Article

S|S|S

Social Studies of Science
2018, Vol. 48(1) 57–79

DOI: 10.1177/0306312717743579
journals.sagepub.com/home/sss
SAGE

From ships to robots: The social relations of sensing the world ocean

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Abstract
The dominant practices of physical oceanography have recently shifted from being based on ship-based ocean sampling and sensing to being based on remote and robotic sensing using satellites, drifting floats and remotely operated and autonomous underwater vehicles. What are the implications of this change for the social relations of oceanographic science? This paper contributes to efforts to address this question, pursuing a situated view of ocean sensing technologies so as to contextualize and analyze new representations of the sea, and interactions between individual scientists, technologies and the ocean. By taking a broad view on oceanography through a 50-year shift from ship-based to remote and robotic sensing, I show the ways in which new technologies may provide an opportunity to fight what Oreskes has called ‘ideologies of scientific heroism’. In particular, new sensing relations may emphasize the contributions of women and scientists from less well-funded institutions, as well as the ways in which oceanographic knowledge is always partial and dependent on interactions between nonhuman animals, technologies, and different humans. Thus, I argue that remote and robotic sensing technologies do not simply create more abstracted relations between scientists and the sea, but also may provide opportunities for more equitable scientific practice and refigured sensing relations.

Keywords
gender, inequality, oceanography, remote sensing, technology

Introduction

In the past few decades, physical oceanography has undergone a massive, though not complete, shift away from ship-based sensing, which entailed labor at sea to collect relatively

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limited data, to the use of robotic and remote sensors, which garner exponentially more data than ever before (Conway, 2006). The daily practices of ‘doing oceanography’ were once centered on taking seawater samples from ships or on dives, deploying various sensing instruments, keeping round-the-clock watches and working in teams in constantly-changing sea conditions on the close quarters of a ship. Doing oceanography has shifted to focus on downloading and modeling data, and piloting or programming undersea vehicles from remote labs. High-speed computing, accompanied by significant advances in miniaturization, battery life and data storage, has led to ‘an explosion … in every branch of physical oceanography’, according to eminent oceanographer Walter Munk (2002: 139). These changes are also reflected in developing practices in other field sciences, particularly the geosciences, which aim at planetary-scale data and monitoring (Edwards, 2010). Yet while these technologies lead to important scientific developments, they increasingly take scientists away from direct engagement with their object of study; as one prominent physical oceanographer told me, ‘armchair oceanography is increasingly part of the deal’.

What are the implications of this shift away from ship-based research, done by scientists at sea, to observations taken by robotic or remotely operated sensors? As Gabrys (2016) points out, sensors and sensing practices are not simply ways of apprehending already-existing environmental phenomena that are inertly waiting for analysis, but rather ways of ‘making present and interpretable distinct types of ecological processes’ (p. 29). Oceanographic sensing practices shape the understandings of the ocean that underlie everything from pop culture to climate change negotiations. New ocean sensing technologies give us the digital representations of the sea that have now become commonplace in web interfaces such as Google Ocean, as well as the more specialized forms of mapping and modeling software that inform planning, mapping, and resource governance, among other activities. This shift in sensing technology and oceanographic practice has undoubtedly had great impact on how we understand the ocean (see especially Helmreich, 2011; Jue, 2014).

Although the field of science and technology studies (STS) has for some time included research on computing and big data in science, there has been only limited research on how changes in environmental sensing have affected the environmental sciences, the understandings of nature they produce and processes of social and political ordering. Remote sensing, measurement and quantification may lead to the illusion of not only complete knowledge but also disembodied objectivity. Thus new sensing practices might be understood as technologies of abstraction in two related ways: They create an abstract notion of the sea as a frictionless field of data and, using a different sense of the word, they abstract scientists away from embodied encounter with their object of study. In both senses, the messy materiality of the sea and the inherently partial nature of humans’ understanding of it recede. Furthermore, some authors argue that such abstractions both overemphasize the extent of human knowledge and make nature more readily available for capture by logics of global capitalism (e.g. Litfin, 1997; Loftus, 2015; Robertson, 2006). Other scholars, especially those firmly in STS, urge closer attention to relations between scientists and novel technologies, and to the representations of nature they co-produce. They argue that the story of these new practices is not so straightforward and that complex and partial configurations of embodied sensing, visualization, computation, and more are involved in the creation of new representations of nature (e.g.

Helmreich, 2011; Myers, 2010; Vertesi, 2012). While these approaches are not necessarily incompatible, I follow here the emphasis of the latter, paying attention to the ways in which new ocean sensing technologies not only refigure relationships between individual scientists and the ocean, but also remake ordering processes within scientific communities. Helmreich (2009b) argues that oceanography has tied a division of labor to a division of perception: How scientists sense the sea depends very much upon their subject positions in terms of class, gender and other markers of difference. Yet representations of the ocean and the daily practices and institutional politics of oceanography are, with a few important exceptions (e.g. Helmreich, 2009a), rarely considered.

This paper focuses on physical oceanography, which is concerned with matters of ocean composition and movement, such as currents, waves, ocean circulation and water mass formation. Physical oceanography is distinct from marine biology and deep-sea exploration, two fields that have received more attention, because it requires, with some exceptions, synoptic measurements: a large amount of data points coordinated across space and time. The latter disciplines rely more frequently on fewer, more direct observations of phenomena of interest, yet singular observations, explorations and experiments yield limited results for physical oceanography, especially on the global scale. Thus physical oceanography currently exhibits more pronounced conflicts between desires for universal, high-quality and high-volume data that can only be produced by remotely operated or autonomous technologies, and many oceanographers' foundational identification of the sea as the site of their science. This is a practical conflict, involving the allotment of research dollars and the focus of capacity-building efforts. Yet it also involves questions of who interacts with the sea and how, and the ways in which meaning is made between humans, machines and the ocean. Thus, an exploration of the changing sensing practices of physical oceanography has much to reveal regarding the entanglements of technology, identity, knowledge and governance when it comes to environmental monitoring and measurement. I also discuss deep sea oceanography, albeit somewhat more briefly, as tensions between direct human presence and remote sensing in this field are related to those in physical oceanography, and are brought into sharp relief in some highly publicized contestations.

