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Mapping Ocean Worlds Through the Data Revolution

Abstract

In an ongoing 'data revolution' in ocean science, scientists are working to close perceived knowledge gaps through novel data technologies, which make previously unseen physical and ecological properties visible. Ocean Data Science Initiatives (ODSIs), initiatives that mobilize data with the express goal of informing or improving conditions in oceans, are central to these endeavors. ODSIs often visualize data in the form of maps, which shape data-based imaginaries of ocean space, creating ocean worlds. In this paper, we ask: what ocean phenomena and data do ODSIs' maps make visible, and what kind of ocean worlds do these maps create? Our analysis reveals that ODSIs map a range of biological and physical phenomena and human activity in ways that (1) depict some or all of the oceans as blank space; (2) reinforce the role of the state in oceans governance and data management; (3) depict the ocean as spaces under threat; or (4) emphasize the presence of data or scientific monitoring activities in oceans. This suite of representations reveals that ODSIs have multiple ways of emphasizing, and as such influencing, the types of data that are relevant, the spatial extent at which those data should be gathered, and the ends to which they should be used. In part through mapping, ODSIs and the heterogeneous forms of data that they collect, process, and share, are continuing a geoepistemological shift away from a single representation of oceans toward multiple possibilities for seeing, knowing, and governing oceans through data.

Keywords: oceans; data; mapping; worldmaking; geoepistemologies; visual analysis; critical cartography

1. Introduction

Although oceans cover 70% of the planet, they are hostile to, and remote from, human habitation and difficult for humans to 'see' beyond their two-dimensional surface (Campbell et al., 2016). Given this opacity, most humans 'see' oceans primarily through maps and other visualizations (Campbell et al., 2022; Lehman, 2022; Steinberg, 2009). Maps not only represent ocean worlds; they help make them (Campbell et al., 2022; Lehman, 2022). They enable some possibilities while foreclosing others, co-producing ocean worlds as actors with varying interests, knowledge, and experiences engage with

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them (Campbell et al., 2022; Kitchin & Dodge, 2007). In the midst of what has been described as an "ocean data revolution" (Leape et al., 2020), a growing number of technological tools and visual interfaces expand possibilities for ocean mapping, and thus worldmaking.[1] In this paper, we seek to understand what kinds of ocean worlds emerge as novel data technologies enable seeing the oceans in ways never before possible.

This question emerges, and is intertwined with, renewed global interest in oceans governance and monitoring. Oceans are tied to the fate of the planet, as mounting evidence of ecological change builds alongside interest in oceans as frontiers for management and development (Johnson & Braverman, 2019; Jouffray et al., 2020; Melvin, 2026). State and non-state actors are seeking new and extended management approaches (Dodds, 2010; Melvin et al., 2023; Silver & Campbell, 2018) that can be informed by new data technologies and digital outputs, open access tools, and user interfaces, including maps. Contemporary efforts to 'govern' and 'know' the ocean in improved and/or innovative ways run in parallel with the United Nations Decade of Ocean Science for Sustainable Development (2021-2030) ("Ocean Science Decade"), which has a vision of "the science we need for the oceans we want" (*UNDOSSD,* 2022).

[1] The concept of worldmaking captures the relationship between 'representing' and 'being' in the world (Escobar, 2018; Goodman, 1978) and has been invoked in a variety of disciplines, including by geographers/cartographers interested in maps (see special issue of Cartographica, Rose-Redwood (Ed.), 2015). The concept is used in other disciplines (e.g. art, architecture) and applies to other devices (e.g. narratives). For oceans, we note that Koro et al. (2023) have demonstrated how indigenous Pacific islanders' epistemologies may be brought into conversation with dominant Western geopolitical concepts to re-imagine the geopolitics of the ocean. Whether, and how, to bring Indigenous worldmaking practices into conversation with ODSIs' data mapping practices is beyond the scope of this paper, and we recognize there is a risk of attempting to translate these knowledges into Western systems (Havice et al., forthcoming; Koro et al., 2023).

Ocean Data Science Initiatives (ODSIs), or initiatives that "mobiliz[e] (often geospatial and temporal) data and/or novel data sources about the ocean with an express goal of informing or improving conditions in the oceans," are key actors in these unfolding processes (Drakopulos, Havice & Campbell, 2022, p. 1). ODSIs mobilize new data technologies, creating architecture for data sharing and collaborative networks that can support new and expanded ocean governance projects (Drakopulos, Havice & Campbell, 2022; Gulino, 2024). ODSIs include state and non-state organizations working alone or in partnership to generate, capture, collate, analyze, and/or share data[2] on oceans' physical and biological properties, and human 'impacts' (Drakopulos, Havice & Campbell, 2022; Melvin, Havice, et al., 2025). ODSIs often communicate data using maps, and these maps reflect ODSI choices about what data to display and how to display them. As the number and types of data-intensive maps proliferate, the ocean data revolution provides a unique moment for understanding ODSIs' role in worldmaking processes.

What ocean phenomena and data do ODSIs' maps make visible, and what kinds of ocean worlds do these maps create? Motivated by our interest in maps and worldmaking—*i.e.*, in understanding how maps both reflect and shape human interests in, and concerns about, ocean space and resources—we explore maps for insights about the role of ODSIs and data in shaping future possibilities for "the oceans we want" in the Ocean Science Decade (*UNDOSSD,* 2022). Our visual analysis of 132 maps drawn from a dataset of 94

[2] Not all ODSI generate their own data; some use (and sometimes transform) data from other sources. For the purposes of this paper, we refer generally to ODSI data, which includes data generated by or accessible to them.

ODSIs suggests that ODSIs' work processing and visualizing data supports multiple representations of ocean space. In particular, we identify four common themes to describe these representations: oceans as blank space, oceans as state territory, oceans under threat, and oceans as spaces of data. Our analysis contributes to understanding the ocean worlds that emerge from these representations, helping to position ODSIs as actors in ocean worldmaking and broader processes of mobilizing data for oceans governance.

We structure this paper as follows. In Part 2, we review the relevance of maps in ocean worldmaking, attending to questions around if and how the ongoing data revolution in ocean science stands to shape these understandings. In Part 3, we discuss the processual role of mapping in co-producing worlds, including detailing how our visual analysis methods inform understanding of the worldmaking power of maps. We then detail our empirical findings in Part 4, demonstrating that ODSIs create static images and interactive tools to map a range of biological, physical, and human ocean variables. We find that ODSIs' mapmaking choices yield diverse ocean representations that create not one ocean world, but many. We conclude in Part 5 by discussing how ODSI data mapping practices are a key avenue for these organizations to mobilize data for oceans governance with potential implications for emerging blue geopolitics (Suarez de Vivero & Rodríguez-Mateos, 2024). In the digital era, ODSI maps communicate data and play a role in determining which knowledge counts for "the science we need," and defining "the oceans we want" (*UNDOSSD,* 2022).

2. Mapping and The Politics of Ocean Worldmaking

2.1. Ocean Maps Reflect Societal Needs and Shape Governance Possibilities

‘Ideal’ cartographic work aims to represent the earth as faithfully as possible, aspiring to create maps that are the “objective, neutral products of science” (Kitchin & Dodge, 2007, p. 331). Since at least the critical turn in cartography, geographers have emphasized that mapping is neither an objective nor neutral process (Kitchin & Dodge, 2007; Lehman, 2022; Pickles, 2003). Maps are embedded in processes of formulating and legitimating power relations and governance institutions (Harley, 2001; Scott, 1998). For instance, states have made maps to translate messy, complex forms of knowledge gained from lived experience into simplified, abstract representations, rendering them legible, controllable, and governable (Scott, 1998; McCarthy & Thatcher, 2019). The resulting maps both reflect societal needs and shape the social and natural world by conditioning governance possibilities (Crampton, 2002; Scott, 1998).

Mapping has long been powerful in conditioning possibilities for oceans governance, because oceans lie outside the lived experience of many humans (Campbell et al., 2022; Steinberg, 2009). From the sixteenth to the eighteenth centuries, colonial states’ ocean visualizations shifted from depictions of textured, natural spaces to spaces of routes and mathematical abstraction, reflecting colonial states’ “changing conception of what the ocean is (or should be)” (Steinberg 2009, p. 481). Depictions of natural oceanic features became ill-suited to mercantilist capitalism’s needs for seamless transport of goods across their surface (Steinberg, 2009). Western visualizations therefore shifted to depict oceans as abstract ‘frictionless’ voids that could be crossed at will.

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As states' ocean governance needs changed, so too did ocean maps. In the nineteenth century, economic uses of ocean space and resources required that oceanographic properties be measured and visualized anew (Lehman, 2022; Reidy & Rozwadowski, 2014). Shipping, whaling, and sealing industries drew ships farther offshore, making scientific exploration of oceans more culturally, economically, and politically relevant (Reidy & Rozwadowski, 2014). Scientists began to study and map oceans in ways that reflected maritime nations' geopolitical ambitions for resource extraction. In connection with the British and U.S. militaries, cartographers constructed hydrographic charts and depicted ocean features, such as depth and seafloor sediment, that supported colonial resource use (Oreskes, 2022; Reidy & Rozwadowski, 2014). These charts reflected advances in scientific knowledge and helped Western eyes 'see' the oceans "as known and legitimate 'places'" (Reidy & Rozwadowski, 2014, p. 339). States employed emerging mapping technologies to render complex oceanic geographies as legible spaces for governance, enabling the projection of state power over both near and far waters (Flint, 2024; Johnson & Braverman, 2019).

2.2. Evolving Mapping Tools and Technologies Enable New Actors to Create and Circulate Maps

Despite its importance, mapping oceans has historically been a challenging technological and political project (Lehman, 2022; Steinberg, 2009). The vast, fluid, and three-dimensional materiality that is central to oceanography, ecology, biology, and human activity in oceans makes them difficult to study and to represent (Adler, 2022; Bode & Yarina, 2020; Campbell et al., 2016). These challenges have led to the development of

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new technologies for state and non-state actors to create and circulate new kinds of maps depicting different ocean phenomena.

For instance, in the twentieth century, colonial and imperial states' need to transform expanses of water into governable, manageable, and usable spaces, in part, motivated the development and subsequent dominance of modern grid systems (*e.g.,* Universal Traverse Mercator (UTM) or Global Positioning System (GPS)) (Rankin, 2016). Grids enabled mapmakers to portray local and global space (Turnbull et al., 1989) and were (and remain) crucial to defining political and economic control over oceans (Lehman, 2022). For instance, precise geospatial science and cartographic techniques were essential to defining states' 200-mile Exclusive Economic Zone (EEZ) boundaries, a key component of the United Nations Convention on the Law of the Sea (UNCLOS) (Lehman, 2022), parceling the oceans into "discrete sites of economic activity" for resource extraction (Ranganathan, 2022, p. 31).

In the digital era, grid systems allow widely available GPS receivers to access and gather geospatial data, which, in turn, enables actors (who may or may not be affiliated with the state) to contribute to the expansion of mass-produced geocoded data (Rankin, 2016). For example, ocean managers now commonly populate available data (ranging from government-sourced topographic maps to user surveys in coastal communities) into open access data portals (Campbell et al., 2020). Some portals invite users to visualize available data according to their own questions and intended goals, creating possibilities for non-state actors to represent ocean phenomena. These processes hold potential for mapping a variety of ocean imaginaries, and, in turn, ocean management projects and goals (Boucquey et al., 2019).

Maps remain essential for 'seeing' oceans, and the digital era has arguably produced a geoepistemological shift: authoritative state-sanctioned mapping has given way to—or at least made more space for—a more diverse range of actors to create and circulate maps of the oceans and other spaces (Rankin, 2016). Contemporary ocean mapmakers include states, non-state organizations, scientific collaborations, and others who elect to map a broad range of variables: economic, biological, ecological, indigenous knowledge, human activity, management dynamics, and more (Campbell et al., 2022; Fairbanks et al., 2019; Gray, 2018; Jay, 2022; Lehman, 2022).

New data technologies are now remaking the process and politics of mapping and taking a central role in environmental governance more broadly (Goldstein & Nost, 2022; Nost & Goldstein, 2022). In the oceans, a "data tsunami" (Brett et al., 2020, p. 182) offers more data about the oceans generated in a single year than over the past century combined (Tanhua et al., 2019). Satellite remote sensing, GPS, and optical imagery illuminate ocean spaces, processes, and species from above, whereas remote and autonomous underwater vehicles do so from below (Campbell et al., 2016; Lehman, 2016). ODSIs have emerged in this context. Reflecting a techno-optimism (e.g., Kourantidou, 2019; Van Dam, 2019) that more and better ocean science will translate linearly to improved policy (Fawcett et al., 2022), policymakers, scientists, and conservationists are increasingly turning to ODSIs to produce, organize, and mobilize ocean data to inform

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governance (Drakopulos, Havice & Campbell, 2022). ODSIs often draw on high volumes of newly available digital (and digitized) data to map previously invisible ocean phenomena.

We argue that the resulting maps make ocean worlds. Among other things, they enable new ways to imagine territory (Lehman, 2022; Steinberg, 2009), visualize environmental threats (Gray, 2018), and support management actions and decision making (Acton et al., 2019; Campbell et al., 2022; Gray, 2018). For example, Gray (2018) describes how Global Fishing Watch (GFW)—a non-profit ODSI working to increase transparency and monitoring of commercial fishing vessels—mobilized an early version of its mapping tool at the 2014 World Parks Congress. A digital map visualized satellite-derived geospatial data of apparent industrial fishing effort to show an ocean 'on fire' with fishing activity, with exceptions within spaces the GFW presenter identified as protected areas. With an emphasis on the global scale, GFW's map made a world in which ocean spaces on the high seas are "both in need of conservation action and amenable to the spatial logic of management typically reserved for state territory" (Gray, 2018, p. 268).

