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The Ocean Decade: A True Ecosystem Modeling Challenge

Johanna J. Heymans[1], Alida Bundy[2], Villy Christensen[3], Marta Coll[4,5], Kim de Mutsert[6], Elizabeth A. Fulton[7,8], Chiara Piroddi[9], Yunne-Jai Shin[10], Jeroen Steenbeek[5] and Morgane Travers-Trolet[11]*

[1] European Marine Board (EMB), Ostend, Belgium, [2] Ocean Ecosystem Science Division, Bedford Institute of Oceanography (BIO), Dartmouth, NS, Canada, [3] Institute for the Oceans and Fisheries, University of British Columbia, Vancouver, BC, Canada, [4] Institute of Marine Sciences, Spanish National Research Council, Barcelona, Spain, [5] Ecopath International Initiative, Barcelona, Spain, [6] Department of Environmental Science and Policy, George Mason University, Fairfax, VA, United States, [7] Centre for Marine Socioecology, Institute for Marine and Antarctic Studies, College of Sciences and Engineering, University of Tasmania, Hobart, TAS, Australia, [8] Oceans and Atmosphere (CSIRO), Hobart, TAS, Australia, [9] European Commission, Joint Research Centre (JRC), Ispra, Italy, [10] University of Montpellier, IRD, Ifremer, CNRS, MARBEC, Montpellier, France, [11] Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER), Nantes, France

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****Correspondence:***
Johanna J. Heymans
sheilaheymans@yahoo.com

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INTRODUCTION

The UN declared the 2021–2030 as the Decade of Ocean Science for Sustainable Development (Ocean Decade). The Ocean Decade's vision is to "develop scientific knowledge, build infrastructure and foster relationships for a sustainable and healthy ocean." The Ocean Decade aims to achieve six societal outcomes: (1) A clean ocean, through identifying and removing sources of pollution; (2) A healthy and resilient ocean, with mapped and protected marine ecosystems; (3) A predicted ocean, enabling society to understand current and future ocean conditions; (4) A safe ocean, protecting people from ocean hazards; (5) A sustainably harvested ocean, providing food and resources for the blue economy; and (6) A transparent ocean, giving citizens equitable access to data, information and technologies. It also aims to provide concrete scientific support to coastal management, adaptation and restoration, marine spatial planning, marine protected areas, fisheries management, sustainable expansion of the blue economy, nationally determined contributions to the United Nations Framework Convention on Climate Change (UNFCCC), national ocean policies, development of national Research and Development (R&D), capacity development, and early warning systems.

The Ocean Decade offers the ocean science community a unique opportunity to change the way we support sustainable development and galvanize ocean sciences for the future (Ryabinin et al., 2019). In addition, the UN Decade for Ecosystem Restoration (2021–2030), gives the ocean science community an imperative to work toward a sustainable future for the ocean.

We challenge the marine ecosystem modeling community to address how we: (i) enable ocean managers and decision-makers to use our science, (ii) communicate our science, and most importantly (iii) ensure co-design of our science to achieve sustainable development. For this, we define ecosystem models as those that span physical and human drivers of change in the full ecosystem from plankton to top predators.

WHAT IS NEEDED TO ACHIEVE THE GOALS OF THE OCEAN DECADE?

Ryabinin et al. (2019) suggested seven research and development priority areas for the Ocean Decade. For each of these, we indicate how ecosystem models can benefit from the data products generated and propose how these models can address the Ocean Decade priorities.

1. A full map of the ocean (or georeferenced digital atlas) is needed for ecosystem models to address sustainable ocean use and operational marine spatial planning (MSP). Well-parameterized ecosystem models can contribute by providing estimates of biological and ecosystem variables in areas hard to observe or with low spatio-temporal coverage, and provide non-measurable information (e.g., flow of ecosystem services) consistent with existing knowledge and ecological principles. The work by the MSP Challenge gives direction (Steenbeek et al., 2020), but there is a more comprehensive ecosystem modeling ensemble should support this work (see below).

