Brucella* spp., *Leptospira* spp., and avian influenza viruses in multiple coastal marine mammal species, particularly bottlenose dolphins, California sea lions, and harbor seals (*P. vitulina*) (Anthony et al., 2012; Bodewes et al., 2015; Bogomolni et al., 2008; Bossart, 2011; Prager et al., 2020; Wu et al., 2014). In fact, a recent study revealed that the adaptation of an influenza virus of avian origin (avian A/H10N7) to seals led to the transmission of the virus between mammals (Herfst et al., 2020).

Surveillance of pathogens in marine mammals, regardless of whether marine mammals are a reservoir for the pathogens, can contribute to the understanding of patterns and severity of contamination in coastal waters. Screening of fecal and blowhole swabs collected from live bottlenose dolphins along the southeastern US coast found multiple bacterial species associated with human illness, including *Vibrio* spp., *Escherichia coli*, and even a strain of methicillin-resistant *Staphylococcus aureus* (MRSA) (Stewart et al., 2014). The study also found widespread antibiotic resistance with the percentage of antibiotic-resistant isolates varying across regional study sites.

A more recent study concluded that microbiomes of gray seals (*Halichoerus grypus*) are modified by their adjacent terrestrial habitat, and the study authors suggest that seal microbiomes could potentially be monitored and contribute as part of an environmental quality index (Watkins et al., 2022).

With a changing climate and resulting potential redistribution of marine pathogens, marine mammals could also become important indicators of shifting disease risk (Gulland et al., 2022). For example, lobomycosis is a chronic, skin and subcutaneous fungal infection known to affect only dolphins and humans.

First described in 1931, human cases have been reported in multiple South American countries, particularly in the Brazilian Amazon region; and, by 1950, cases were also reported in Central America (Francesconi et al., 2014). Dolphin cases are also observed in tropical regions (Van Bressem et al., 2007); and the fungal disease has now become endemic in bottlenose dolphin populations in transitional tropical regions of North America (e.g., Florida) (Hart et al., 2011; Murdoch et al., 2008), and at least one dolphin case has now been reported as far north as the North Carolina coast (Rotstein et al., 2009).

As the Arctic has warmed due to climate change, screening of polar bear (*Ursus maritimus*) serum has revealed an increase in the prevalence of antibodies to several bacterial pathogens (*Francisella tularensis*, *Bordetella bronchiseptica*) and zoonotic parasites (*Toxoplasma gondii*, *Trichinella* spp.) (Pilfold et al., 2021).

Live catch-release assessments and screening of tissues from stranded or harvested marine mammals detected the emergence of *V. parahaemolyticus* (Vp) in regions of Alaska where the bacterial pathogen, which proliferates in waters of 15°C or above, had not previously been detected (Goertz et al., 2013). Sea otters (*Enhydra lutris*), which consume primarily shellfish, had the highest prevalence of Vp isolates, but bacteria were also detected in tissues of a beluga whale (*Delphinapterus leucas*) and harbor porpoise (*Phocoena phocoena*) (Goertz et al., 2013).

All the aforementioned pathogens can infect humans, and their detection outside of previously known ranges underscores the utility of marine mammals as sentinels for the shifting distribution of infectious agents as marine ecosystems are altered by climate change.

19.9 Coastal human health observing system: A vision for the future

Approximately one-third to one-half of the global population (depending on country and region) reside in a narrow band of shoreline land that borders oceans, seas, estuaries, and very large lakes such as the Lawrencian Great Lakes and Lake Baikal. In addition, 8 of 10 of the world's largest cities are coastal UN Atlas of the Oceans, 2022, with some facing existential threats from global sea level rise (see Chapter 1).