Tying the analysis to then ongoing efforts by conservation advocates to enable the extension of marine protected areas to the high seas, Gray's (2018) example illustrates that ODSIs and their maps are part of an open process of evolving global geopolitics (Suarez de Vivero & Rodríguez-Mateos, 2024). Ocean science, long entangled with state interests, is relevant to geopolitical considerations beyond the state alone (Lehman, 2019). Data generation, gathering, collation, organization, interpretation, and sharing enhance knowledge of the oceans and are mobilized in contested geopolitical concerns, including sovereignty (Lehman, 2019), resource claims (Havice et al., 2022), conservation (Campbell et al., 2022; Gray, 2018; Havice, 2018), and global inequalities (Lehman, 2018). In the context of the data revolution, ODSIs' mapping choices and products are therefore embedded within "a new geopolitics" that will shape global relations for years to come (Jones, 2024, p. 670).

3. Mapping and the Co-Production of Knowledge

3.1. The Processual Role of Mapping in Worldmaking

Our understanding of mapping and map reading informs this research in several key ways. Here, we describe this understanding generally, before detailing the specifics of our visual methodology in section 3.2.

First, although the capacity to map is expanding in the digital era, mapping is always selective. Creating fixed visual outputs of data collected by measuring three-dimensional, liquid, and dynamic space requires choices that demand simplification; not all data can be visible at any given time (Bode & Yarina, 2020). All maps produce a "selective, incomplete view of reality" (Monmonier, 1996, p. 1) determined by data availability, capacity limitations, the extent to which data can be interpolated and visualized, and a cascade of decisions about how to collate data, construct categories, draw boundaries, and edit the resulting maps as fixed visuals (Acton et al., 2019; Fairbanks et al., 2019). For oceans, most maps focus on biological, geophysical, and chemical processes (Warren et al., 2023). Though the data revolution is contributing to mapping human impacts on the oceans and marine life (e.g., Halpern et al., 2008), these are difficult to quantify and are often "statistically buried under aggregation algorithms" (Warren et al., 2023, p. 559),

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particularly at larger spatial scales. Moving beyond human impacts to understand and map human relationships and values is even more challenging (Boucquey et al., 2016, 2019; Fairbanks et al., 2018, 2019). Spatial representation of the ocean hinges, in part, on which data are available and amenable to the task at hand (Acton et al., 2019; Boucquey et al. 2019).

Like all maps, maps of ocean data are visual representations that "make certain things visible in particular ways, and other things unseeable" (Rose, 2023, p. 216). They reflect the conscious and unconscious choices of mapmakers (Harley, 2001; Monmonier, 1996), including decisions on which phenomena to depict and how to symbolize geospatial variables, which can simplify reality (Harley, 2001; MacEachren, 2004). The mapmakers' technical choices—often hidden in maps—influence how map readers see oceans and what future possibilities they can imagine. As researchers, we recognize that mapmakers are constrained by available and amenable data and must make choices to produce any map. Although we explore the resulting consequences for worldmaking, in this paper we do not infer the intent of any mapmakers beyond the map and its presentation.

Second, maps do not make ocean worlds on their own. They are transitory and contingent products (Kitchin & Dodge, 2007) embedded in historical context, operating within a "horizon of possibility" (Crampton, 2002, p. 4). Maps are multifaceted visual representations that acquire meaning through visual, cognitive, and social processes (MacEachren, 2004). Maps are not ontologically secure; they are "of the moment"—remade every time map readers engage them (Kitchin & Dodge, 2007, p. 335). Mapmaking and map reading are inseparable processes through which spatial knowledges and

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practices are shaped and transformed based on the embedded knowledge, experience, interests, and skills of participating individuals. As map readers, we approach ODSIs' maps informed by our long standing research interests in: the role of science in oceans governance; ocean mapping and worldmaking; and the diverse governance actors interested in the conservation and development potential of oceans, both generally and in relation to specific governance debates (e.g. about seabed mining or marine conservation on the high seas (see also Table 2)).

Third, the data revolution is transforming not only mapmaking possibilities, but those for user engagement. Digital technological advancements further blur boundaries between knowledge production and circulation via tools that enable map users to manipulate images themselves (Gautreau & Noucher, 2022). In some cases, users may be empowered to explore geospatial data directly via portals and technical opportunities (Boucquey et al., 2019; Gautreau & Noucher, 2022), a process through which maps continue to "become" (Kitchin & Dodge, 2007). Thus, as part of our analysis, we reflect on how available technical opportunities to users might translate into worldmaking possibilities. Many of the ODSIs in this study provide tools that enable users to read, circulate, revise, and re-produce map images. With this in mind, we seek to understand the choices ODSIs offer, and what ocean phenomenon—and ocean worlds—they make visible.

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3.2. Visual Analysis as a Tool for Understanding the Worldmaking Potential of ODSIs and Digital Data

We developed a visual analysis method to answer our research questions. We analyzed ODSIs' static map images and interfaces used to convey data, seeking to understand how these products are embedded within processes of meaning making (see Kitchin & Dodge, 2007). We sought to identify the choices ODSIs make regarding what phenomena they map, the extent to which users can modify the resulting visuals, and the worlds created for us, as map readers.

We first reviewed the publicly available websites of an existing purposive sample of 94 ODSIs working at a global or regional scale in three defined focal areas (basic science (n=44), fisheries extraction (n=27), and biodiversity conservation (n=23)) (Melvin, Havice, et al., 2025). ODSIs included various organization types: NGOs/non-profits, universities, intergovernmental organizations, international state-sponsored research collaborations, national government agencies, and corporate entities. The ODSI catalog was originally assembled in 2022 (Drakopulos, Havice, Crisp, et al., 2022) and updated in 2025 (Melvin, Havice, et al., 2025). As part of the update, we identified maps that ODSIs presented as primary outputs or data products, excluding, for example, maps that merely illustrated the ways data might be used.[3]

[3] For detailed explanations of our selection process, see Melvin, Zurita Posas, et al., 2025 and the Visualization Notes column of Melvin, Havice et al., 2025].

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This review resulted in a dataset of 132 maps from 43 ODSIs.[4] ODSIs from all three focal areas and every organization type in our dataset produced maps.[5] Half (66) of the maps in our dataset are static images that do not facilitate user manipulation (e.g. image files (*e.g.* .jpg, .png) and animations (.gif)), and half (66) are interactive maps—software intermediaries that allow users to customize and manipulate data visualizations. We captured and stored all static images and default images of interactive maps (*i.e.* the map image that appears when the user first navigates to the map webpage).

To answer our research questions, we identified categorical codes to capture what type(s) of ocean phenomena each map depicts. We recorded the variables represented in each static map and default images of interactive maps. Recognizing that the worldmaking power of digital maps includes the possibilities available to the end user (Gautreau & Noucher, 2022), we also analyzed the customizations available in interactive maps, including what data layers users can add to the map and the available options to customize image aesthetics within the ODSI's software intermediary.[6]

With this structure in place, we identified themes using an iterative qualitative coding process. In early coding of the first thirty maps, we drafted open-ended memos (see Mihas, 2019) to capture our 'reading' of the role of data mapping in ocean governance: this included analyzing the purpose the maps serve, the general impressions they give, and the

[4] For the complete map dataset, including captured images, see Melvin, Zurita Posas, et al., 2025. For purposes of image quality and/or to comply with ODSI terms and conditions regarding data use, Figures 6A, 6B, 7B, 9, 10A, and 10B, were re-captured prior to publication. There were no changes material to our analysis since the original date of capture.

[5] An analysis of the maps by focal area and/or organization type is beyond the scope of this paper.

[6] Beyond our own experimentation with these interfaces, we did not examine how users engage with interactive maps.

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spatial questions they address (Melvin, Zurita Posas, et al., 2025). Finally, we analyzed our memos to develop a codebook of inductive and deductive themes. After drafting memos for thirty maps, we reached saturation of our codebook, ceased writing memos, and directly coded maps.

4. Visualizing Myriad Ocean Worlds in the Ocean Data Revolution

Our analysis revealed that ODSIs engage in diverse mapping practices that create not one ocean world, but many. ODSIs represent a diverse range of ocean phenomena, using mapping tools that range from static images to highly customizable interfaces that present many options for user engagement. We attend to the worldmaking power of ODSIs' maps as encompassing both the technical practice of mapping and the interpretive practice of map reading. We begin by identifying ODSIs' technical mapping practices, exploring how the data and visualization selections they make, and make available to users, result in maps with worldmaking possibilities. We then review the qualitative themes that we identified as map readers.

4.1. Diversity in ODSI Mapping Choices

ODSIs choose which of the available data to make visible and how to display them, including to what extent the end user can modify the resulting image. In this section, we describe these choices, highlighting what aspects of which ocean phenomena and activities ODSIs make visible and invisible.

ODSI maps visualize data on a range of biological, physical, and human ocean-related phenomena, on their own or in combination (Supplemental Table). Forty-two maps

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(32%) portray biological data, which include information on animal abundance, distribution, or movement obtained from a variety of remote sensing, tagging, observational, and telemetry methods as well as scientific assessments and modeling. In addition to these forty-two maps, another 11 maps (8 %) allow users to add biological data through customization. Thirty-seven maps (28%) depict physical data, which consist of specific, discrete, or time-bound measurements of ocean and weather conditions sourced primarily from satellite imagery, buoy data, or other techniques, including global efforts to map bathymetry using LIDAR, SONAR, or satellite altimetry. An additional 18 maps (14%) allow physical data to be added through customization. Seventeen maps (13%) visualize data relating to human uses of and presence in oceans, including information regarding fisheries catch and/or effort, pollution, or management efforts, and a further seven maps (5%) allow human use data to be added through customization. These data are sourced from a wide range of remote sensing, satellite imagery, fisheries stock assessments, scientific literature, or protected area databases.[7] Additionally, twenty-six (20%) maps visualize the geolocation of data sources that we refer to as ‘ocean science infrastructure’. This includes, for example, the discrete location of data-collecting buoys, defined tracks of scientific cruises, or the geographic sources (collection, management, or storage) of relevant databases. Most maps are populated with at least one data variable, but fourteen customizable maps begin with a visual of a blank default basemap, which users can populate with available datasets (*e.g.*, Figure 1).

[7] In some cases, underlying data may be based on human engagement, such as workshops and focus groups, but these data are not made visible in the map.

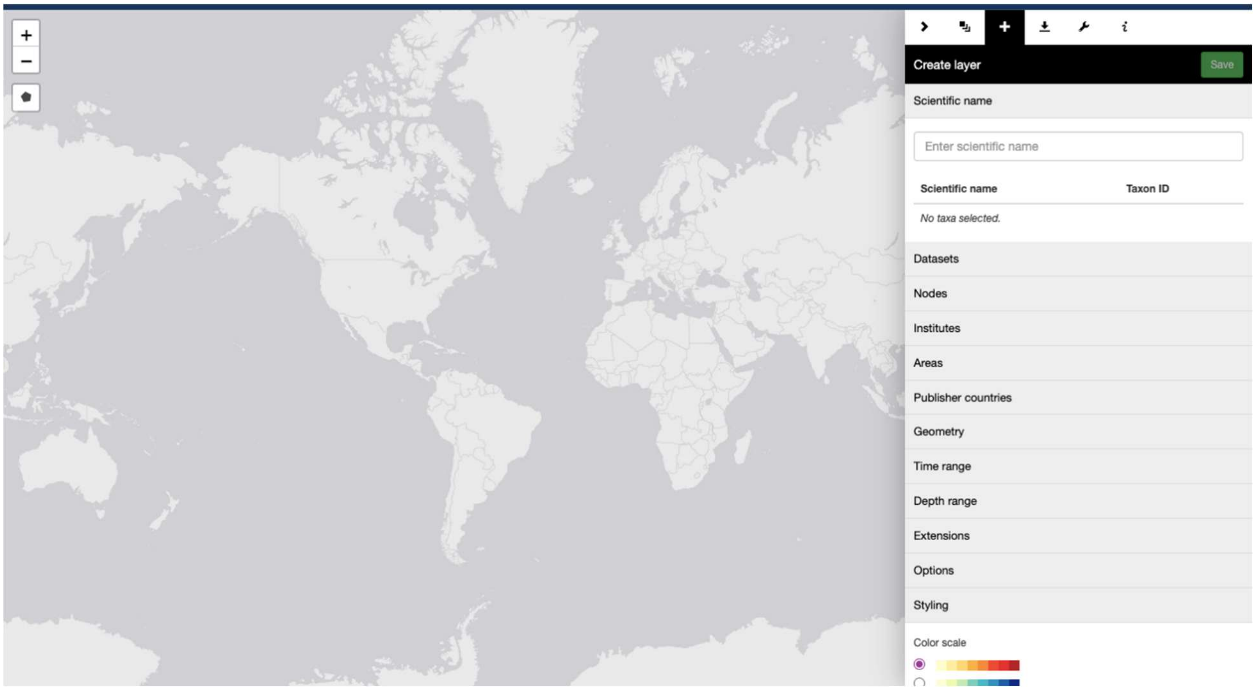

Figure 1. Default view of OBIS interactive map. https://mapper.obis.org/ (Captured June 3, 2024.)

All of these mapped phenomena are quantifiable and capable of being visualized across large geographic scales, using data generated by technology or algorithms and scientific analysis. For example, the Animal Telemetry Network (Figure 2) and the State of the World Sea Turtles (Figure 3) produce interactive maps that allow users to select remotely sensed tracking data of animal observations in ocean basins. Likewise, OceanDataLab maps (Figure 4) enable users to select various satellite-detected and derived physical and biogeochemical oceanographic features at global or ocean-basin scales.