In this paper, I first explore the literature on new sensing technologies. I follow those scholars who pay careful attention to the effects of new technologies and practices not simply on representations of the ocean, but also on social and political ordering. Here, I take inspiration from Stengers who, following Whitehead, urges us to *think with* scientific abstractions rather than simply obeying them (and by extension the technologies that produce them) (Stengers, 2011). To accomplish this, I contextualize these new technologies in regimes of oceanographic sensing, which have undergone significant changes in a few short decades, and have resulted in a shift away from ship-based sensing, which some scientists worry will have deleterious effects on the discipline. I argue that close attention to the practices these new technologies enable, not just the representations they produce, shows that while a shift to robotic and remote sensing may limit certain meaning-making practices, it might also open up a host of new ones. In particular, I focus on the ways in which novel sensing regimes could thus allow the discipline to depart from what Oreskes (1996) has called 'ideologies of scientific heroism' (see also Myers, 2010; Traweek, 1992). I explore the ways in which today's practices of measuring the ocean are reconfiguring traditional notions of who does oceanography, and argue that new ocean technologies create new sensing relations not just between individual scientists, technologies, and the ocean but also amongst scientists themselves. Throughout this analysis I draw on a variety of primary and secondary source material, including interviews with approximately forty oceanographers in the United States, the United Kingdom, and South Africa. They are tied more or less tightly into the same research networks, meaning that together they have participated in many of the major international research projects in oceanography in the last fifty years, and have witnessed firsthand the shift from ship-based to remote and robotic sensing. The interviews that inform this research were primarily conducted with senior- and mid-career scientists who work on global-scale oceanography. More men than women were interviewed, reflecting the representation of women in the discipline at this career stage. In addition to interview data, I rely on science writing from mid-twentieth-century oceanography, arguably the modern origin of the discipline. One source deserves special mention: *Sea of the Beholder*, the autobiography/biography co-authored by Henry Stommel, considered by many to be the founder of dynamical oceanography, and his wife, Elizabeth 'Chickie' Stommel. Excerpts from Henry Stommel's (1995) portion of this text were published in his Collected Works; Elizabeth Stommel's contributions remain unpublished. Henry Stommel's writings provide rare reflections on concepts of the ocean and practices of ocean sensing, which changed rapidly during his career, and to which he was a central observer and participant. *Sea of the Beholder* also offers even rarer reflections on the personal impacts of being the partner of a sea-going scientist. I use this and related texts as windows into the worlds of present and past oceanographers, as well as into the ways in which particular practices have fueled ideologies of scientific heroism or their alternatives.

New ways to sense the sea

Critical literature has much to say about satellites, distributed sensors and remotely operated and autonomous underwater vehicles, the technologies that dominate new regimes of ocean sensing. Each kind of technology, and also technologies within each kind, have their own sensing practices. A brief overview of the technologies and their associated critical literatures will have to suffice here. Satellite measurements are the most well-established – and are, consequently, the most explored in social sciences and humanities literature (e.g. Benson, 2012; Dodge and Perkins, 2009; Litfin, 1997; Mack, 1990; Parks, 2001; Perkins and Dodge, 2009) – and make it possible to get a view of the entire ocean at once, to envision a truly global ocean. The impact that satellites have had on oceanography, and on other sciences, is difficult to overstate. In the words of one oceanographer with whom I spoke, 'the ability to image the entire sea surface every I don't know, week maybe, through … compositing satellite tracks, was a real revolution' (see also Conway, 2006; Höhler, 2017). As Shim (2014) writes, satellites are not neutral accomplices in scientific knowledge; they 'participate in constructing both geographical information and geographical imagination' (p. 152). Similarly, Benson (2012) shows that satellite programs can support different geographical visions and data needs within the same network. Yet some authors argue that, no matter their espoused purpose, satellites are inescapably 'eyes in the sky', promoting problematic illusions of scientific neutrality,

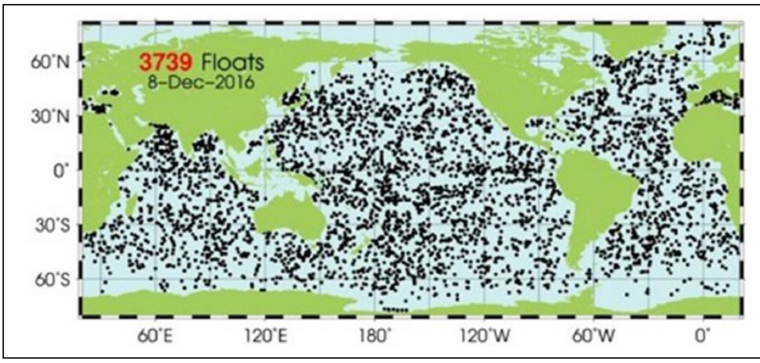

Figure 1. Global distribution of Argo floats at time of writing.
Source: Argo Program (http://www.argo.ucsd.edu, http://doi.org/10.17882/42182). Reproduced with permission.

rationality and certitude with their distancing gaze, and in effect masking their military legacies and ongoing ties (e.g. Litfin, 1997; Perkins and Dodge, 2009).

Like satellites, distributed sensing networks contribute to contemporary understandings of nature in particular ways. Distributed sensors differ from remote sensing, as they make *in situ* measurements of ocean properties and provide comparatively high-resolution temporal and spatial monitoring data. Yet while the view of individual sensors is much more myopic than that of satellites, taken together they represent similar dreams for universal data coverage and complete knowledge. Along with other sensor systems, which are becoming increasingly ubiquitous in the geosciences and beyond, ocean sensor networks 'present the possibility for understanding environmental processes and relations more thoroughly by providing real-time data that are more detailed than existing modes of data collection' (Gabrys, 2016: 34). Chief among ocean sensor systems is Argo, a program of over 3500 drifting floats that measure temperature and salinity in the upper 2000 meters of ocean; the distribution of Argo floats is shown in Figure 1 (see also Gould et al., 2004; Wilson, 2000). With a large number of floats and new ice-sensing technology, Argo has been able to achieve near-global coverage, making it a proxy for satellite coverage under the ocean. Argo data is automatically reported via satellite and made available for free to online users in two forms: Uncorrected real-time data and quality-controlled delayed-mode data. Haklay (2013) cautions against the rhetoric of democratizing science that so often accompanies such open-access data projects, noting ideologies of 'anywhere, anytime, anyone' mask values that structure data collection and display, as well as inequalities in who can make meaning of such data.

Argo is not, it should be mentioned, fully autonomous. Human labor is necessary at a few steps in the process: Deploying the floats, which is usually done from a research, commercial or sometimes sport vessel; quality control, which takes an international team of data experts; and in analysis and processing for various outputs, including models. But the floats themselves (shown in Figure 2) lead lives that are mostly their own; unlike most other oceanographic equipment, they are not designed to be retrieved once deployed. For the standard Argo floats, it is not cost-effective to find and fix broken floats, and even at the end of their lives (generally five to eight years) there is no recovery plan. Moreover,

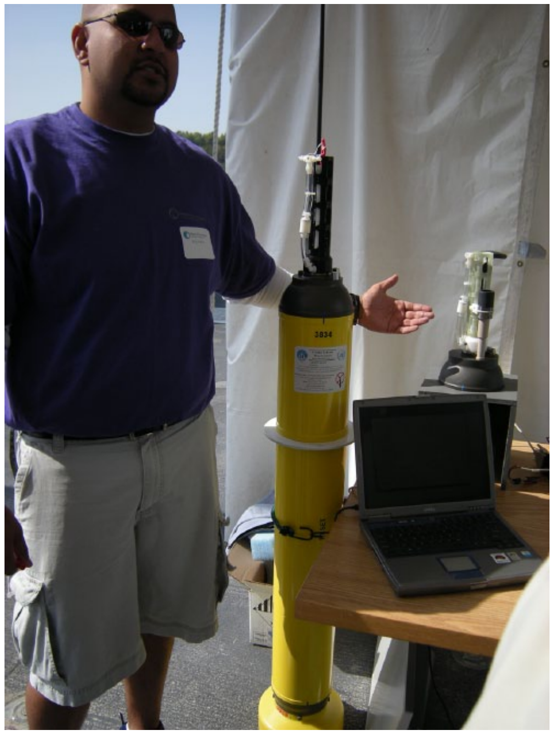

Figure 2. Argo float aboard the US research vessel Thomas Thompson.
Source: Photo by Joe Mabel CC-BY-SA- 3.0, via Wikimedia Commons.

in addition to promoting disembodied sensing, sensor systems treat the ocean (and the Earth more broadly) as 'an entity to be sensed and transformed into data', subject to heightened regimes of design, control and management (Gabrys, 2016: 36; see also Lehman, 2016).