Coastal areas are particularly vulnerable to a range of climate change effects due to their high population densities (in the US, coastal shoreline and watershed counties have 3–4 times the population density as inland counties), the relatively greater proportion of retired and elderly people who live there, their typically low elevation above sea level, and their large contributions to national economies, tourism, and fishing industries (Sandifer and Scott, 2021). Other coastal areas of the world have similarly high population densities, particularly in Asia (e.g., China), with rapid growth also in Africa (Neumann et al., 2015).

Recent studies have reported significant associations between better self-reported health and very near-coast residency and even following short-duration visits to coastal areas (White et al., 2020). However, most of these reports are based on data from developed countries, and the situation in lesser developed areas is poorly explored. A few studies have found no association or negative results for health and/or resiliency in some coastal areas (Sandifer et al., 2021b; Summers et al., 2021) (see Chapter 8).

Living, working, or visiting coastal areas also results in exposure to a wide range of potential health hazards, including HABs and their toxins; naturally occurring and pollution-derived infectious disease organisms; chemical pollution; risks of drowning and mechanical injury from storms and floods; stress-associated mental health disorders resulting from potential or realized loss of livelihoods, housing, and way of life from coastal disasters; and others (see Chapter 9). Thus, at local to global scales, a substantial portion of the global population is regularly exposed to both potentially health-enhancing and health-threatening characteristics associated with being near the ocean or other large bodies of water.

Environmental observing systems (e.g., for weather and climate) provide the data that underpin daily weather forecasts that, in turn, give rise to critical warnings for major hazards such as tropical cyclones, floods, and droughts, as well as longer-term predictions of climate trends. Many people throughout the world depend on such forecasts for making decisions about daily life, business, protection of life and property, and long-term survival and resiliency of their communities.

Unfortunately, similar comprehensive observing systems that continuously collect baseline health information for human populations and enable robust predictions and timely warnings of a broad range of potential health hazards are generally lacking. The dearth of baseline health information for populations that may be exposed to environmental disasters like the 2010 Deepwater Horizon oil spill prompted the development of a framework for a community health observing system in the US Gulf of Mexico region (Sandifer et al., 2020) and the potential to use it as a basis for the creation of linked regional health observing systems in the United States and elsewhere (Sandifer, 2022).

The Gulf of Mexico human health observing system framework uses national, mostly cross-sectional health and community surveys [e.g., the US Centers for Disease Control and Prevention's (CDC) Behavioral Risk Factor Surveillance System (BRFSS)] to provide general population health and community characteristics for comparative purposes. However, its central components are proposed long-term, longitudinal, cohort studies comprised of volunteer participants.

In this context, a "cohort" is a group of people each of whom agrees to participate in periodic health assessments over a relatively long period of time (e.g., 10 years to multiple generations) to enable health professionals and scientists to track changes in health parameters over time and identify specific causes of certain effects. While only aspirational as of this writing (late Fall 2022), there is potential for the development of enhanced human health observing systems, not only in disaster-prone regions such as the US Gulf of Mexico, but also more generally (Sandifer, 2022) (see Chapter 20).

Building on the Gulf community health observing system framework and the observing and monitoring sections in this chapter, we envision the potential to develop "a coastal human health observing system."

An existing example of such a coastal observing system for environmental data is the US Integrated Ocean Observing System (IOOS, 2022). The IOOS encompasses a network of 11 connected regional ocean and coastal observing programs that cover most of the US coastline and provide significant additional information for weather and climate models and predictions beyond that gathered by national programs.

A similar coastal observing system for health-related information could assimilate data from existing and developing environmental observing systems and exposures and combine them with information from clinical health examinations, ongoing community surveys, wearable health devices, social media postings, and other sources (Fig. 19.24).