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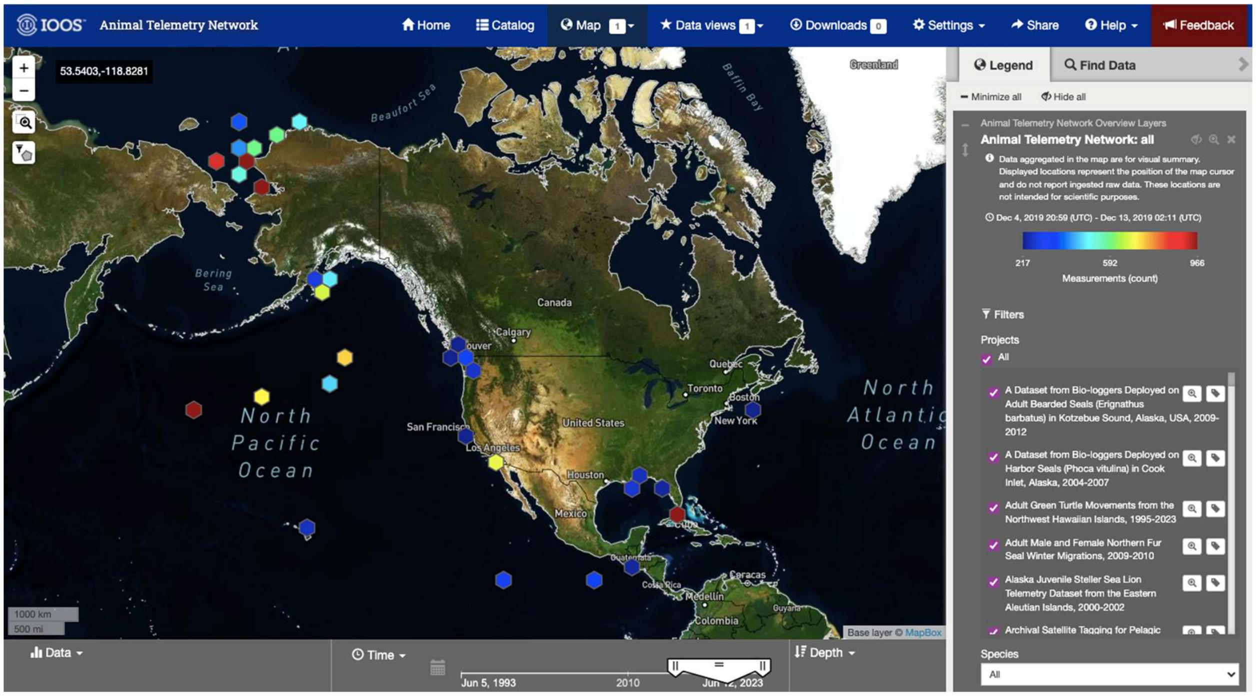

Figure 2. Default view of Animal Telemetry Network interactive map, showing aggregated counts of animal telemetry observation within hexagonal bins. https://portal.atn.ioos.us/#map (Captured July 4, 2023.)

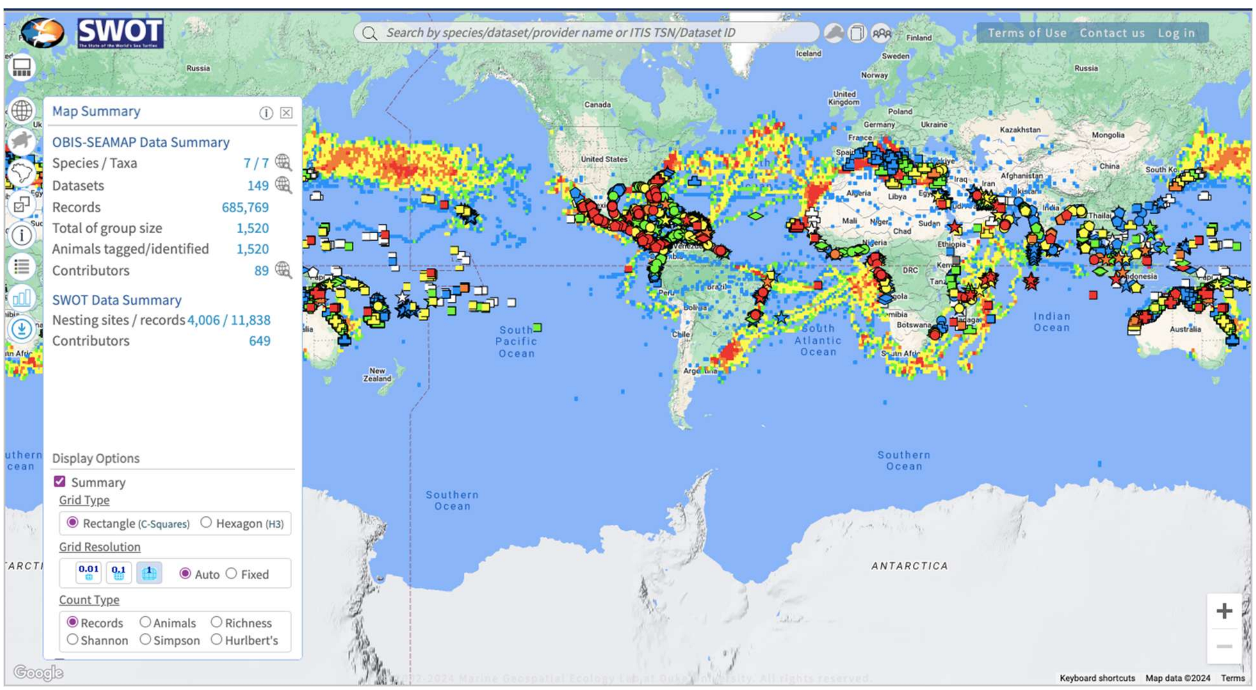

Figure 3. Default view of State of the World Sea Turtles interactive map showing tagged sea turtle data. https://seamap.env.duke.edu/swot (Kinan, 2005; captured June 11, 2024.)

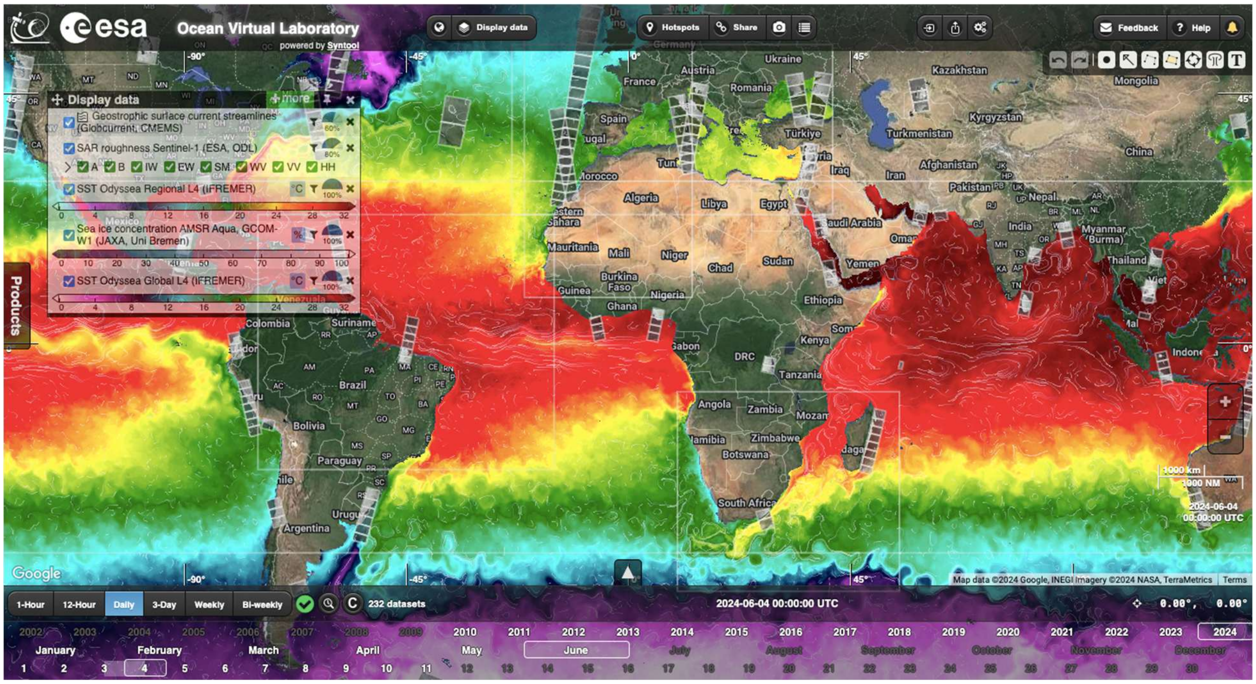

Figure 4. Default view of the Ocean Virtual Laboratory interactive map showing sea surface temperature, currents, and sea ice concentration. https://ovl.oceandatalab.com/ (Captured June 11, 2024.)

ODSIs' maps of human activity at sea most commonly use data related to fishing activity that have, generally, been interpreted or aggregated according to scientific practices. For example, the Sea Around Us map of spatial distribution of fish using the catch reconstruction method that builds on the Food and Agriculture Organization of the United Nations (FAO) official state fisheries catch data (Figure 5**)**. The underlying complexities between these two data sources are not visible on the map, and the resulting image is a product of FAO's collection and the ODSI's additional analysis. This is consistent with prior commentary that maps of ocean data often represent human data only as interpreted through algorithms (Warren et al., 2023).

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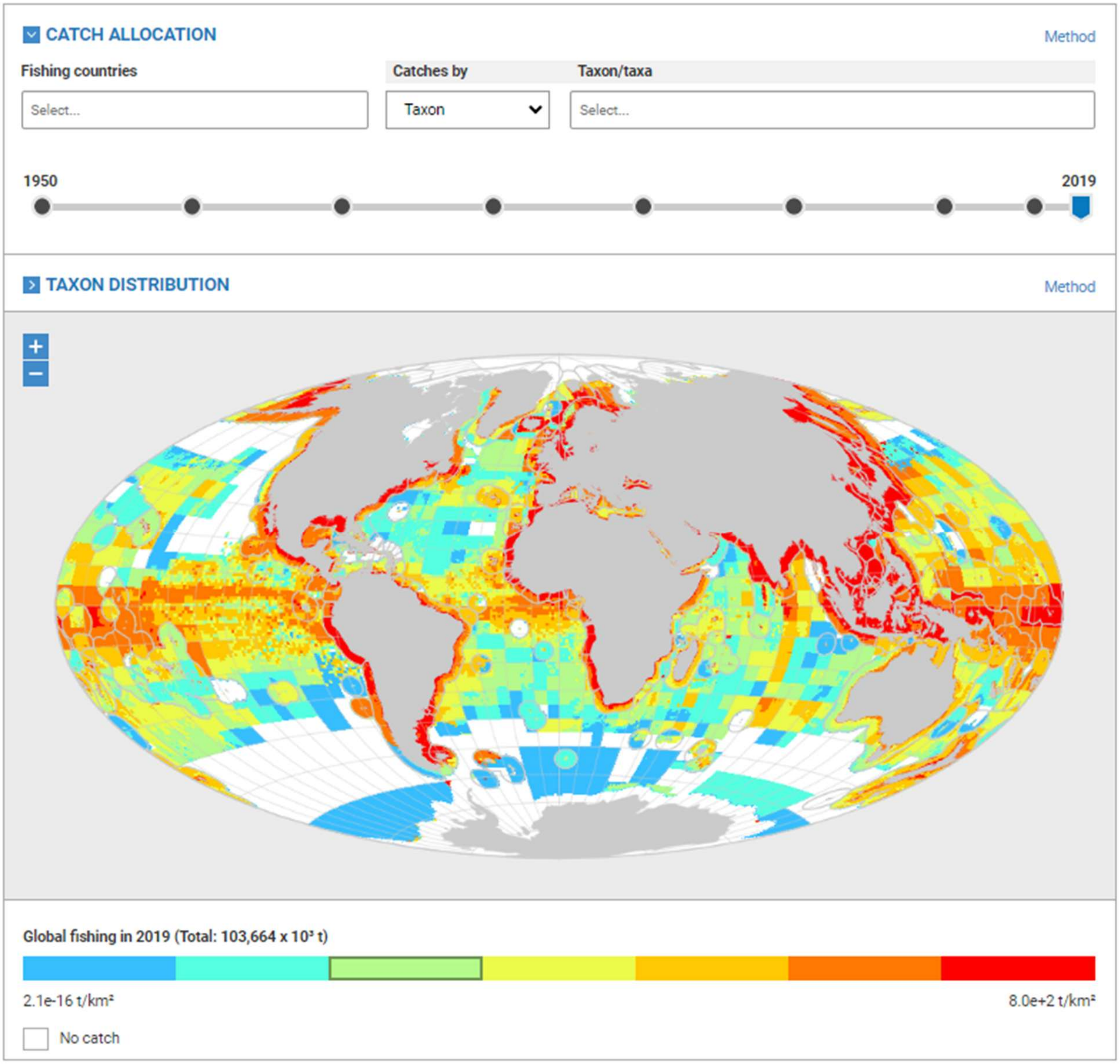

Figure 5. Default view of the "Spatial Catch" interactive map from Sea Around Us showing reconstruction of catch data from the FAO. https://www.seaaroundus.org/data/#/spatial-catch (Blondel, 2023; captured July 6, 2023.)