A third kind of sensors encompasses the closely-related remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). ROVs and AUVs are forms of *in situ* sensing with different scales and purposes than those of distributed sensing networks. ROVs are generally 'driven' by a human operator, and have a much higher cost than Argo's drifting floats, although some generate their own power by harnessing the energy of ocean waves. AUVs are similar, but they are pre-programmed, rather than directly piloted by humans. Instead of aiming for large-scale coverage, ROVs and AUVs are usually used exclusively by researchers, and on shorter spatial and temporal scales, to understand smaller-scale processes and the intricacies of fluid dynamics that can shed light on larger-scale processes or dynamics in other locations. There are many designs of ROV; Figure 3 shows one. For critical scholars, ROVs and AUVs introduce a number of issues that are related to those raised by satellites; yet they also introduce distinct issues, given that ROVs in particular are like undersea drones. In addition to presenting a detached view, drones and ROVs seem to promise a 'world-spanning

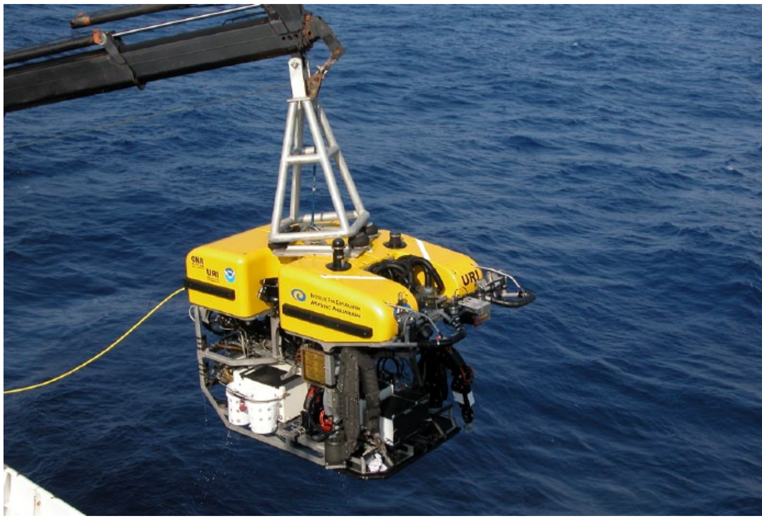

Figure 3. Example of an ROV.
Source: Photo by Brennan Phillips at English Wikipedia (Public domain), via Wikimedia Commons.

ability to track and fix threats', (weather, climate change or terrorism) through a vision 'more penetrating and powerful than any human could offer' (Greene, 2015: 241). Drone or ROV vision, then, does not simply hide its infrastructural conditions of possibility but gives the illusion of having 'outpace[d] the practices which enable it in the first place' (Greene, 2015: 241).

The emergence of big data in oceanography is inseparable from the shifts in sensing technologies that I have detailed above. The amount of data generated by satellites alone has presented unprecedented challenges and opportunities for oceanographers (Conway, 2006; Munk, 2002). What had previously been a discipline characterized by a dearth of data has had to deal with information overload (Conway, 2006). Additionally, the discipline has increasingly turned toward an open-access system of data distribution. Hence, alongside specific sensing technologies, significant infrastructures have been developed for storing, analyzing, and distributing data. These systems must now be considered a significant part of oceanography, not simply an accoutrement. Furthermore, the emergence of access to big data has permitted, for the first time, the emergence of data users who are not the same people as the data producers. Taken together, from satellites to tiny *in situ* sensors, new generations of ocean sensors take part in a broader field of environmental sensing, and 'generate[s] sorts of data that, through algorithmic parsing and processing, are meant to activate responses, whether automaton or human-based, so that a more seamless, intelligent, efficient, and potentially profitable set of processes may unfold', thus making the ocean (and the Earth) programmable (Gabrys, 2016: 8).

Helmreich (2011) names what could be understood as an overarching critique of the technologies above: Taken together, they create a 'media ecology' that 'tends to occlude its infrastructural history and conditions of possibility' (p. 1211). Here, Helmreich points out that these technologies generally hide the specific geopolitical and social contexts from which they emerge, not to mention the relationships that they produce and modulate between scientists and their objects of study. Perhaps most fundamentally, technologies such as satellites, drifting floats, ROVs and AUVs can effectively obscure the fact that they are situated in particular social and geographical contexts. Views 'of infinite vision', the type to which robot and remote sensors might aspire, are 'not just mythically about the god trick of seeing everything from nowhere, but … have put the myth into ordinary practice' (Haraway, 1988: 581–582). Scientific knowledge is too often understood both by its proponents and its critics as 'signify[ing] a leap out of the marked body and into a conquering gaze from nowhere' (Haraway, 1988: 581). The key to dispelling this illusion is to expose the ways in which all knowledge is *situated*, produced from a particular perspective by embodied eyes (human or machine) and as such necessarily incomplete. Yet remote and robotic sensing technologies tend to obscure the fact that any view of the world is a view from somewhere. It is here that an STS approach to new sensing technologies is particularly relevant, bringing science down from 'Olympian heights of abstraction': Revealing not only the fraught nature of its conclusions, but also the value systems and political contexts in which it is inevitably situated, has been a main role for STS (Hoppe, 2005: 205).