Some tools to provide situational awareness information to the public about potential health threats from the ocean already exist in the form of predictive modeling and warnings about harmful algal blooms and bacterial levels, as mentioned in previous sections of this chapter. The "How's the Beach" Case Study 19.1 presented below

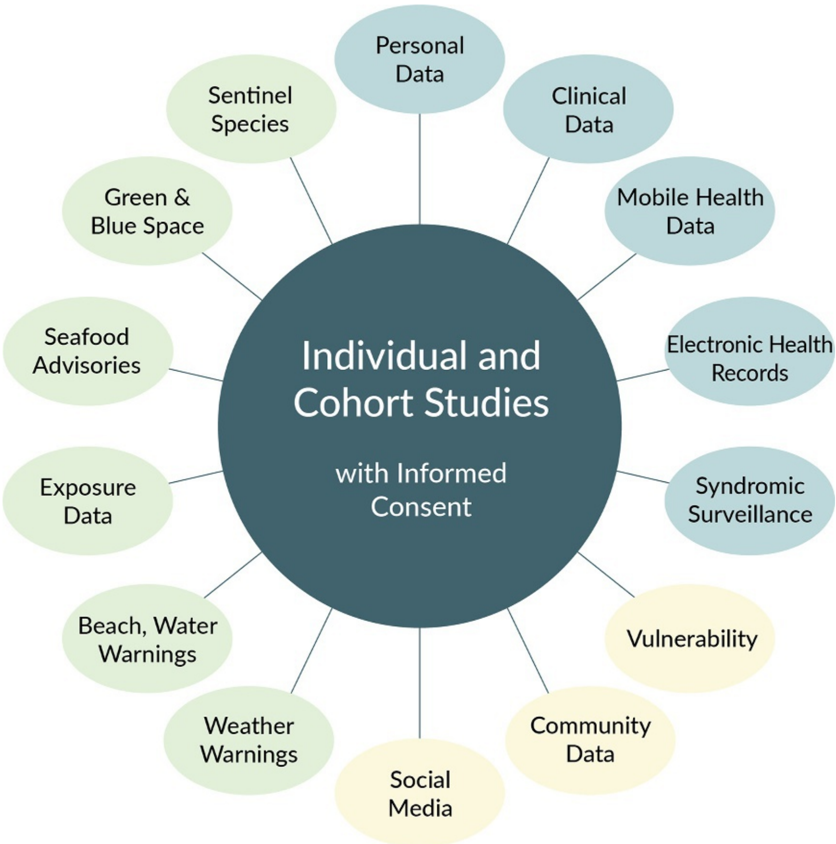

FIG. 19.24 Schematic diagram of a possible future Coastal Human Health Observing System. *Blue color* refers to health data derived from specific individuals; *light tan* denotes data for both individuals and communities; *light green* denotes ancillary data from warnings, forecasts, and environmental characteristics. *Copyright P.A. Sandifer; used with permission.*

Case Study 19.1 How's the beach.

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Introduction

Enterococci are bacteria that normally inhabit the intestinal tracts of humans and animals. The presence of these bacteria can be an indication of fecal pollution, which may come from stormwater runoff, pets and wildlife, and human sewage. If enterococci are present in high concentrations in swimming and recreational waters, it is more likely that pathogens that cause disease, infections, rashes, and respiratory disorders may also be present.

These pathogens can cause harm if they are ingested while swimming or enter the skin through a cut or sore. For this reason, water quality monitoring programs across the United States and around the world collect periodic measurements of enterococci in marine locations that are popular sites for water-based recreation. Recreators are then informed if bacteria levels exceed safe thresholds (see Chapter 12).

Why are tools like "How's the Beach" needed?

A significant challenge for public health managers is that bacteria levels can change very rapidly between sampling dates. Stormwater runoff, sewage overflows from heavy rainfall, and other events can quickly increase bacteria levels, introducing undetected risk to recreators.

To fill in the gaps between water quality measurements, scientists at the Arnold School of Public Health at the University of South Carolina, the University of Maryland Center for Environmental Science, the Southeast Coastal Ocean Observing Regional Association (a US IOOS regional association), and the EPA collaborated to develop the "How's the Beach" decision-support tool (https://howsthebeach.org/) (Fig. 19.25).

What does "How's the Beach" do?