The sixty-six interactive maps in our dataset vary in their customizability and manipulability. We identified and defined eleven potential modifications, ranging from minor aesthetic changes to enabling users to add and remove data layers (Table 1). Eighty-three percent (n=55) of interactive maps enable data customization and 92% (n=61) enable aesthetic customization. Most offer multiple customization options: on average they offer

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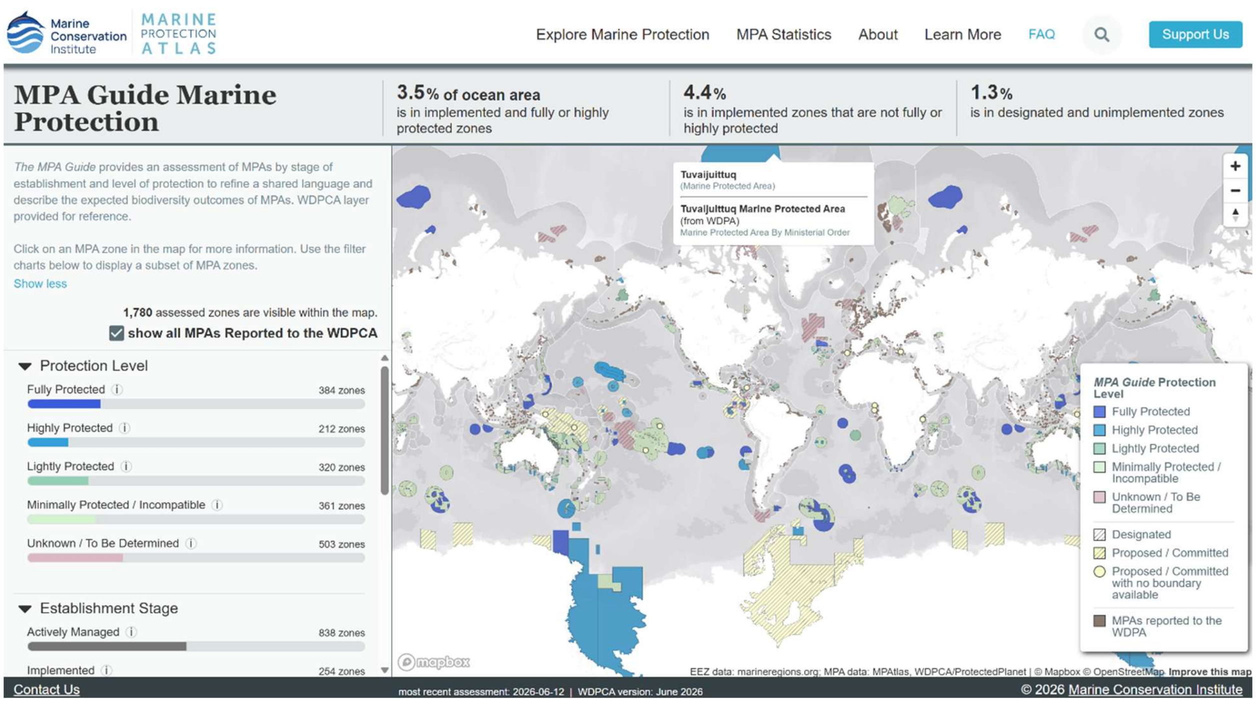
four customization options (of the eleven identified), including 1.5 (of 4) types of data customization and 2.5 (of 7) types of aesthetic customization. No interactive map offers all eleven types of customization, but 52% (34) of interactive maps allow users to download raw data, which, theoretically, enables users to produce their own visualizations outside the ODSI interface.

Table 1. Customizability of Interactive Maps.

Customization	**Defined by User Ability to:**	**Number (Percent) of Interactive Maps (n=66)**
Data Customizations (n=54)		
Input Data Layers	Add/remove data layers in their entirety	38 (58%)
Time Scale	Visualize data in varying time windows	34 (51%)
Data Filters	Select or filter certain categories of data (e.g. filter by species)	22 (33%)
Depth	Visualize data collected at different depths	4 (6%)
Aesthetic Customizations (n=61)		
Map Scale	Change the map scale (i.e. zoom in and/or out)	57 (86%)
Map Center	Change where the center of the map is located (e.g. click and drag)	56 (85%)
Basemap	Change the basemap	19 (29%)
Boundaries	Add or remove defined spatial boundaries (e.g. EEZ or MPA)	10 (15%)
Projection	Change the projection	9 (14%)
Symbology (e.g. color, opacity, fill pattern)	Change which symbology is used to symbolize the data	7 (11%)
Geographic Labels	Add or remove geographic labels	7 (11%)

Data availability and customization options influence how map users ‘see’ the oceans. However, ODSI choices can produce different visions, even when underlying data are similar. We illustrate this by comparing how two different ODSIs interested in Marine Protected Areas (MPAs) visually depict data about them: The Marine Protection Atlas (MPAtlas), an NGO focused on biodiversity conservation, and The Sea Around Us, a university-based ODSI focused on the environmental impact of fisheries extraction through catch reconstructions. The maps in Figures 6 and 7 both portray MPAs through interactive maps with customization options. The MPAtlas map interface allows the user to filter data based on the selected attributes of each area; this is the only data customization option in either ODSI map. Both maps allow users to adjust the map scale and center. Neither map offers symbology options (i.e., including color, opacity, outline, fill pattern) frequently available in cartographic or GIS software.



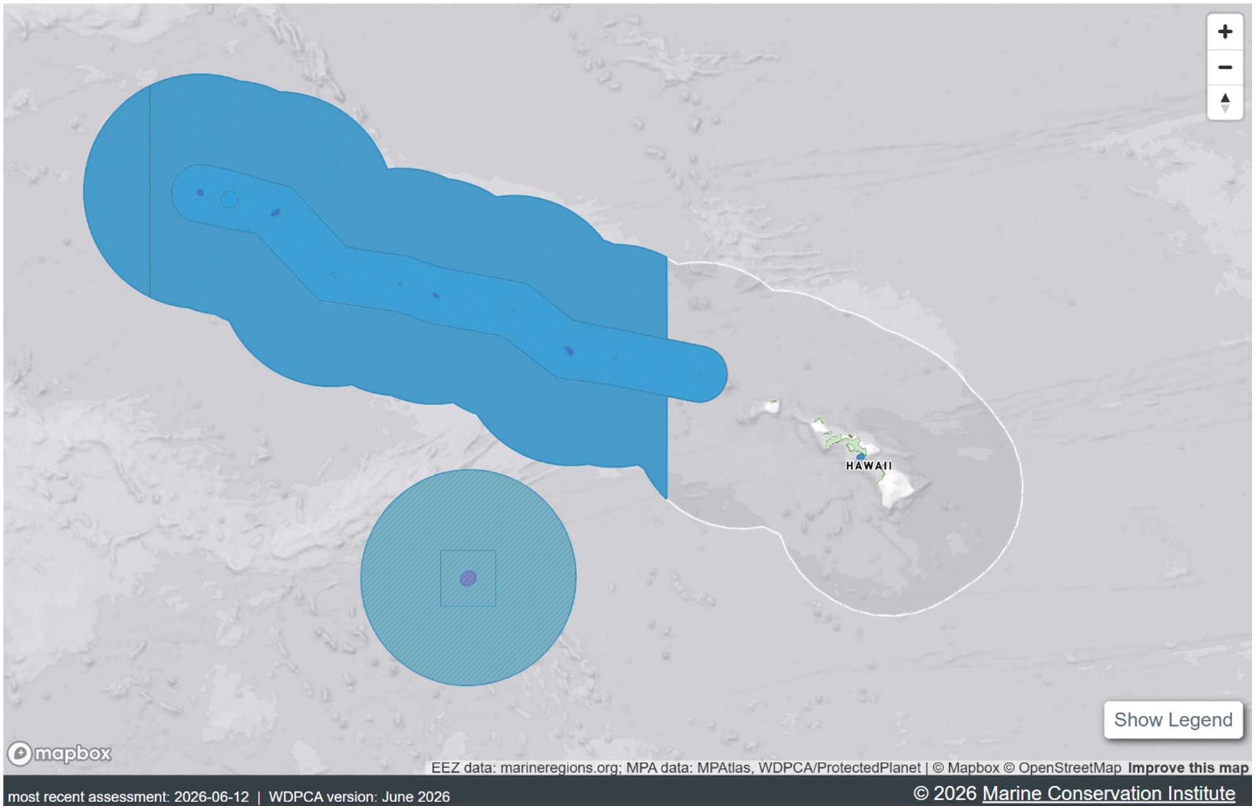


Figure 6. Interactive map of MPAs from MPAtlas. https://mpatlas.org/mpaguide/ (Marine Conservation Institute [and Partners], 2024; captured June 17, 2026.) A. Default image of global-scale map. B. Scaled to fit the Papahānaumokuākea Marine National Monument. [8] This map range depicts the Monument as multiple polygons and uses symbology to show that it is actively managed and highly protected. The white line depicts the Exclusive Economic Zone of the United States.

[8] The above image may not reflect the current designation status.

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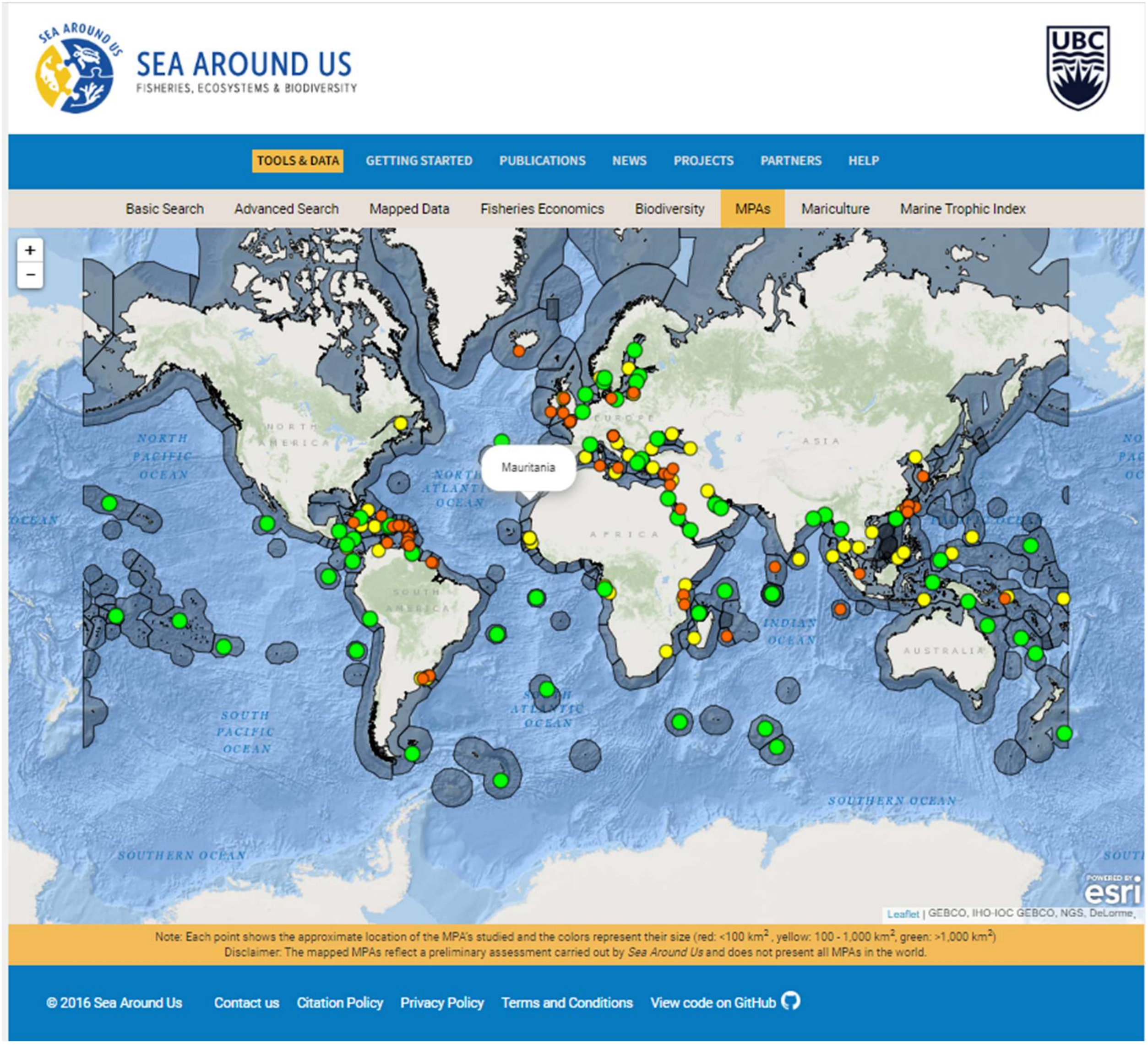