Indeed, scholars in STS and related fields have begun to analyze representations of the ocean that have emerged from the data produced by the above-mentioned technologies. Representations of the ocean are increasingly informed by data collected by satellites and robotic sensors; moreover, because of the amount of data they collect, the paradigm of open-access data that governs most of them, and their instantaneous data reporting capacities, these technologies facilitate ever more dynamic representations of the ocean. These interfaces give the impression that one is observing or exploring the ocean in real time, even from behind a computer screen far inland. Several scholars are alert to the ways these representations risk reproducing and enhancing the 'view from nowhere' and erasing the ocean's messy materiality. For example, Jue (2014: 252) argues that such representations seek to 'seamlessly link the real ocean with its digital replica', treating the ocean not simply as a potential source of data, but as data itself. She argues that this consideration of the ocean as data privileges the satellite's view of the world given in Google Ocean, which also lends itself to notions of disembodied observation, mastery, and control. Similarly, Messeri (2017) argues that satellite-based web mapping traffics in tropes of exploration, perhaps seemingly democratic but in fact 'ultimately state-sponsored, politically motivated, and hierarchically ordered' (p. 91). Moreover, web interfaces like Google Ocean take the ocean as a kind of spatial container and seawater as transparent, not only ignoring the physical capacity of seawater to chemically transform matter, but also providing the prerequisite imaginary for imperial expansion (Jue, 2014). Helmreich (2011) makes a slightly different argument, asserting that data-driven representations such as Google Earth, while the latest iteration of scientific attempts to make the ocean visible and/or transparent, stray from the photographic and toward a 'mottled mash' of representational layers (p. 1211). This allows Google Earth to provide a unifying view, as in 'whole earth' representations, and also to exhibit rhizomatic qualities, multiplying perspectives and possibilities (Helmreich, 2011).

If we were simply to extrapolate from these analyses, we might assume that such critiques can be extended beyond representations of the ocean to the practices of sensing themselves. Just as Google Ocean and similar data visualizations lend themselves to notions of a distanced, transparent and manipulable ocean, the practices of collecting data using remote and robotic sensors might be seen as a withdrawal from the materiality of the sea, leading to the reduction of the ocean's complex and unknowable materiality to streams of data, gridding, territorialization and economic exploitation. These visualizations also lead to alienation from the daily reminders of human fallibility and scientific uncertainty offered by life at sea. Oceanographers piloting remote vehicles from their desk chairs or tinkering with large data sets on their computer screens can be expected to forget that their knowledge is in fact situated – in a vast, wet, largely inscrutable space that is perceived differently by different humans, other animals, and machines.

However, as McCormack (2012) suggests, while the shift away from ship-based sensing seems to move away from recognizing the situatedness of oceanographic knowledge toward an abstracted notion of the ocean, and toward an abstraction of scientists from the ocean, we must interrogate these technologies and their effects more closely. Here, I follow some critical scholars who have begun to call for a more careful approach, even an affirmative critique, to new technologies, conceptual abstractions and the representations that result (McCormack, 2012). The purpose of such a critique, as McCormack points out, is not to separate 'good' technologies or representations from bad. Instead, the objective is to understand how these representations are made and what they do, 'the multiple ways in which abstraction participates both in the worlds we inhabit and in our efforts to make sense of them' (McCormack, 2012: 716). Rather than being set against sensing practices that seem to betray, we must pursue our analyses with the perspective that 'the question of how abstraction works and comes to make a difference remains an open one' (McCormack, 2012: 716). If we fail to consider the specific mechanisms of these new practices and associated technologies, then we risk falling into the trap of abstracting them ourselves, or evaluating them absent their social, political, and environmental situatedness.

Of course, any such analysis must first recognize that there is no clear line between new forms of ocean sensing and old, neither in their quotidian realities nor in the representations they produce. This observation resonates with work in STS and related fields that complicates lines between remote sensing, machine autonomy and digitization on one hand and embodied sensing on the other (e.g. Goodwin, 1995; Helmreich, 2007; Mindell, 2015; Turkle, 2009; Vertesi, 2012). For example, Goodwin (1995) details how the complex interactions between scientists and the instruments they are remotely operating in the sea below constitute the spaces of ship-based science (see also Höhler, 2002). Furthermore, abstract concepts are necessary for making meaning of the ocean. Indeed, tensions between remoteness, abstraction, place and embodiment can be found in many disciplines; for example, Messeri (2016) analyzes the complex links between the intangible imaginary necessitated by planetary science and the place-making practices of space scientists. Similarly, in ship-based oceanography, scientists engage as a matter of necessity in abstract and large-scale thought, even as they both enjoy and endure more 'direct' engagement with their object of study. Stommel's words, written before the widespread use of computer models, provide an illustration in his writing of the mind's eye, or the 'sea of the beholder'. Contrasting imaginaries of the ocean with various views from aboard ships or on coasts, he writes,

> By tricks of image-processing, masking and referencing – above all by focusing, it can form pictures of the ocean that the optical eye itself can never see. These strange pictures are in the eye of the beholder and are sometimes closer representations of the ocean than what we can hope to perceive from the bridge of a little vessel plodding over the top surface of a dark, invisible, three-mile deep mass of water below. Our physical eyes do not see the system of great currents that make up the ocean circulation on a grand scale. Even the wide perspective of the artificial satellite does not encompass these depths (Stommel, 1995: 7–8).

Carrying Stommel's words into the present, we might note that while the data and digital representations emanating from robotic and remote sensors may obscure the infrastructures that make them possible, they, along with their accompanying algorithms, also make perceptible patterns and phenomena that would otherwise be incomprehensible (Amoore, 2016; Helmreich, 2011). The blurring of lines between remote, autonomous and embodied sensing extends to efforts to explore the deep sea. Mindell (2015), an engineer on early deep-sea remote sensing, recalls, 'sometimes, if someone would bump your chair in the control room, for a moment you'd be convinced that the robot down below had crashed into a rock – until you "woke up" and untangled your body from your mind' (p. 57). Thus these technologies can be understood to extend and multiply embodied relations, even if they remove human oceanographers from the ships and submersibles.

In the remaining sections of this paper, I attend to the relations that proliferate around new ocean sensing technologies and attendant practices. In particular, I argue that while the shift away from ship-based sensing may indicate somewhat of an identity crisis for the discipline of oceanography, as well as a sore spot for individual scientists, it may also help to do away with ideologies of scientific heroism in the discipline. Oreskes notes that oceanography and other field sciences have been characterized by the image of the intrepid, innovative, independent and usually white male scientist, which belies both the degree to which discoveries in these disciplines depend on much more mundane work such as data processing, and the exclusionary and discriminatory nature of many such sciences. This means that stories of women are written out of mainstream accounts of science – both women scientists relegated to the unglamorous tasks of data processing and the like, excluded from the more adventurous yet no more scientifically important components of discovery, and spouses who served to support the men who found such rewards in sea-going voyages. Similarly, oceanographers from institutions without funding for global-scale oceanographic expeditions have been largely relegated to the margins of the discipline's history.

New ocean sensing technologies emphasize the important work of data processing, quality control, distribution, and modeling, making the science available to more people and showing the degree to which the development of oceanographic science depends not on the intrepid discovery of any individual but on a distributed set of tasks. New sensing practices also fight ideologies of scientific heroism because they highlight the degree to which meaning is made not just between scientists but also through relations with machines and with the materiality of the sea itself. Therefore, while new technologies may seem to obscure their infrastructural histories and conditions of possibility, a closer look, to return to Helmreich, shows that they in fact reconfigure sensing relationships in such a way that the celebration of the (white, male) entrepreneurial scientist as the sole or even catalytic protagonist of science is increasingly difficult.