How's the Beach is a tool that provides daily predictions of bacteria conditions to inform beach managers, public health officials, and the public of potentially unsafe conditions for swimming and other in-water recreation. How's the Beach is operational in public waters at multiple locations along the southeast coast of the United States including the Kill Devil Hills region of North Carolina; the Myrtle Beach, Surfside, Charleston Harbor, and Folly Beach regions of South Carolina, and Sarasota and Manatee County beaches of Florida.

How does it work?

Predictions by How's the Beach are based on historical relationships, discovered through previous sampling, between bacteria level and environmental factors such as rainfall, salinity, wind conditions, and water temperature. These relationships are used to create daily estimates of bacteria levels at each site.

The predictions do not represent official swimming advisories, which urge recreators to avoid contact with the water; but, rather they provide estimates of the likelihood that bacteria conditions would warrant issuing an advisory if sampling were conducted that day. As such, the forecasts are for informational purposes only: they represent the probability that the day's bacteria level will exceed the safe swimming standard, based on an automated prediction system.

The validity of the tool's estimates for this informational purpose has been assessed through comparison with data derived from sampling and in comparison to a commonly used tool, Virtual Beach, developed by the EPA (Neet et al., 2015). Machine Learning (ML) and Artificial Intelligence (AI) modeling techniques have been implemented for improved model accuracy, in particular in those swimming beaches and recreational waters where there are limited data and/or limited variability in water quality.

Conclusions

The How's the Beach initiative informs decision-making about recreational use of coastal waters by fostering timely access to accurate water quality data and daily "nowcasts" of water quality conditions for public health officials, resource managers, and recreators. Members of the public can readily access the tool via their smartphones, tablets, or computers to assess whether any given day is likely to be a safe or potentially risky day to visit the beach for in-water recreation. In addition, detailed daily reports are provided to interested beach managers, shellfish managers, and public health officials.