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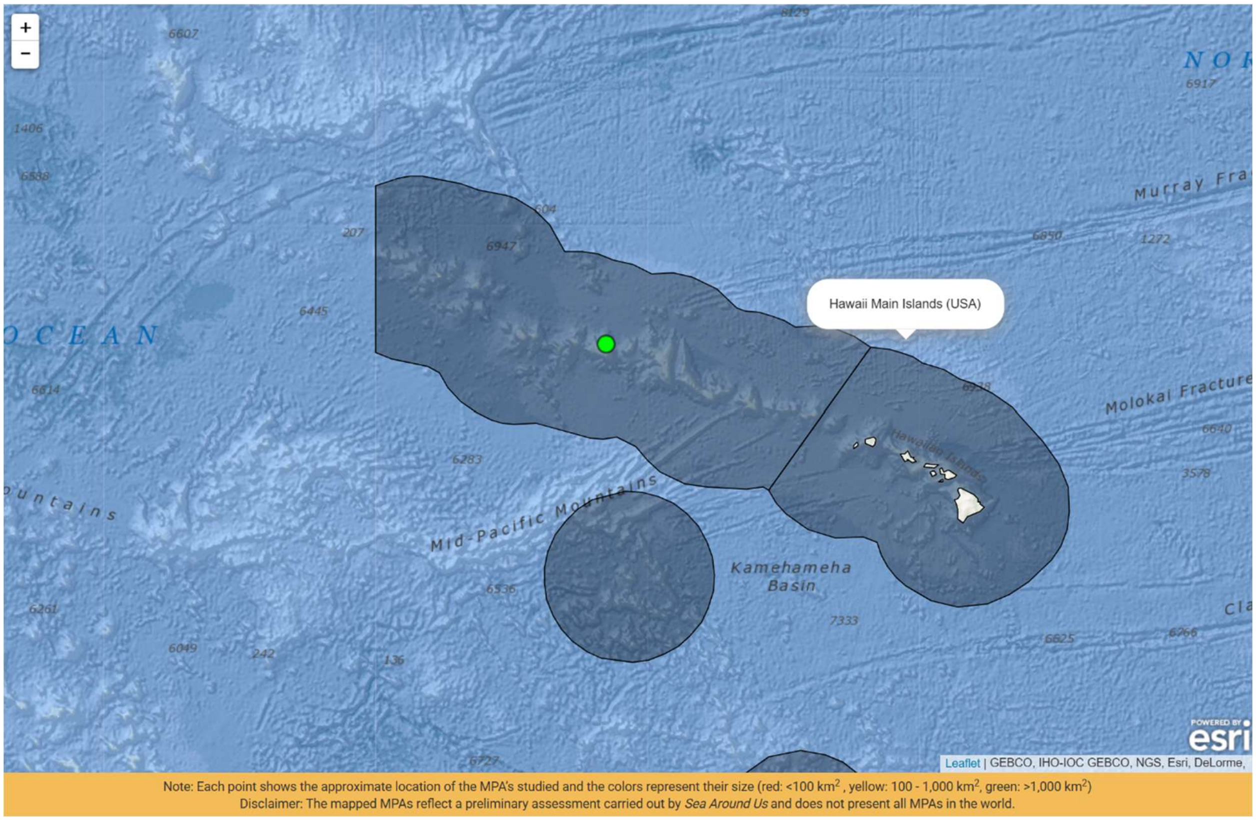

Figure 7. Interactive map of MPA from Sea Around Us. https://mpatlas.org/mpaguide/ (Pauly et al. 2020; captured July 12, 2023.) A. Default image of global-scale map. B. Scaled to fit the Papahānaumokuākea Marine National Monument (captured June 12, 2026). The Monument is defined through point data symbolized with a green outlined point, with green indicating the MPA is greater than 1,000 km^2. The dark grey polygon depicts the Exclusive Economic Zone of the United States.

Further inspection reveals how these maps lead to different understandings of ocean space, although they represent similar phenomena. In Figure 6, the MPAtlas represents each MPA as a polygon that captures its spatial extent and uses color coding to indicate protection level. The default map extent (Figure 6A) makes large MPAs prominent. If a user selects a global scale, smaller MPAs are obscured. In contrast, in Figure 7, The Sea Around Us represents each MPA in its database as a point, color-coded by the MPA’s total area. The default view (Figure 7A) uses the same point size for MPA symbology, regardless of its spatial extent. This cartographic practice can obscure the coverage of

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large MPAs, but make smaller coastal MPAs visible. This map does not depict any other data related to management or level of protection; data on human dimensions are accessible by a separate pop-up accessed by clicking on the map, but they are not visible on the static map image.

These two ODSIs (Sea Around us and MPAtlas) enable users to adjust the scale of their maps and also determine the scope and impact of those adjustments. The MPAtlas polygons depict the fixed spatial boundaries of each MPA (Figure 6B). In contrast, Sea Around Us maps (Figure 7B) MPAs using point data rather than polygon data so that each MPA remains visible on the map regardless of the map scale (although they sometimes overlap). Each point has a color that indicates MPA size, but the maps' visual impression does not emphasize MPA size. Large MPAs such as the Papahānaumokuākea Marine National Monument are visually depicted with the same size symbol as the world's smallest MPAs (*compare* Figure 7B *with* Figure 6B). Point data makes small MPAs visible even when viewing a global map (*see* Figure 7A). Thus, the maps demonstrate that while choices must be made, these choices reinforce how maps can impact what ODSIs make visible and what remains "unseeable" (Rose, 2023, p. 216), offering distinct visual impressions that relate to political debate over MPAs, including, for instance, the spatial extent of MPAs, geographic gaps in protection, and the level of protection (see Gjerde et al., 2016; Sala et al., 2021).

In short, ODSIs make choices about what data—and subsequently, which ocean activity—they make visible in mapping and how. Even in interactive maps, users' choices for mapping an ocean world are finite. While not all of the images and tools in our data set are maps produced using traditional cartographic techniques, they are enrolled in the process of *mapping* oceans, producing visual imagery by which users 'see' and imagine the geography of the oceans (Campbell et al., 2016; Lehman, 2016). Our thematic reading of these maps reveals the worlds that we, as map users, 'see' as a result of both ODSIs' choices and our research interests.

4.2. Worldmaking Possibilities in the Ocean Data Revolution

Maps are constantly "becoming" through user engagement (Kitchin & Dodge, 2007), and as map readers, we are embedded in the worldmaking process. As described in section 3.1, our map reading reflects our interests in how ocean science intersects with oceans governance and our understanding of the role of mapping in ocean worldmaking (Table 2). Our reading across the dataset of 132 maps revealed four visual themes and related implications for oceans governance. The first three themes described in Table 2 emerged deductively from our interests in concepts previously established in the literature and revealed in our analysis; the fourth emerged inductively from our analysis.

Table 2. Thematic Analysis.

Theme	**Research Interests Reflected**	**Key Elements**
Oceans as Blank Space (n=24, 18%)	Historic production of oceans as outside capitalist society, frictionless space for easy movement (Fawcett et al., 2022; Steinberg, 2001, 2009); ontological dichotomy between high seas and near shore spaces (Anderson & Peters, 2016; Steinberg, 2001); perceived knowledge gaps for oceans (Campbell et al., 2016).	Oceans shown as uniform undifferentiated space, in whole or in part; representation of data is disconnected from geospatial, ecological, and oceanographic details

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Theme	Research Interests Reflected	Key Elements
Oceans as State Territory (n=17, 13%)	State projection of power onto ocean space for territorial control (Lehman, 2022; Reidy & Rozwadowski, 2014; Steinberg, 2001, 2009)	State boundaries visually emphasized and bound data collection and analysis; state is unit of analysis
Oceans Under Threat (n=19, 14%)	Role of data and mapping in making visible the nature and extent of anthropogenic threats to oceans (Gray, 2018)	Color used to emphasize anthropogenic threats and communicate extent and intensity of specific problems
Oceans as Spaces of Data (n=22, 17%)	Proliferation of ocean data, linear relationship between data and governance (inductive)	Emphasizes existence of ocean data rather than data themselves.

The four themes illustrate the breadth of worldmaking possibilities in ODSI maps; none emerged as dominant. Some maps reflect more than one theme; for example, a map may represent the high seas in undifferentiated blue (oceans as blank) and depict near-shore data by EEZ (oceans as state territory). Some maps do not reflect any of the themes. We explore each theme in detail below.

4.2.1. Oceans as Blank Space

Twenty-four maps (18%) depict oceans, in whole (14, 11%) or in part (10, 8%), as a uniform, undifferentiated space, with no political, physical, geospatial, ecological, or oceanographic details visible. This theme reflects our interest in early Western practices of mapping blank ocean spaces that were amenable to mercantile capitalist activity, which required seamless flow over ocean space (Steinberg, 2009). "Silences" in maps may be due to technological limitations or political choices, but in any case, they are "as much a proper field for enquiry as that which is present" (Harley, 2001, p. 86). Whether intentional or not, omissions imply that information omitted is irrelevant (Harley, 2001), serving to legitimate the simplified representations in the maps (Scott, 1998). Thus, the blank spaces in ODSIs' maps are positive statements, not passive gaps (Andrews, 2001; Harley, 2001). Yet unlike historical maps where the blank space was tied to the needs of mercantilist capitalism, the blank space in ODSIs' maps serves as a blank slate on which the ODSIs (or their users) can project messages in different ways.

For example, the default map in for OBIS, a university-based ODSI, is an empty basemap of a grey global ocean underlying white continents (Figure 1), which serves as a blank slate on which users can visualize data. All data visualizations are determined by users, who can select from a vast selection of data layers to populate the basemap. The basemap serves as a blank slate for users to produce new images, which may be as complex as the user desires. Other maps in this category differ from this example and include those that project limited data representations on a similarly blank slate. For example, Figure 8 is a static map of fishing catch from the RAM Stock Legacy database, a university-based ODSI focused on fisheries extraction through fish stock data. The map projects statistical plots (pie charts and line graphs) of fishing catch over time atop a basemap of grey land and white oceans. The blank ocean serves as a backdrop to the graphs. These graphical inserts are geographically relevant—they are roughly organized by region—but the background map lacks related detail, such as the bounds of each region. This map is silent as to the jurisdictions around which fishing stock assessments and catches are organized and spatial information regarding where fish are present or caught in ocean space. Whether the visualization is meaningful as a map is debatable; it is perhaps better categorized as an infographic.

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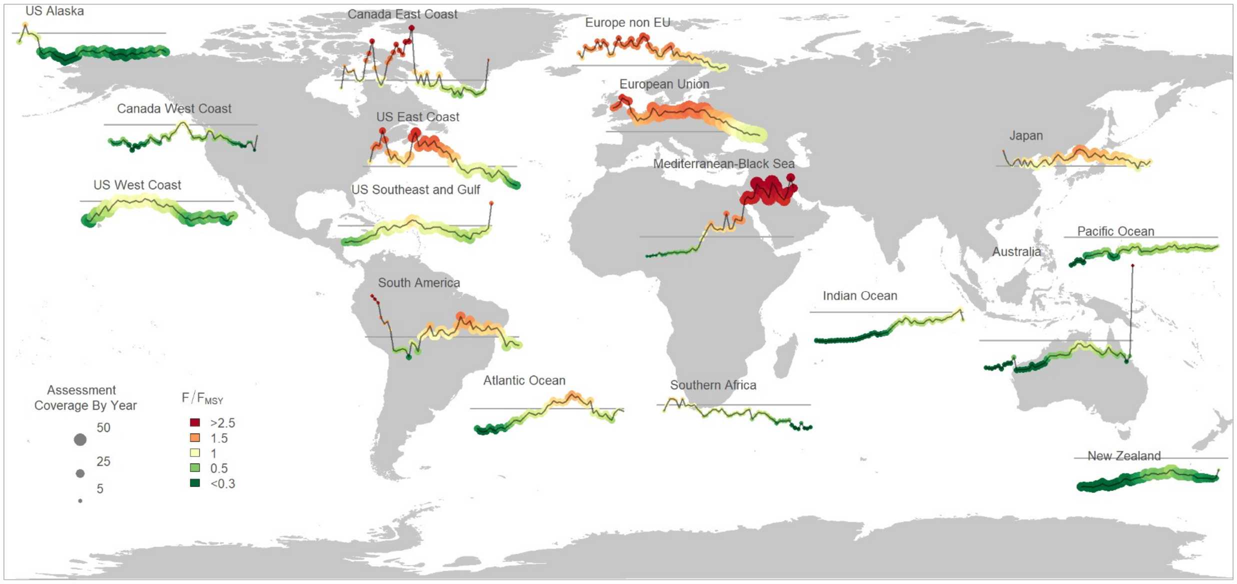

Figure 8. RAM Legacy Stock Assessment Database static map of regional observed fishing mortality to target fishing mortality over time. https://www.ramlegacy.org/ (Captured September 8, 2023.)

In many cases, maps that project selected data onto an otherwise blank ocean both highlight data and simultaneously decontextualize them. For example, the Animal Telemetry Network map (Figure 2) shows an inky-black ocean populated with color-coded hexagons that differentiate the frequency with which tagged animals were located within them. The spaces are not defined based on underlying geographic features—they are hexagons—and there is no information on oceanographic or biological features that might suggest why some hexagons are more frequented than others. Furthermore, the default view shows hexagons that combine observations across different species and for different time periods, information revealed in a pop-up when users hover over a particular polygon. Users can also customize the map for time periods and for species/project specific data sets. These customizations highlight the available data in contrast to the inky-black background, separating the specified data from the ecological context.

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Finally, some maps in this theme further an ontological dichotomy in which areas beyond national jurisdiction remain unknown, while coastal areas are amenable and knowable for data collection and organization (Anderson & Peters, 2016; Steinberg, 2001). For instance, the Ocean Health Index is an NGO focused on basic science that collects and analyzes data to assign an Ocean Health Index Score to each country. The interactive map depicts an 'ocean health' score organized by state-space: EEZ (Figure 9). Users can adjust the map center and filter by score components, but can only view scores within an EEZ. There is no option to view scores in areas beyond national jurisdiction, spaces that remain grey in the map, signifying that they do not have any score.[9] We read this map as reproducing areas beyond national jurisdiction as spaces outside society and/or about which we lack knowledge; the lack of data in these spaces suggests its lack of relevance to the ODSI's analysis of ocean health (see Harley, 2001).

[9] While the Ocean Health Index website includes some discussion of global assessments, including the high seas, these data are not depicted visually in the map, which is the subject of our visual analysis.