While there is nothing inherently emancipatory about new ways of sensing the ocean, attention to the relations that proliferate around them shows the social and geopolitical context in which oceanographic science has been situated and thus shows that inequalities in science are not simply a matter of recruiting more nontraditional or minority students, but attending to the technologies and practices that constitute the field. Haraway (2004) writes: ‘Neither gender nor science – or race, field, and nation – preexist the heterogeneous encounters we call practice’ (p. 208).

Scientific adventures and heroes at sea

In the beginning of his unpublished autobiography, Stommel (1995) writes,

> What distinguishes my life has been the happy chance to study the ocean. This marvelous opportunity has meant more to me than acquiring power over others, than making money, than seeking publicity or academic distinctions. By comparison with the chance to contemplate the oceanic portion of the universe these worldly goals have seemed mere dross. (p. 6)

In Stommel’s career, which spanned most of the second half of the twentieth century, the chance to study the ocean meant going to sea for large periods of time. Even previously, it was the challenges and opportunities offered by research vessels that defined the work of entire oceanographic institutes; as Schlee (1980: 49) writes, the Woods Hole Oceanographic Institution’s R/V *Atlantis*, launched in 1930, was ‘the tail that wagged the entire dog’ in the Institution’s early years. Indeed, at this time, frequently considered the beginning of modern oceanography, scientific explorations of the ocean were seen as closely related to military and geographical marine expeditions, and all were carried out on ships (Oreskes, 1996). Being an oceanographer meant going to sea. It entailed leaving behind families, students and laboratories for days and nights, wrestling with the object of one’s study. Extending tropes of seafaring adventure and exploration, oceanography was characterized at mid-century as ‘a science pursued by barefoot youths in ragged shorts and greasy shirts on the wave-swept decks of sailing ships’ (Sullivan, 1961: 246).

Not only did oceanography draw from legacies of oceanic exploration and conquest, but ship-based oceanography also seemed to be the way of the future, especially for global-scale (also called ‘blue-water’) oceanography. Enhancing its fleet of research vessels was seen as among the most important investments a nation could make to develop its expertise in oceanography. Expansion in many national oceanographic programs was catalyzed by the success of the International Geophysical Year (1957–1958) and the subsequent declaration of the 1970s as the International Decade of Ocean Exploration, as well as by WWII and post-war military funding (Oreskes, 2003). In 1955, Stommel outlined the problems that physical oceanography was attempting to solve, and the progress that had been made in doing so. Here is how he described the first stage of oceanographic problem-solving:

> Before there is a problem in physical oceanography we have to recognize a phenomenon in a mass of observational detail. … The recognition of a phenomena sometimes arises from a lucky

> chance observation but more often as a result of extensive exploratory survey work, such as that of the *Challenger*, the *Meteor*, and the early *Atlantis* cruises. (Stommel, 1955: 1)

Exploring the ocean was not limited to surface ventures. The deep sea had become a realm of intrigue; the 'inner space' that provided a counterpoint to concurrent outer space explorations (e.g. Rozwadowski, 2008). This is poignantly evident in the words of Athelstan Spilhaus (1959), a scientist at the forefront of both space exploration and oceanographic research:

> Even though I was one of those who early urged that our government should support the development of research vehicles such as satellites and rockets to probe space, I wonder now whether enthusiasm and the propaganda race in space are perhaps causing us to over-emphasize outer space at the expense of understanding the unknown reaches of the earth on which we live. … [W]e should not forget the earth on which we stand and the great storehouse of living needs … ours for the taking … held for us in the seas. (p. 44)

Investment in inner space exploration was perhaps most obvious in the development of the first bathyscapes, including the *Trieste*, an underwater vehicle built by Auguste and Jacques Piccard, and piloted down 10,915 meters to the bottom of the Mariana Trench (Challenger Deep) in 1958, a feat that would not be repeated for another 35 years (Yasso, 1965). The *Trieste* is perhaps the most remarkable in a set of submersible manned research vessels that seemed, during the 1960s and 70s, to be the future of oceanographic research. Mainly capable of operations along the continental shelf, these included Jacques Cousteau's *Denise*, a 'two-man diving saucer', Westinghouse's self-propelled *Deepstar* and Woods Hole's *Alvin*, a research submarine with capacities for observation and sampling (Yasso, 1965: 155). In addition to technological capacity and exploratory spirit, the enthusiasm for research submersibles and ship-based oceanography highlighted a desire to immerse oneself in the ocean environment and a belief that this was necessary not only for scientific research but to expand the limits of human capacities (e.g. Daughterty, 1961; Mindell, 2015). A film on oceanographic research produced by the US Navy (1972) used somewhat whimsical terms: 'Must man depend on remotely controlled devices, or can he learn to work in the deep ocean himself, free like the fish and the porpoise and the seal, to move where he will?'.

It was not just national programs that equated oceanography with sea-based exploration. The individual oceanographers with whom I spoke echoed Stommel's enthusiasm. Research at sea was an exceptional experience for oceanographers who began their careers prior to the 21st century. Being at sea facilitates single-minded obsession, as not only are there few distractions, but also collecting and processing samples and participating in round-the-clock watches require near-constant attention during waking hours (see also Goodwin, 1995). As one oceanographer put it to me,

> It's just being away from it all that makes it, it's a different life. I mean it does become sort of a bit repetitive. But I, I don't know, it's just being at sea and having hands on experience, and seeing your data come up.

Furthermore, while the ship has a carefully maintained order, it is also a place where hierarchies, such as those between professor and student, are frequently relaxed in the face of common goals and shared experiences isolated from normal institutional structures. Stommel's (1995) analysis is illustrative:

> Let me contrast the life of a professor at an important university to that of a scientist at sea. Each professor is an individualist, bent on carving out a specialty, a special place for himself in his discipline. He is a little king with a coterie of students and laboratory assistants. He is very much on his own, and takes all the credit he can. … Life on board ship is different. The technical jobs that need to be done are joint tasks. One grows to respect the homely knowledge of the bosun, the quiet skill of the captain. It is an enlarged family. Cooperation, working together under sometimes difficult circumstances is the rule. Tasks are undertaken with deliberation. The sea, and not one's fellow man, is the enemy. (p. 45)

In their excitement for research conducted directly in or on the sea, many scientists did not anticipate that mere decades later much oceanographic research would be done using remote and robotic sensors, and that oceanographers would spend much more time on land, most of it behind computers. In addition to the development of new technologies, factors influencing this shift include increased costs for fuel and salaries on ocean expeditions and the increased professionalization of oceanography and science more broadly. Writing of natural history, Wilcove and Eisner (2000) note that as a discipline matures, prestige goes to those scientists who are able to synthesize large amounts of data and produce theoretical innovations, rather than those making descriptive observations of natural phenomena. In general, the second half of the 1900s saw both a shift in oceanographic sensing technology and the discipline's falling increasingly under the purview of academia rather than the Navy, thereby changing the everyday practice of oceanography. As Stommel (1995) writes,

> academic schedules do their awful work in keeping students and their professors from the sea. Even in the summer when one might expect to find young people enjoying a shipboard apprenticeship one is much more likely to find them in a semidarkened office hunched over a computer terminal. (p. 53)

Oceanographers still undertake ship-based research; those with whom I spoke were always quick to assert that this research is still necessary to the integrity of their science. Yet many of them feel that ship-based oceanography will be reduced even further, replaced by satellites and networked, robotic and remotely operated sensors. As one scientist said to me,

> The idea is that instead of a ship going out there to make a measurement, or a ship going out there to replace a piece of instrumentation, maybe you're going to have a robotic vehicle that does that. That's important and it's all part, but what it is, is more like the cable TV truck, or, you're maintaining a network, right, you're deploying sensors and you're maintaining these things and it's sort of the sensing and network and communications that's really making the discoveries, and part of what we're doing is basically just enabling that to be successful.