Continued

Case Study 19.1 *(cont'd)*

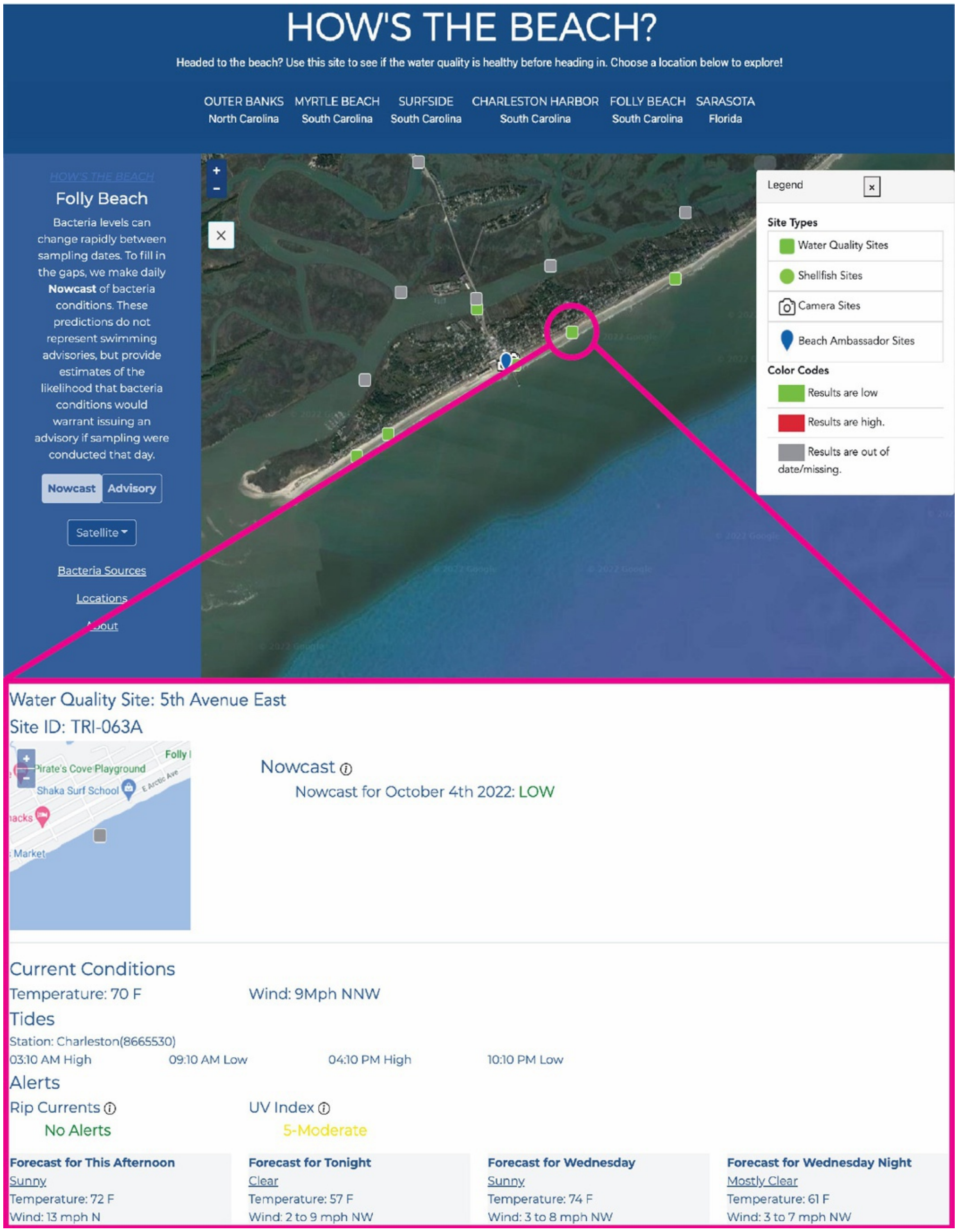

FIG. 19.25 Example of How's the Beach responsive website tool, accessible by computer or mobile devices. This is a screen shot from the How's the Beach website taken on 10.04.22 for a popular tourist site on the South Carolina coast, Folly Beach, near Charleston, SC. Top: Polygons along the beachfront represent sampling sites, green color on the pull-down legend indicates low estimated bacterial levels. Bottom: Pull-out from one Folly Beach polygon provides more detailed information, including estimated bacterial levels, current temperature and wind conditions, times of tides, UV index, and a National Weather Service alert for dangerous rip currents (if any) at the date and time indicated. *Credit: University of Maryland Center for Environmental Science; used with permission.*

Managers for the tool continue to evaluate additional sites to expand How's the Beach coverage. Consistently collected data on water quality and key environmental parameters dating back at least several years and ongoing are essential to modeling conditions at any site.

Reference

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is another step in this direction. Although primarily aspirational at this stage, over time, the establishment of a linked network of regional health observatories focused on residents of coastal areas could provide powerful tools for understanding the health effects of coastal living, both good and bad, and lead to better health protections and enhanced well-being.

19.10 Conclusions

Now, more than ever before, it is essential for humankind to observe, monitor, and understand the world's oceans and their coastal environs. The oceans play crucial roles in climate regulation, food security, global trade and transportation, defense and military operations, and human culture to name just a few of its spheres of importance; and coastal areas are home to a significant portion of the global human population as well as its biodiversity.

This chapter introduced and explored some of the technological and other approaches to monitoring a variety of key ocean features including its physical environments and contributions to weather and climate, the massive problem of distribution and accumulation of plastic waste in the ocean, how we can measure and manage the ocean's immense biodiversity and marine fisheries, how surveillance of harmful algal blooms and infectious disease organisms can be conducted and occurrences predicted, and how health assessments of sentinel organisms such as marine mammals can provide insight into ocean health threats to humans.