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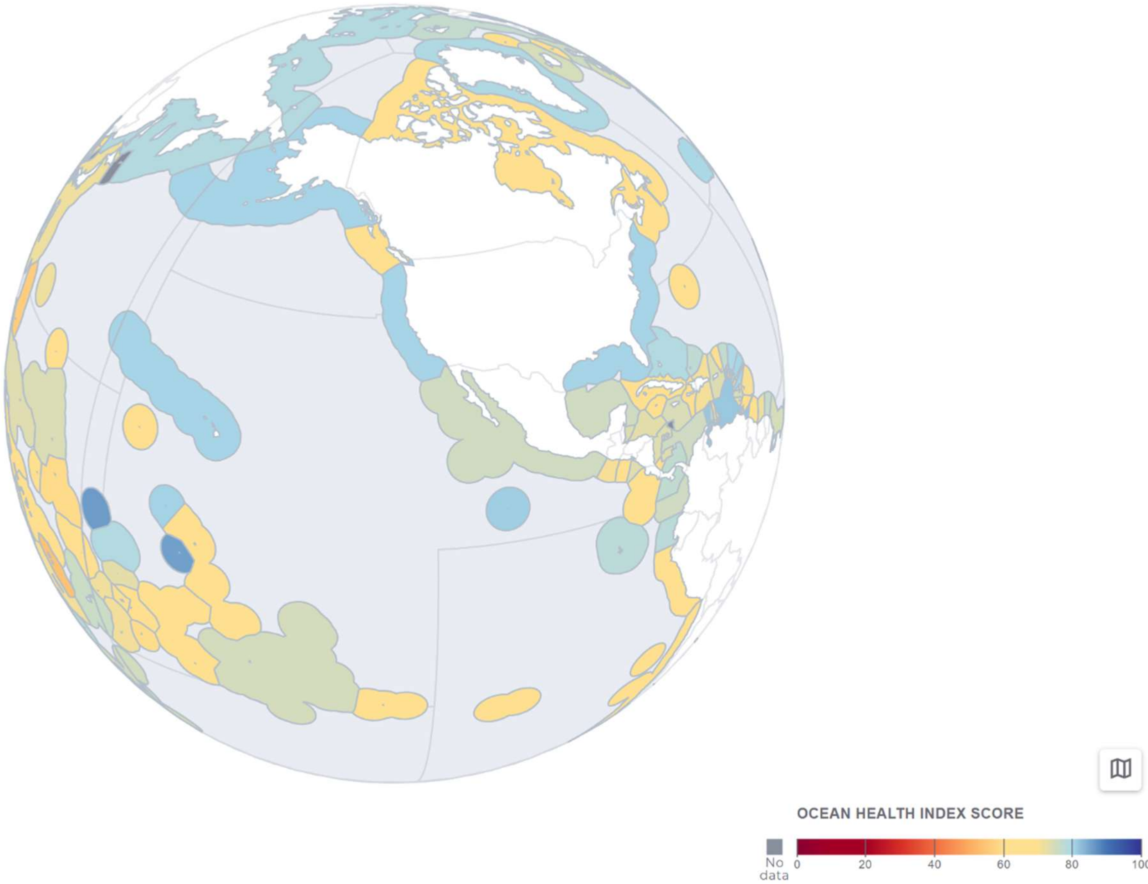

Figure 9. Screen capture of the Ocean Health Index interactive map, depicting the Ocean Health Index Score for each country, organized by EEZ. While the default view of this map is over Africa, we include this view to illustrate the uniform treatment over a non-contiguous EEZ (the United States). https://oceanhealthindex.org/global-scores/ (Captured June 12, 2026.)

The silences in these maps, whether temporary to facilitate customization by the user or permanent to meet the ODSIs' communicative needs, serve to produce the ocean as a backdrop, or blank slate, on which ODSIs or their users can project the selected data they consider relevant. By providing basemaps that remove complexity, the ODSIs simplify the underlying ocean space to serve as a blank slate on which specific data can be written. In some cases, such as OBIS, the users can use that blank slate to create their own representations, which can be as complex as they desire. On the other hand, where the

ODSIs offer decontextualized or limited representations atop the blank slate, the ODSIs create an impression that the omitted data, or spaces, are irrelevant to their ends or unknown. In some cases, such as Ocean Health Index (Figure 9), that blank space of areas beyond national jurisdiction stands in contrast to state space, emphasizing the role of the state in oceans governance.

4.2.2. Oceans as State Territory

Seventeen maps (13%) emphasize oceans as state territory, through symbology, color, or labeling. This theme reflects the historical role of geospatial technologies (including maps) in establishing and reinforcing state boundaries, including through interstate coordination over oceans in venues such as UNCLOS (Lehman, 2022; Reidy & Rozwadowski, 2014). We read the maps in this theme as emphasizing the ongoing central role that the state plays in knowing and governing oceans, reinforcing the state as the relevant unit of analysis.

For example, the Ocean Health Index map discussed above exemplifies this theme (Figure 9). The Oceans Health Index displays a uniform ‘ocean health’ score throughout each state’s EEZ; the eastern coast of the United States is geographically and ecologically distinct and subject to different anthropogenic impacts than the coast of Hawaii, yet the index score is uniform because both areas are part of the US EEZ. This focus on the nation-state as the unit of analysis obscures differences within the state.

Several maps reaffirm state obligations for management *within* national jurisdiction. The Sea Around Us interactive map (Figure 7) shows individual MPA data points and allows the user to examine MPAs by nation-state. The user can click on the EEZ,

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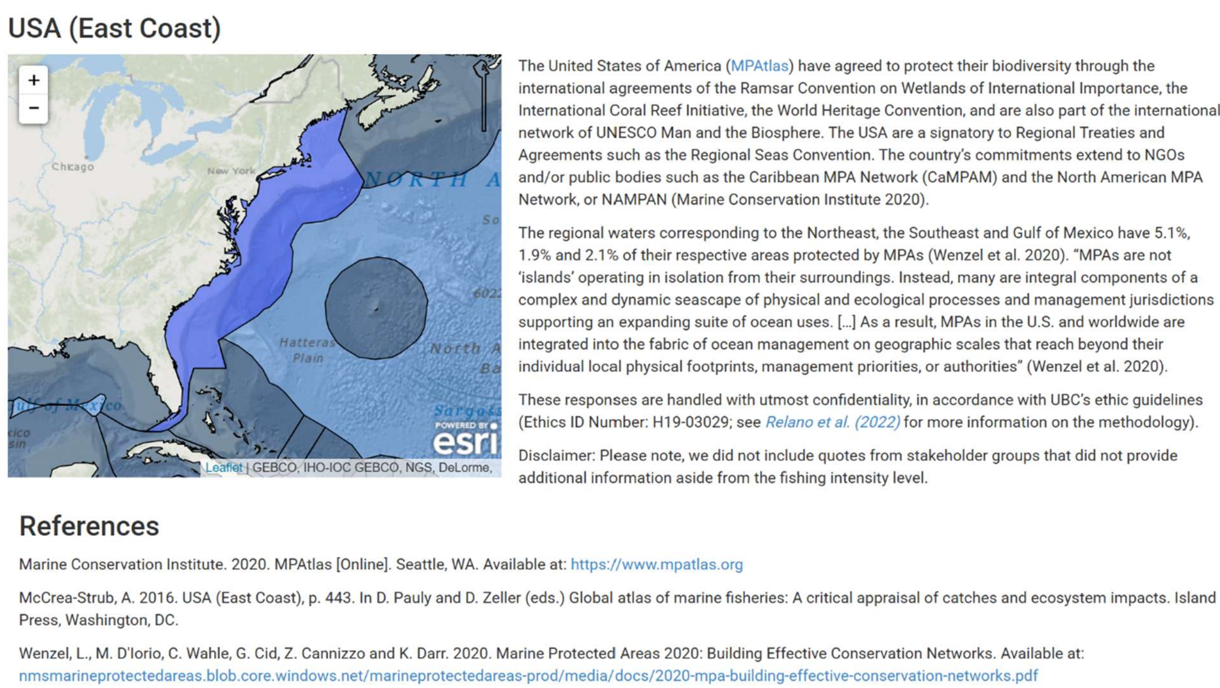
and a pop-up provides information about the MPAs within that EEZ. The quantity and nature of the state-level data vary (Figure 10). Some state data are limited to information about MPA coverage, while others are more detailed, including the results of stakeholder interviews about MPA protection and efficacy. This map reinforces that states are the relevant unit of analysis for understanding MPA efficacy and MPA policies, and highlights variation among states.



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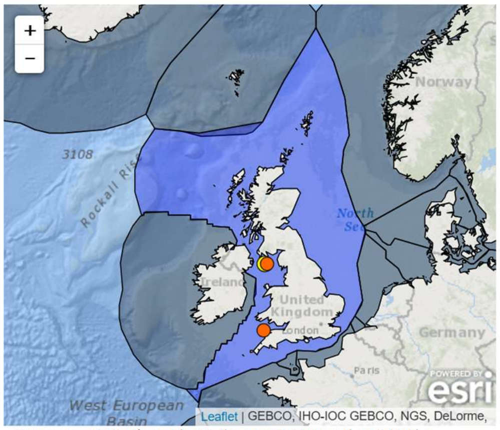

United Kingdom

The United Kingdom has agreed to protect its biological diversity through the international agreements of the Convention on Biological Diversity (Aichi) and the Ramsar Convention on Wetlands of International Importance. The country is also a signatory to the Natura 2000. Its commitments extend to NGOs and/or public bodies such as the OSPAR Convention (Marine Conservation Institute 2020).

The United Kingdom has 1,425 implemented, 198 unimplemented, and 44 proposed Marine Protected Areas (MPAs; MPAtlas; Marine Conservation Institute 2020). However, bottom trawling is allowed in many of these areas. There are not many sites with no-take areas such as Lundy, Flamborough Head and Lamlash Bay, which together constitute less than 20 km2 of highly protected areas (Johnson et al. 2019).

Lundy was established in 2003 with a marine area of 30 km2 (Marine Conservation Institute 2020), its no-take zone (MPAtlas; WDPA) covers 3.3 km2 (Lundy Management Forum and Macdonald 2017). Within Isle of Man, in between UK and Northern Ireland, there is the Ramsey Marine Nature Reserve and the West Coast Marine Nature Reserve. The Ramsey Marine Nature Reserve (MPAtlas; WDPA) is located in northeast Isle of Man and was established in 2011. Ramsey Marine Nature Reserve has a total marine area of 94.5 km2 (Biosphere Isle of Man 2020), which is similar to the area mentioned on MPAtlas. The West Coast Marine Nature Reserve (MPAtlas; WDPA) was established in 2016 and is in northwest Isle of Man. West Coast Marine Nature Reserve covers 184.82 km2 (Isle of Man Government 2021), similar to the area mentioned on MPAtlas.

Currently, the percentage of MPA coverage in the UK's Exclusive Economic Zone (EEZ) appears as follows: Western Channel and Celtic Sea 17.7%, Eastern Channel 21.3%, Southern North Sea 74.1%, Northern North Sea 11.9%, Scottish Continental Shelf 15.2%, Irish Sea 43.9%, Minches and Western Scotland 50.3% and Atlantic North-West Approaches 19.6%. The UK Government created the 'Blue Belt' (in 2015) in order to offer marine protection across its 14 Overseas Territories. "By 2020, this initiative will have designated over 4 × 106 km2 of ocean" (Johnson et al. 2019). Under these circumstances, many experts question the real protection that these remote MPAs offer.

"Thus, whilst the UK has made exceptional progress with quantitative MPA coverage (and promises ambitious further progress still), it is imperative to substantiate that these areas offer effective protection. The UK has applied OSPAR Commission questions to evaluate progress towards being well managed; namely, whether management is documented, measures are implemented, monitoring is in place and how well the network is moving towards conservation objectives (OSPAR Commission 2017, p. 34). In 2016, whilst shortcomings were acknowledged, partial progress in all four areas was significant and endorsed by a repeat evaluation in 2018. Detailed monitoring strategies have been produced by the JNCC and Marine Scotland (in partnership with the JNCC and Scottish Natural Heritage) to help address this as part of a cost-efficient and integrative approach. Furthermore, the UK has recognized the value of an effective stakeholder process as part of establishing MPA networks, and has made significant efforts to be open and transparent (e.g. House of Commons Environmental Audit Committee 2017; which was critical of the UK Government's communications strategy for both UK and UK Overseas Territories MPAs)" (Johnson et al. 2019).

To assess the effectiveness and level of protection of Lundy [no-take zone], Ramsey Marine Nature Reserve, and West Coast Marine Nature Reserve, the *Sea Around Us* team sent a questionnaire to various stakeholders in UK, and Isle of Man to compare their perceptions of the fishing level in the protected areas. The table below contains the most frequent fishing level provided by the different stakeholders. Below the table, there are quotes that reflect the most common response among the interviewees.

These responses are handled with utmost confidentiality, in accordance with UBC's ethic guidelines (Ethics ID Number: H19-03029; see *Relano et al. (2022)* for more information on the methodology).

Most frequent fishing level provided					
MPA Name	**Academic**	**Fishers**	**Government**	**Journalist**	**NGO**
Lundy [no-take zone]	3			3	1
Ramsey Marine Nature Reserve (Isle of Man)			2		
West Coast Marine Nature Reserve (Isle of Man)	2		2		
1 = no fishing, 2 = light fishing, 3 = moderate fishing, 4 = very intense fishing					

Figure 10. Details available from clicking on the Sea Around Us MPA interactive map depicted in Figure 7. A. Detail of the United States East Coast. https://www.seaaroundus.org/data/#/mpa/851 (Pauly et al., 2020; captured June 12, 2026.) While the map provides details regarding MPA extent, it provides little information regarding level of protection or efficacy. B. Detail regarding the United Kingdom. https://www.seaaroundus.org/data/#/mpa/826 (Pauly et al., 2020; captured June 12, 2026.) For this EEZ, the map provides information on the efficacy of protection, including the results of stakeholder interviews. It goes on to provide specific quotes from stakeholder interviews (not shown).