Another corroborated: ‘I think the push now is to go into this sort of robotic state’.

Many contemporary oceanographers began their careers before remote sensing of the ocean was even possible, when data was scarce and difficult to share. Furthermore, most of the oceanographers I encountered got into oceanography because they love the ocean. From Stommel to the young graduate students whom I met in each institute I visited, they are surfers, fishers and sailors. They are enthusiasts for marine life, even if their days are occupied with numerical models. They are fascinated with the ocean and the mysteries it hosts, prone to statements such as this:

> I mean, I chose oceanography because I wanted to go to sea. So if we start seeing a shift in that I think … I’m not attracted to running models, or just doing number crunching. I go to sea, collect data so I have an ownership of what I’ve done and an experience of what I’ve done and then I put that into my research. And if I was, if you were to remove that, oceanography wouldn’t be sexy for me, it wouldn’t be fascinating.

These kinds of statements stray from science’s normative emphasis on objectivity as the most important element of scientific work. In fact, when oceanographers speak of their love for the sea and their enthusiasm for being away from land, they contradict traditional scientific values of objectivity and neutrality and the normative priority of capturing as much high-quality data as possible. As Oreskes (1996) points out, ‘good’ science, conventionally understood, should be boring: easily replicable, independent from environmental context, and devoid of emotion.

Beyond personal proclivities, without the shared experience of going to sea oceanography as a discipline might face an identity crisis. In 1980, a prominent South African oceanographer published an essay called ‘Oceanography is what oceanographers do!’ (Brundrit, 1980). If so, then oceanography, normally defined by material engagement with the sea, may be becoming indistinct from some information sciences. Oceanography’s disciplinary cohesion is already fragile, as it is a relatively young science and one composed of many different methods and foci borrowed from other disciplines (Oreskes, 2014). With the turn to remote and robotic sensing, oceanography’s unifying features may be lost. Of course, oceanography is not unique in this regard; other fieldwork- and observation-based disciplines, from archaeology to natural history to astronomy, have faced similar anxieties in the rapid onset of the digital era (see, e.g., Hoeppe, 2012; Olsen et al., 2012; Wilcove and Eisner, 2000). When it comes to oceanography, as Helmreich writes, cruises are not simply about gathering information, but about making meaning: ‘[O]ceanographic discovery is about *human* encounter with the sea’ (Helmreich, 2009b: 133, emphasis in original). This tension concerns cultural imaginaries of the sea, of exploration and knowledge, and of the human. It also has practical implications regarding the allocation of research dollars and the training of scientists; the question of whether remote sensing should be prioritized over ship-and submersible-based research has ‘affected government science policy and funding’ (Mindell, 2015: 62). But for scientists, ‘the most heated arguments are less often about technical capabilities than about pride, culture and professional identity’ (Mindell, 2015: 63). Tracing resistance to remote sensing in deep sea science, Mindell (2015) writes, ‘this argument is about professional identity – we are field scientists, we go into the field, and our field is the deep ocean’ (p. 64).

This is a view echoed in the words of the scientists with whom I spoke. For example, an Earth observations specialist told me he wasn't really sure what oceanography was anymore, saying that any problem he could imagine oceanographers currently puzzling over seemed like a data management problem to him. An oceanographer put it this way: 'Oceanography is not a science. It's a place where you do whatever you do'.

Of course, as suggested above, scientists themselves express some ambivalences about the shift away from ship-based research and toward satellite, robotic, and remotely-operated sensing. Many of the same scientists who work on cutting-edge iterations of these technologies and express excitement about their potentials also bemoan reductions in ocean-going capacity and loss of ship time for scientists. Mindell (2015) notes that even when scientists inhabit submersible research vessels, they often rely on cameras and screens to see what is in their immediate vicinity. The scientists with whom I spoke also widely agree that ship-based measurements will never be phased out entirely, as they are needed to calibrate instruments, a process that deserves its own analysis. Yet, the widespread nostalgia about a bygone or rapidly waning era of ship-based oceanography remains notable.

Although the narratives above might be understood as scientists' own appreciations for their situatedness as researchers as sea, they can also be read as expressions of Oreskes' (1996) 'ideology of scientific heroism', which she argues has particularly affected the field sciences. In the narratives above, ship-based oceanography is painted as virtuous, facilitating the leveling of hierarchies and passionate and singular focus on the ocean; they also play off tropes of daring, heroic seagoing exploration. Adventuring to sea for science is beguiling both for scientists' self-image as exceptional observers of the natural world and for the public and private funding agencies that support their work. Oreskes (1996) writes, 'Heroic attributes and self-sacrifice make the scientist worthy of praise, admiration, and support, and thus connect him as an individual to human ideals shared by a larger community' (p. 103). Ideologies of heroism are evident in Stommel's characterization of life on board ship, where the sea is the enemy bravely fought by the enterprising scientists. Now, we can look at the social media feeds of the US's major oceanographic institutes to see the emphasis on ship-based sampling and ocean exploration in contrast with much less frequent mention of the remote sensing, data analysis and numerical modeling that occupies many oceanographers' time; examples are given in Figure 4. Rather than emphasizing objectivity, as critical scholars might expect, these posts highlight the adventure and hardship of ocean exploration.