While ocean and coastal observations utilize a diverse array of technologies, in many cases the same or similar approaches can be employed to monitor a number of ocean features. These include remote sensing via satellites; a variety of airborne sensors on manned and unmanned aircraft, ships and unmanned surface, and undersea vessels; anchored sensor arrays; ocean drifters; collection and analysis of biological samples including eDNA; and numerous others. Future ocean observing and monitoring activities will require the establishment of common standards for data quality, format, and connectivity accompanied by significant enhancements in computing capacity, observational technologies, and "big data" integration.

As ocean surveillance technologies improve over time, outputs from many different observing efforts can be assimilated to provide an ever-more nuanced picture of ocean conditions, how they are changing, and importantly how they may affect the health and well-being of individuals and groups of people, including those most vulnerable.

19.11 Brief horizon scan

All areas of ocean and coastal observing and monitoring will increase their reliance on remote and electronic mechanisms for collecting, storing, analyzing, and using data for predictive modeling, resource management, regulatory compliance, public health protection, and ongoing research. Increasingly, data will be collected by sensors mounted on a broad range of autonomous, fixed, and movable platforms that traverse all areas of the ocean, with rapid telemetry of data to researchers and other users in near real time.

As a result of more extensive and, in some cases, almost continuous data collection, virtually all areas of ocean observation and monitoring are rapidly entering the "big data" era. This era will require more technologically advanced observing technologies and data storage, coupled with cutting-edge computing capacity, use of artificial intelligence and machine learning, and reliance on open-source software to facilitate global sharing of data streams and models.

These data streams and models will drive increased consumption of ocean observations for scientific, public, and commercial uses, to better understand and protect ocean ecosystems and public health. As examples, we expect they will underpin the future implementation of comprehensive, integrated ocean observing systems for ocean physical conditions, plastics and other pollution, marine biodiversity, marine fisheries, and disease-causing organisms such as harmful algal blooms and *Vibrio* bacteria (e.g., see Figs. 19.8, 19.9, and 19.12 herein).

The use of sentinel species such as marine mammals, whose biology is similar to that of humans, and filter-feeding molluscan shellfish that tend to concentrate a variety of harmful microbes and toxic chemicals, will expand to provide more information to improve the protection of marine mammal and human health.

Advancements in observing and monitoring tools for health threats from ocean disease-causing organisms, coupled with significantly enhanced community engagement activities and visualization tools, will advance the understanding of harmful algal bloom and *Vibrio* ecology and their associated illnesses and support robust public health warnings. Future models will include antibiotic resistance, virulence, and toxin production as well as occurrence and abundance forecasts to increase the accuracy and utility of forecasts.

It is likely that ensemble modeling approaches, such as those employed in hurricane forecasting where several different models are run simultaneously to produce forecasts of a range of possible future outcomes rather than a single prediction, also will be employed for these ecological forecasts.

Finally, human-health relevant data from numerous coastal, ocean, and other data streams are expected to be harvested, integrated, and used to enhance public health and well-being.

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Discussion questions

1. What types of technologies are used for monitoring the physical and biological characteristics of ocean and coastal waters?
2. What is the "One Health" approach? Why is it important in the context of oceans and human health?
3. Why are plastics included in a textbook on oceans and human health?
4. What are harmful algal blooms and why are they considered important from a human health perspective?
5. Are there different kinds of harmful algal blooms?
6. What are examples of infectious disease organisms that occur naturally in ocean and coastal waters? How would a person be most likely to come into contact with such organisms?
7. What is a sentinel species? What is an example in the marine environment?
8. Why is marine biodiversity important? What is eDNA and why is it of special importance for marine biodiversity monitoring?
9. What are the most important reasons for observing and monitoring marine fisheries? What are IUU fisheries and why is it critical that expanded surveillance capacity be developed for these fisheries?
10. Why are physical and biological characteristics of ocean and coastal waters important from a human health perspective? How can ocean modeling be used to improve human health?

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