By focusing on oceans as state space defined and reinforced via EEZ boundaries, the maps in this grouping de-emphasize interstate governance, such as regional forms of management that are common in the oceans, especially in fisheries, but also in the seabed and the high seas (see, e.g., Havice, 2018). However, our findings also revealed that many ODSIs depict data to illustrate biodiversity crises in ways that transcend state boundaries.

4.2.3. Oceans Under Threat

Nineteen maps (14 %) represent oceans under threat by visualizing anthropogenic impacts with bright colors, such as red, orange, and yellow. As with any aesthetic choice, the choice of color influences the perceptions of the map reader (Harley, 2001; Monmonier, 1996). Colors have emotive impact and maps of environmental hazards often use a scheme that associates red with danger, yellow with a need for caution, and green with lower risk (Monmonier, 1996). While humans generally perceive water as blue, critical cartographers have noted that this, too, is a stylistic choice that maps produce as much as they reflect (Harley, 2001). We read the red in maps that visualize human impacts on oceans to suggest that oceans are in danger and under threat due to specified activities.

For example, three maps depicting fishing effort illustrate ocean threats in diverse ways. First, an interactive map from the Sea Around Us shows fish catch per square kilometer, portraying areas of high catch as bright red and low catch as blue (Figure 5). Most of the image, particularly in coastal areas, is ablaze with bright colors, while blue regions are sparse and offshore. The user can change the time scale of the map from 1950 to present, with intensifying geographic extent of red over time. The user can filter by fishing country or taxa; the color ramp automatically adjusts. Similarly, Figure 11 is an interactive map from Fish and Resources Monitoring System (FIRMS) Global Tuna Atlas, an inter-governmental ODSI. In this map, the ODSI depicts tuna catch globally, with areas of

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highest catch in the darkest red; this color extends across vast areas of ocean corresponding to tuna's range. This map is customizable and the user can adjust the time frame, projection, basemap, labels, and the color scheme. These options enable users to experiment with alternative ocean imaginaries, but the default image in red conveys threat.

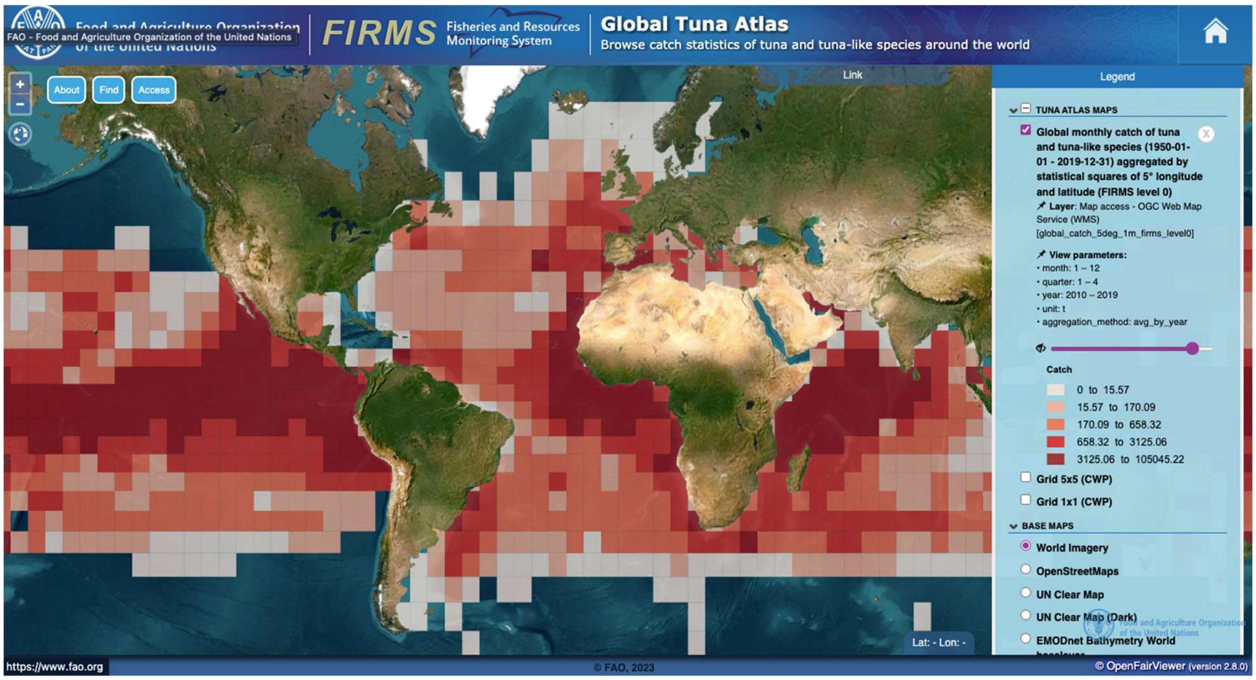

Figure 11. Default view of the Fish and Resources Monitoring System Global Tuna Atlas interactive map depicting global monthly catch of tuna. https://firms.fao.org/firms/en (Blondel, 2023; captured December 13, 2023.) Source: Food and Agriculture Organization of the United Nations. Reproduced with permission.

Some maps distinguish fisheries threats in different parts of the ocean. The graphical insert approach in the RAM Legacy Stock Assessment's map (Figure 8) also uses color to convey different messages about changing fish mortality—and perhaps fisheries management—in different ocean areas over time: the inserted graphs use red to show when fishing mortality exceeds maximum sustainable yield (MSY) levels, and green when fishing is at or below MSY. In contrast to the maps from FIRMS and the Sea Around US, this map shows the fisheries threat decreasing over time in most areas of the ocean, except in

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the Mediterranean and Black Sea, where the graph continues to appear bright red in recent years, suggesting an ongoing, and escalating threat.

Consistent with contemporary global concern about the impacts of industrial overfishing (Palomar et al., 2020; Roberts et al., 2024), in each of these maps, color alerts viewers to fisheries threats in at least a part of the oceans. The spatial extent of the threat differs depending on what data the ODSI chooses to visualize and how. The resulting maps offer different impressions of where threats are located and thus where management action might need to be directed, although none of the maps included data on fisheries management. The RAM legacy database suggests that fisheries are primarily unsustainable (in relation to MSY) in the Mediterranean and Black Sea but not elsewhere, Sea Around Us suggests that the threat is global but particularly intense in coastal areas, while the FIRMS Global Tuna Atlas suggests fishing is a threat throughout the tuna's range, including in the high seas. In all cases, an ODSI's choices in mapping data make these threats visible.

Some ODSIs depict anthropogenic impacts other than fishing—such as warming oceans—through red, a color also associated with heat. For example, in Figure 12, Argo, an international state-sponsored ODSI focused on basic science, depicts sea surface temperature data gathered from its floats throughout the ocean. In this static image, much of the ocean appears bright red. We read this map as illuminating climate impacts that threaten oceans as temperatures rise. As with all map readings, this understanding is informed by historical context (Crampton, 2002), including public concern about warming oceans (e.g., Cheng et al., 2019). Using red to designate heat is intuitive, but Fish (2018) shows how concerns about climate change have shifted how map makers visualize planetary temperatures; temperatures that in the past were represented with cooler colors are now shown in red. Moreover, by furthering a perception that these aesthetic conventions are “normal”, shifting color conventions in mapping acquire a particular authority (Harley, 2001). The increased use of red thus reflects both warming oceans and widespread societal attention and concern about the thread of ocean warming.

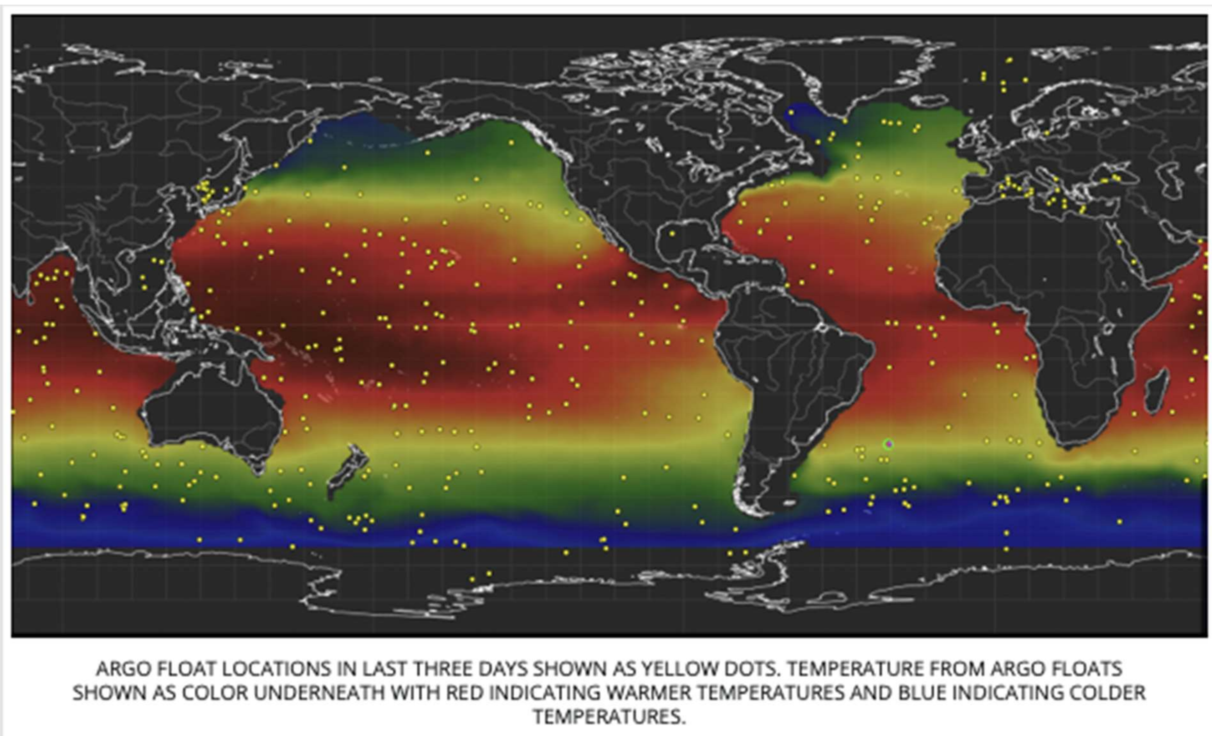

Figure 12. Static map from Argo showing temperature data collected from Argo floats.[10] https://argo.ucsd.edu/about/status/

In these maps, ODSIs mobilize data to map otherwise invisible threats. Visualizing threats may show ways in which oceans are amenable to spatial management (Gray,

[10] These data were collected and made freely available by the International Argo Program and the national programs that contribute to it. (https://argo.ucsd.edu, https://www.ocean-ops.org). The Argo Program is part of the Global Ocean Observing System. (Argo, 2000.)

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2018), and capture the attention of the public and policymakers, alerting them to problems that may otherwise be overlooked. For example, Stafford & Jones (2019) have argued that plastic pollution has received disproportionate attention compared to threats like climate change and biodiversity loss from overfishing, in part because the problem and potential solutions are highly visible. Mapping threats that are otherwise 'unseeable' thus has the potential to motivate actors to address them. The maps in this theme suggest that data and the ODSIs that visualize them play a role in this process. Yet not all maps use data to portray *what* we know about the oceans; some illustrate *the extent* to which the oceans are known.

4.2.4. Oceans as Spaces of Data

Given our understanding of historical mapping processes and the increasing interest in "knowing" the oceans, we anticipated that ODSIs' maps would convey biological, physical, or human properties about the ocean. We also anticipated that these data would intersect with representations of political and management spaces in the oceans. However, we did not anticipate that many maps (n=22, 17%) would visualize the existence of data, rather than the data themselves. These maps represent oceans as spaces of data, showing the location of datasets, monitoring stations, or research activities. We read these maps as positioning ODSIs as relevant collectors, holders, and/or distributors of scientific information that can help fill perceived gaps in ocean knowledge.

For example, Figure 13 depicts an interactive map from PANGAEA, a university-based ODSI focused on biodiversity conservation that hosts a repository of georeferenced datasets about oceans. The map depicts each dataset as an icon symbolizing peer review status and whether the dataset is from a single point or an expanded geographic region. Users can click on an icon for dataset details. Collectively, the mapping tool reveals datasets that span physical and biological scientific disciplines. The tool lacks a mechanism to sort, filter, or search the datasets depicted in the map. It functions to visualize the plethora of ocean datasets available, but it does not visualize their content.