While imaginaries of scientific adventure can help to garner public support and increased funding for more mundane scientific practices, they '[leave] invisible the woman scientist on shore' (Oreskes, 1996: 100; also Oreskes, 2000). These ideologies also leave out the work of those who cannot afford to undertake heroic oceanic voyages, such as scientists from institutions and/or nations without large oceanography research budgets. These scientists are not lesser scientists nor mere technicians: Their work is not necessarily more mundane, nor less objective, and it frequently is crucial to scientific advances, yet because the researchers are unrecognized as conquering heroes, professional and public acclaim frequently eludes them. Moreover, repeated performances of masculinity and agonism as the compulsive culture of science reinscribe narrow gender roles for both male and female scientists, despite the diversity of affective relations that

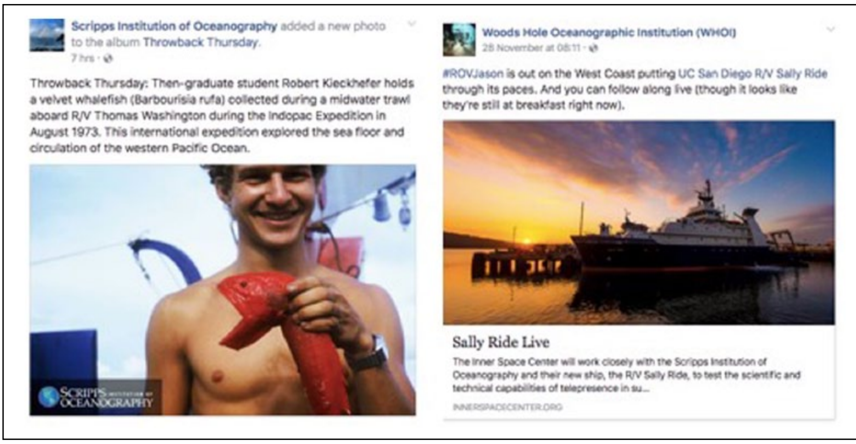

Figure 4. Screenshots of Scripps Institute of Oceanography and Woods Hole Oceanographic Institute social media posts.

actually exists in most scientific communities. These framings ultimately affect who chooses to do science and what scientists are permitted to 'see, say, imagine, and feel' (Myers, 2010: 828).

Sensing inequality in ocean science

The shift from ship-based to remote, autonomous and remotely-operated sensing may be understood to oppose ideologies of scientific heroism in two related ways. First, it opens oceanography to a wider range of actors. Second, as the following section will discuss, it may emphasize the crucial ways in which nonhuman actors such as technologies and ocean participate in making sense of the sea. Clearly, women, minorities and people from underfunded institutions are capable of doing research on ships, and disability need not be an obstacle to ship-based research (for example, Amy Bower is a prestigious US oceanographer who has done a great deal of research at sea despite being blind). Nonetheless, due in large part to ideals about masculinity and exceptionalism, for much of oceanography's history only white men were allowed to go to sea, especially in Western nations. Elizabeth Stommel (Stommel and Stommel, 1984: 20.4) describes the gender dynamics of Woods Hole Oceanographic Institute in the 1940s and '50s in straightforward terms: 'Women, working as laboratory assistants or secretaries, didn't go to sea because they weren't allowed. Living conditions on shipboard were said to be too primitive to accommodate both sexes'. Historian of science Schlee (1980) writes that the sanitary conditions on the Woods Hole Oceanographic Institute's first global-scale vessel *Atlantis* 'effectively barred women from using the ship' (p. 51). Henry Stommel (1995) recounts an incident involving a female scientist who attempted to join a coastal cruise in 1956:

> Roberta Eika, a Harvard student, had to hide herself in the bilges of the Caryn in order to go on a three day cruise. After a day and night lying on the lead-pig ballast, when she emerged as the

> first woman stowaway, her faculty advisor […] nearly cancelled her fellowship, and the episode was regarded as a scandal. There was a strong current of disapproval, especially amongst that portion of our crews who counted the absence of females as one of the felicities of life at sea. (p. 52)

Since mid-century, women have made great advances in oceanography. A recent study found that 'women in oceanography are better represented at all ranks, except department head, than the geosciences as a whole' (O'Connell and Holmes, 2005: 21). Nonetheless, of 428 cruises with principal investigators (PIs) on global-class research vessels logged in the University National Oceanographic Library System (UNOLS) database between 2010 and 2016, only 96 had female PIs. It would be a conjecture to suggest that the discrepancy between these figures and the relatively more equal overall status of women in oceanography is due to the use of new sensing technologies. Nonetheless, the changing lifeworlds that oceanographers are experiencing, in which scientific community is increasingly based on attending workshops, co-habiting robotics labs, and communicating electronically – rather than bonding in the homosocial spaces of the seafaring research vessel – may serve to benefit women and others previously marginalized in oceanography.

Of course, women were not only disadvantaged by being excluded from ship-based oceanography; they also had to perform the kinds of labor that would allow the male scientists to be absent at sea for long periods of time, whether that was in the lab or the home. Again, Elizabeth Stommel's words are illuminating: In *Sea of the Beholder*, she mentions frequently the loneliness and hard work she endured while her husband enjoyed what he calls 'large tastes of saltwater' (Stommel and Stommel, 1984: 6.20). Perhaps most plainly, she states, 'Henry returned home invigorated and renewed by his adventures; I felt emotionally exhausted by double parental and household duties' (Stommel and Stommel, 1984: 20.17). Of her frustrations, she writes, 'I don't know whether to blame him or the science of oceanography' (Stommel and Stommel, 1984: 20.9).

Again, there is nothing inherent in the material conditions of ship-based oceanography that makes it inaccessible for most individuals. But the actual capacity of different individuals to do ship-based work is somewhat beside the point, since 'the ideology of science bears a stronger relation to the belief structure of the scientific community than to the nature of the scientific work itself' (Oreskes, 1996: 104). Thus, while ship-based work is not necessarily more difficult, the ideologies of heroism, conquest and adventure that surround it lead to the exalted personal and professional status of those who do this work. New regimes of ocean sensing might work against ideologies of scientific heroism by valorizing different kinds of scientific labor. Gender is not the only factor that makes ship-based oceanography exclusive. Research vessels are very expensive, especially those with the capacity to venture beyond coastal seas on longer expeditions. A day at sea on a US global-class research vessel can cost $20,000 or more, not including the cost of salaries for any scientists on board. Therefore, it has been mostly white men from elite universities in the global North (and, increasingly, the BRIC countries, Brazil, Russia, India and China) who are able to take to the seas in pursuit of science. Military and economic goals have been thinly veiled in these scientific ventures, as discussed extensively elsewhere (see for example Hamblin, 2005; Lehman, 2016). This is not to say, of course, that robotic and remote sensors escape this legacy. For example, as verified by a number of scientists with whom I spoke, the US Navy is perhaps the most significant funder and user of Argo data. The Navy is interested in the changing structure of the sea in areas where it has marine interests, not just off the US coast but also, for example, in the South China Sea; Argo readily provides that data.

Nonetheless, scholarship done using data from remote and robotic sensors may be more accessible to wider range of actors. It is much less expensive than ship-based research; much of the data can be downloaded for free online. Even the purchase of robotic sensors is relatively inexpensive: an Argo float costs approximately $16,000 over its lifetime and its purchase enables its owner to participate in the international Argo community, including setting the research agenda. Furthermore, due to the need for uniform datasets and the large amount of data now available, significantly more resources are focused on workshops, conferences and capacity-building exercises, creating an international community of data analysts, quality controllers and data processors. Although some of this work is automated, much of it must still be done by humans, who are now gaining increasing recognition in the scientific community. While we might imagine scientists now alone, in front of the computer, downloading data and monitoring robots, this kind of science requires much human and machine interaction, as well as an intimate knowledge of the ocean's material properties. Thus new sensing practices may not simply extend opportunities in oceanographic science to a wider range of participants, but may also reshape ideologies of scientific heroism by emphasizing the work of data analysis and processing as well as float construction and deployment.