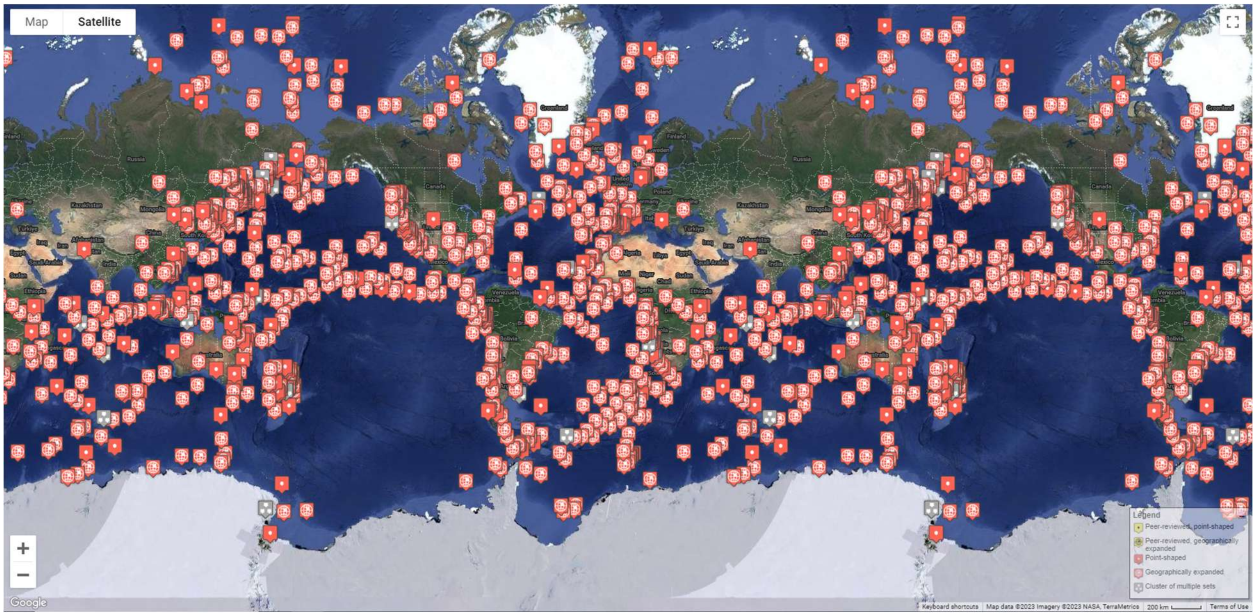

Figure 13. Default View of the PANGAEA interactive map depicting geolocation of datasets by peer review status. https://www.pangaea.de/advanced/gmap.php?t=Oceans (Map Data: Felden et al., 2023; accessed September 8, 2023. Basemap ©Google 2023.)

In other maps in this theme, ODSIs illustrate the ability to monitor oceans and collect data. For example, Figure 14 is an interactive map from a state-based ODSI focused on basic science, the US National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center (NDBC). The map locates offshore stations and provides details: if the station is collecting data, including wave height, winds, and temperature (both air and water); station status (reporting or non-reporting); and whether the NDBC has recent data, historical data only, or no data in the last eight hours. The data themselves are not visible on the map.

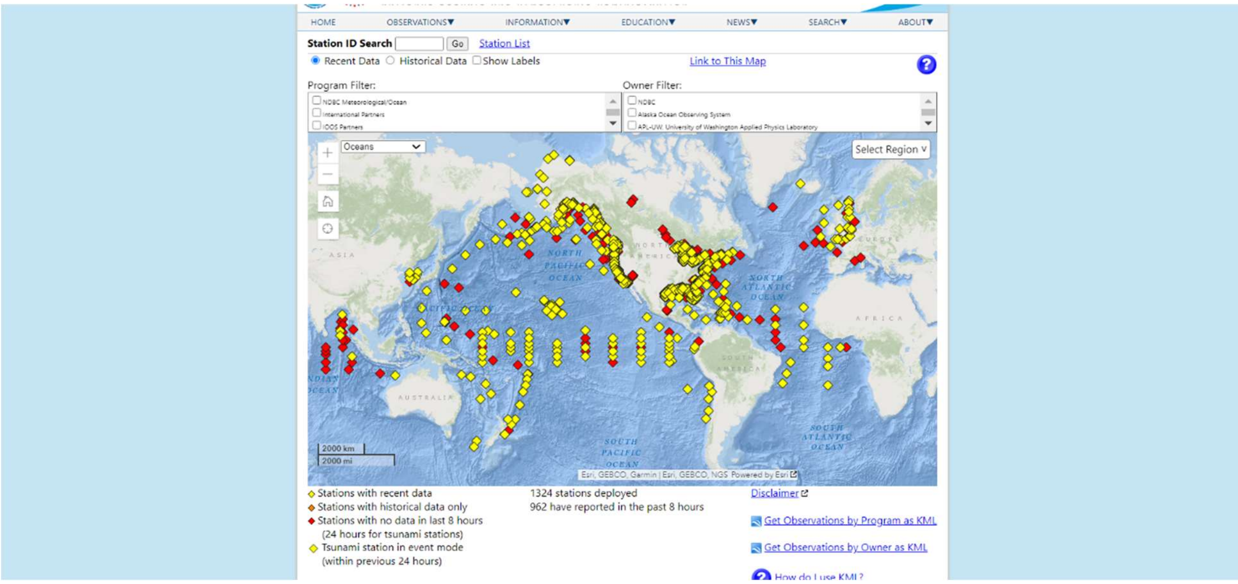

Figure 14. Default View of an interactive map from the National Oceanic and Atmospheric Administration's National Data Buoy Center depicting monitoring location and status. https://www.ndbc.noaa.gov/ (Captured March 29, 2024)

The maps in this theme visualize not *what* we know about the oceans but *that* we know the oceans. The emphasis on increasingly 'knowable' oceans may reflect ODSIs' progress toward their data collection goals. It also reinforces a commitment to gathering more data as an end in and of itself. We read into these maps the techno-optimist belief that more data will lead to better (if unspecified) outcomes in the oceans and oceans governance/management, and that the ODSIs have a role to play in collecting, organizing, and/or disseminating them.

Furthermore, these maps demonstrate that ODSIs have the capacity to gather and mobilize data on a global scale and organize those data both through and beyond geopolitical jurisdictions and institutions. For instance, NOAA is a United States federal agency, but Figure 14 illustrates that it is compiling ocean data sourced in areas beyond national jurisdiction and the EEZs of other states. Thus, unlike the maps that produce oceans as state territory, maps like this one show that ODSIs gather and organize data globally and regionally, illustrating their relevance to geopolitical questions and interests that are not confined by jurisdictional boundaries (Lehman, 2019).

5. Conclusions: The Role of ODSIs in Mapping the "The Oceans We Want"

Maps have long reflected and shaped human interests in, and concerns about, ocean space and resources. Today, as ODSIs employ novel data technologies to map oceans in ways never before possible, the moment is ripe to explore what new ocean worlds emerge. With this context in mind, we conclude with five insights into ocean mapping and worldmaking in the digital age.

First, we find that ODSI maps depict a wide range of phenomena, related to biological, physical, and human elements of oceans. Data are primarily quantitative, applied across large geographic scales, but some interactive maps are enlivened through pop-ups that reveal further details, e.g. descriptive information on data sources or management arrangements. As in previous studies, we find human elements are mostly mapped as impacts arising from economic activity and, to a lesser extent, as management or political boundaries; other potential relations and values are rarely acknowledged, never mind represented. This may, in part, be due to practical limitations: maps are always partial, reflecting data availability, technical capacity, and the interests and priorities of those who create them. While 'silences' related to human relations and values may reflect existing data availability and amenability, they can also reinforce an understanding that human data are not a priority for knowing oceans. Our focus on the global scale matters here, as many efforts to better visualize human elements have been associated with marine spatial planning at smaller geographical scales, and managed through participatory processes (Beaty et al., 2024; Boucquey et al., 2016, 2019; Jay, 2018). Mapping human interests in global oceans is simultaneously more complex due to scope and potentially dismissed as irrelevant; oceans have long been imagined as 'outside' of society (Steinberg 2001).

Second, our thematic analysis finds that ODSI maps reveal not one ocean world, but many. ODSIs mobilize data through diverse mapping practices that create possibilities for imagining ocean worlds: (1) as blank space on which data can be projected in different ways, (2) as national spaces where the state remains the appropriate unit for data management and oceans governance more broadly, (3) as spaces under threat from human activities, or (4) as 'known' spaces where data can be gathered and organized by ODSIs, including in ways transcend political boundaries. We have elaborated on each of these above, but here we reflect more broadly on the first and fourth themes. For the theme of oceans as blank space, we were surprised by the number of maps in this theme given the ocean data 'tsunami'. But perhaps the theme of oceans as blank *space* might also be read as oceans as a blank *slate,* upon which data can be projected. In interactive maps, the slate can be wiped clean and repopulated over and over again, with distinct worldmaking possibilities. For the theme of oceans as spaces of data, we see this inductive and unexpected finding as critical to our overall argument about ODSIs as actors in oceans governance. Maps in this theme help to position ODSIs as critical to "the science

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we need for the oceans we want" (UNDOSSD, 2002) and reinforce an understanding of the role of more and better data in "improved" oceans governance (Fawcett et al., 2022).

Third, our finding of multiple ocean worlds, co-produced by new data technologies, ODSIs, and others who mobilize them, illustrates a (at least partial) departure from state-sanctioned ocean maps that delineate the boundaries and aims of state power (see Lehman, 2022), and such a departure is key in Rankin's (2016) geoepistomology. ODSIs are comprised of diverse governance actors from the public, private, and nonprofit sectors, and their interactive platforms further expand the scope of mapping actors to individual users. Who those users are, how they engage with these platforms, and what kinds of images they create are beyond the scope of this paper, but we see the emergence of these tools as opening new possibilities for a broader range of actors to participate in how oceans are envisioned in the future. Mapmaking is no longer an activity limited to a select trained few, undertaken at the behest of the state. At a time when the responsibility for global oceans observations is shifting in ways that remain uncertain (Lehman et al., 2026), this diversity of maps and mapmakers suggests possibilities for imagining oceans 'otherwise', outside of dominant framings and governance regimes. We caution, however, that this diversity remains incomplete, and while contemporary mapping tools can create "genuine opportunit[ies] for new alternatives," they can also "amplify existing power asymmetries" (Rankin 2016, p. 297). The data mapped by the ODSIs in our sample are produced via Western science; we found no data generated via other ways of knowing or understanding oceans, including by Indigenous Peoples. Despite the plurality of ocean worlds these maps reveal, the emphasis on Western science alone gives rise to potential

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concerns about whose knowledge systems that plurality reflects, and which are excluded (*see also* Havice et al., forthcoming).

Fourth, although critical cartographers have argued for decades that maps are always 'becoming' and never ontologically secure, our research suggests this takes on new meaning in the digital age. This is most obvious in interactive maps where maps can be easily produced or changed by users. We also see ontological insecurity in the way ODSIs interested in the same ocean phenomenon (e.g. MPAs, fisheries) visualize these phenomena and alter our understandings of them in different ways. Additionally, individual ODSIs make changes in their own maps and tools, as technology and the capacity of ODSIs advance. For example, the Animal Telemetry Network has replaced the inky black ocean shown in Figure 2 (captured July 4, 2023) with a base layer with standard global satellite imagery. Thus, maps also 'become' through "a back-and-forth relationship" between how oceans are imagined and technical innovation (see Adler, 2022, p. 43). Put differently, technological innovation in mapping decreases the ontological security of maps.

Fifth, our findings may lend support to arguments that new mapping technologies and the associated shift in geoepistemology have resulted in maps carrying less authority than they did in the past (Rankin, 2016). However, we are not fully convinced, at least not for oceans, where representation remains central to how most people see and know them. While we agree that there is no single authoritative ocean map, series of maps, or mapmaker, ocean *mapping* remains central to knowing and governing the oceans, *i.e.* to making ocean worlds. This is particularly true in the midst of an ocean data revolution,

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where new data technologies promise to fill long standing knowledge gaps. The ocean data 'tsunami' is arguably feeding an ocean mapping frenzy. It remains to be seen whether the proliferation of ODSIs and their maps merely reflect and reinforce techno-optimism (De Oliveira Paes & Okafor-Yarwood, 2024; Nyman, 2019), or if the maps we review will be taken up in governance and policy proposals, where they may take on new meaning. ODSIs themselves may engage in such processes, beyond their role in making maps. This will not be determined by the maps alone; although the possibilities for data-based governance are expanding, it is often constrained by pre-existing practical and political realities of how oceans governance is done (see Acton et al., 2019). Moreover, we heed Campbell et al.'s (2020. p. 295) caution against naivete: "The ability to act on the results of these visualizations requires political, regulatory, and economic power; not everyone can implement their own ocean vision." Although these extended worldmaking impacts by ODSIs and their maps are beyond the scope of this paper, we note an emerging body of research on Global Fishing Watch (Campbell, et. al., forthcoming; Carmine et al., 2020; L. Drakopulos et al., 2023; Gray, 2018) that suggests at least some ODSIs are positioned to enact ocean worlds. Perhaps the most successful ODSIs will be those in our fourth group that make ocean worlds in which they emphasize their own roles in ocean management or policymaking.

We began this paper citing mounting concern of ecological change and increased interest in oceans as frontiers for management and development (Johnson & Braverman, 2019; Jouffray et al, 2020; Melvin, 2026) as part of the context in which ODSIs have emerged, and why their work is important. Oceans are central to ongoing political

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negotiations (*e.g.* for mining the seabed) and sites of tension between global cooperation and national, territorial based forms of power (Suarez de Vivero & Rodríguez-Mateos, 2024). This tension is evident in our analysis: ODSIs represent ocean space through both transboundary and nationally oriented dynamics. While an analysis comparing whether mapping practices vary across different types of ODSIs with different focal areas and mandates is beyond the scope of this paper, it is a potential research avenue for positioning and differentiating ODSIs within broader political processes. Moreover, future research might trace how ODSIs, state institutions, and international bodies mobilize maps in lobbying and decision-making, to understand the potential implications for sovereignty and global inequalities in gathering and mobilizing data (see Lehman, 2019). Understanding which types of ODSIs are producing which types of understandings, and tracing their political connections to larger geopolitical processes, is an important agenda for future research.

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