Conclusion: New sensing relations

The ways in which new practices and paradigms of ocean observations reconfigure sensing relations extend from who does oceanography to how they do it. The shift to robotic and remote sensing may not abstract oceanographers away from the materiality of the sea, but it creates new relationships that emphasize the linked materiality of the ocean and the technologies necessary to sense it. As Helmreich and others have pointed out, it is virtually impossible to encounter the ocean without mediation, let alone produce meaning about it (Helmreich, 2009b, 2011; see also Goodwin, 1995). The ocean's temperature and pressure extremes and lack of light and oxygen mean that humans must have relationships with machines to make sense of it.

New sensing technologies may make oceanographers and their publics increasingly aware that human influence extends to the deepest and most far-flung seas. Rather than a great pristine expanse seen from onboard a ship, the ocean revealed to new sensing technologies bears the marks of acidification, toxic dumping, microplastics and climate change (Alaimo, 2013). I can think of no one who understands the issues better than scientists and technicians who design and implement ocean robotics. The ocean is a very difficult environment in which to deploy and maintain robotics, or any kind of machinery for that matter. This is especially true when it comes to designing instruments such as Argo floats, for which repairs and re-calibrations are rarely deemed viable. The ocean subjects Argo floats to immense pressures, extreme temperatures, and various forms of chemical assault; these challenges are experienced even more acutely by instruments that operate at greater depths. Furthermore, Argo floats and other *in situ* sensors are affected by marine life as well. Mollusks and marine microorganisms colonize any surface of an instrument that operates in the upper layers of the ocean, where light can reach (Roemmich et al., 2001). This presents significant problems for sensing technologies; for example, it causes inaccuracies over time in Argo's salinity sensors, requiring the data to be corrected using ship-based measurements and laboratory-prepared standards. Thus the materiality of the sea is far from absent in remote and robotic sensing. Even if these factors do not appear in the representations of the ocean given by visualizations such as Google Earth, scientists are the first to recognize that they are very significant in creating these images and interfaces. A reduction in ship-based oceanography does not mean, then, a wholesale withdrawal from the ocean's materiality; it may mean contending with it in other ways, not as a solitary explorer but in concert with many other humans and nonhumans.

It is not just through material wear and tear and biological interference that the materiality of the ocean asserts itself to today's oceanographers. It is also a matter of communicating with the technologies, whether they are relatively simple Argo floats or more complex robots. As one oceanographer described,

> The ocean is just so different in terms of supporting many of the ways in which we … think of communicating and building our technologies, it's you know, there's not only tremendous pressures and cold temperatures but there's really importantly no way for us to talk to our sensing network, or talk to our robots, right, except when they come to the surface, or through very imperfect and difficult to deploy means of communication. [There's] no GPS underwater, so you know where nothing is.

Helmreich has argued that even though humans using new sensors may not be physically entering into or onto the ocean, many scientists who use remotely operated vehicles 'feel a direct body-to-body connection with these objects'. This leads him to argue that they are not so much technologies of remote sensing but of 'intimate sensing' (Helmreich, 2009b). Rather than being abstracted from nature, such technologies build on notions of 'the union of self and sea as one of the most privileged ways to appreciate nature' (Helmreich, 2009b: 141). At the same time, he argues, such technologies give the impression that immediate and unbiased views of the sea are possible, given the proper perhaps-not-yet-invented equipment. There is a difference between the remotely operated deep sea vehicles that Helmreich discusses and the physical oceanographic sensors I am discussing here, as the latter are not precisely aimed at directly extending vision to the sea. They do further the goals of metaphorically or literally 'seeing what's happening', but they are less interested in 'looking around' than in creating quantitative data. Nonetheless, parallels can be drawn between human and machine sensing, even with distributed networks of sensors like Argo. The words of the oceanographer quoted at length above are again illustrative:

> 'Human' can be a network of neurons, right? And those are incredibly simple distributed systems. That's human. And you know in a certain sense that kind of sensing network, which could be taste buds on a tongue or nerves on a fingertip, I mean those can be human and they can be incredibly powerful concepts in terms of sensing the ocean environment. … Because the

> ocean is so vast and because it sort of, it basically is just vast, the challenges that come up with streamlined lower cost solutions that give this sort of wide-area view of the ocean and through that you get many different sort of senses of scale. So you know, maybe to use the nerves on your fingers as an analogy, an individual nerve can feel one thing, but it's not until you sort of map them together that you make more interpretive and important discoveries.

The ability of remote and robotic vehicles to allow people to sense the sea within the intimate spaces of their home offices inaugurates, for Helmreich (2009b), 'a new order of intimate sensing' (p. 149). In following what abstractions and their technologies do, then, we can find an alternative both to the figure of the enterprising solo scientist in command of technology and nature, and to the notion of an ocean gridded, measured, falsely transparent and devoid of oceanographers. Rather, we see that a heterogeneous set of relations and activities goes into producing contemporary knowledge about the ocean. New sensing practices draw attention to the always-partial nature of ocean knowledge, and the degree to which this knowledge is made (and unmade) by a diverse set of actors, including different humans, nonhuman animals, and increasingly independent technologies themselves. In fact, new sensing practices might proliferate relations that de-center not just the (white, male) scientist but the human itself as the omniscient witness and draw attention to different dimensions of the ocean's materiality.

The shift from ship-based to robotic and remote sensing has changed relations between individual scientists and technologies, and relations among different scientists and institutions. There are ambiguities in the significance and problematics of new technologies. By critically examining what is lost and what may be gained in the shift away from ship-based sensing, oceanographers and science studies scholars alike may be able to find new ways to identify the elements of meaning-making and engagement with the sea that they find crucial, such as more cooperative working environments and the immediacy of the ocean's materiality. While sensing technologies are not in themselves emancipatory, scientists may be able to use the openings they provide in order to shape the work environments they seek.

Acknowledgements

The author is grateful for the time and insights of the oceanographers who participated in the study, as well as the archivists and librarians at the Woods Hole Oceanographic Institute and Scripps Institute for Oceanography. Financial support for this project was provided by a Doctoral Dissertation Grant and a Thesis Research Grant from the University of Minnesota and a grant from the Consortium on Law and Values in Health, Environment, and the Life Sciences at the University of Minnesota. The author thanks the Marine Research Institute at the University of Cape Town for hosting the author's residency in 2014. Finally, the author is beholden to Bruce Braun, Laura Cesafsky, Sophie Webber, and the members of Lisa Naughton's Biological Interest Group at the University of Wisconsin for their insightful comments on earlier versions of this paper. All errors and shortcomings are solely the fault of the author.

Funding

Funding Sources University of Minnesota, (Grant/Award Number: 'Consortium on Law and Values in Health, Environmen', 'Doctoral Dissertation Grant', 'Thesis Research Grant').

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Author biography

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