2. A comprehensive Ocean Observing System (OOS) should include observations of biology at the appropriate temporal and spatial scales (Miloslavich et al., 2018; Claudet et al., 2019; Mackenzie et al., 2019). Currently, OOSs provide some of the essential physical, chemical and biological data to parameterize models, which are combined into databases such as the European Union's Earth Observation Programme "Copernicus," where they are re-analyzed to provide free and open information on the physical and biogeochemical state of the ocean. However, not all regions of the world or types of data are equally represented. Physical and chemical parameters are better represented in the northern hemisphere while in the south the frequency of observations generally is insufficient to achieve well-calibrated physico-chemical models (López-Ballesteros et al., 2018). Biological observations and data are much less prevalent (Miloslavich et al., 2018), since very little R&D or funding has gone into observing biology, and with the lack of taxonomists globally, this priority will be difficult to achieve (Pinheiro et al., 2019). Data collection could be enhanced if more ocean transport undertakes physical, chemical and biological observations, as is done by Ships of Opportunity. In addition, for the OOS to be used in operational models, observations of industrial uses, human behavior, social change and economy should be included (Miloslavich et al., 2018; Bax et al., 2019; Jouffray et al., 2020). This will come with substantial (but surmountable) challenges for how to store, organize, integrate and distribute such data (Guidi et al., 2020).

3. A quantitative understanding of the ocean structure and functioning is imperative for management of ecosystems. This priority encapsulates the need for observations of the full ecosystem, and is important for achieving the societal goal of predicting the ocean (Claudet et al., 2019). This priority is where the ecosystem modeling community can contribute the most through an ensemble of possibly coupled ecosystem models, each with its own properties and uncertainties (Heymans et al., 2018; Lotze et al., 2019). Marine ecosystem models span a highly diverse range of approaches, which between them capture much uncertainty about marine ecosystem structure and function. We must make best use of that diversity. This is happening to some extent through European projects (Piroddi et al., 2017; Serpetti et al., 2017; Spence et al., 2018) and in international initiatives such as Fish-MIP (Lotze et al., 2019) that are already informing management. However, these initiatives should be extended to marine ecosystems globally and at local, regional and global scales. Marine ecosystem modeling has started to embrace new technological data and advances such as eDNA, metabarcoding, Big Data, machine learning and Artificial Intelligence (Guidi et al., 2020)—a trend with great potential. To be fully operational, the models must be validated in real time and should continue the expanding inclusion of diverse modeling approaches (Coll et al., 2019).

4. A fully open data and information system will enable the futuristic vision put forward in the epilogue of Navigating the Future V (EMB, 2019), of a virtual ocean or "digital twin," where citizens can follow the ocean in real time. This will require a much more in-depth understanding of the structure and function of marine ecosystems and their connected human systems. For both, we will need better integrated databases, and for the latter, new data streams. Data richness and accessibility could be improved if all databases were linked to those developed for ocean-related activities such as fisheries, energy industries and shipping. The recovery of data into an open system would provide the information needed to drive an ensemble of ecosystem models and may revolutionize the ability of modelers to make priority 3 a reality. In addition, ecosystem models applied across the world can highlight the data gaps that need to be addressed to sustainably use the ocean. Ecosystem models can identify the parameters with the biggest impact on key management questions, and point to the efficient use of funding for future ocean observations, as has been done with physical models and ARGO floats (Wang et al., 2018).

5. A fully integrated Multi-Hazard Warning System will be enhanced by the ability of the ensemble of ecosystem models to predict possible impacts from a specific hazard and from multiple hazards. For instance, current ecosystem models already address possible impacts of climate change on species' habitats and food web interactions (Spence et al., 2018; Lotze et al., 2019) and are considering evolution and acclimation (Fulton et al., 2019). However, there is significant scope for expansion and refinement of a more comprehensive ensemble of ecosystem models to provide more reliable predictions of future impacts. This is currently being undertaken by the Joint Research Centre of the European Commission under the Blue2 Project and Marine Modeling Framework (Stips et al., 2015), which uses a pan-European ensemble of ecosystem models to assess the impact of selected EU policies (Macias et al., 2019). This approach needs to be undertaken comprehensively across the globe. In addition, possible impacts from storms or high temperature events on coastal ecosystems could be addressed through full end-to-end interdisciplinary models, as is already done by assemblages of models informing Louisiana's Coastal Master Plan, the restoration of the Mississippi River Delta (De Mutsert et al., 2017; Baustian et al., 2018), the Baltic Sea (Niiranen et al.,

2013) and the Great Barrier Reef, making this priority achievable in the Ocean Decade.

6. The Ocean and Earth-System Observation, Research and specifically Prediction of the future state of the ocean will require ecosystem models to include a broader set of industries and human behavior, including social change, requiring social and economic data (Ryabinin et al., 2019). This challenging frontier is being tackled to some extent in ecosystem models that are co-designed for fisheries management (Bentley et al., 2019a,b,c), coastal planning (Fulton et al., 2017) and in initiatives linking ecosystem and economic models (Weatherdon et al., 2016). However, these are rare and currently only a small subset

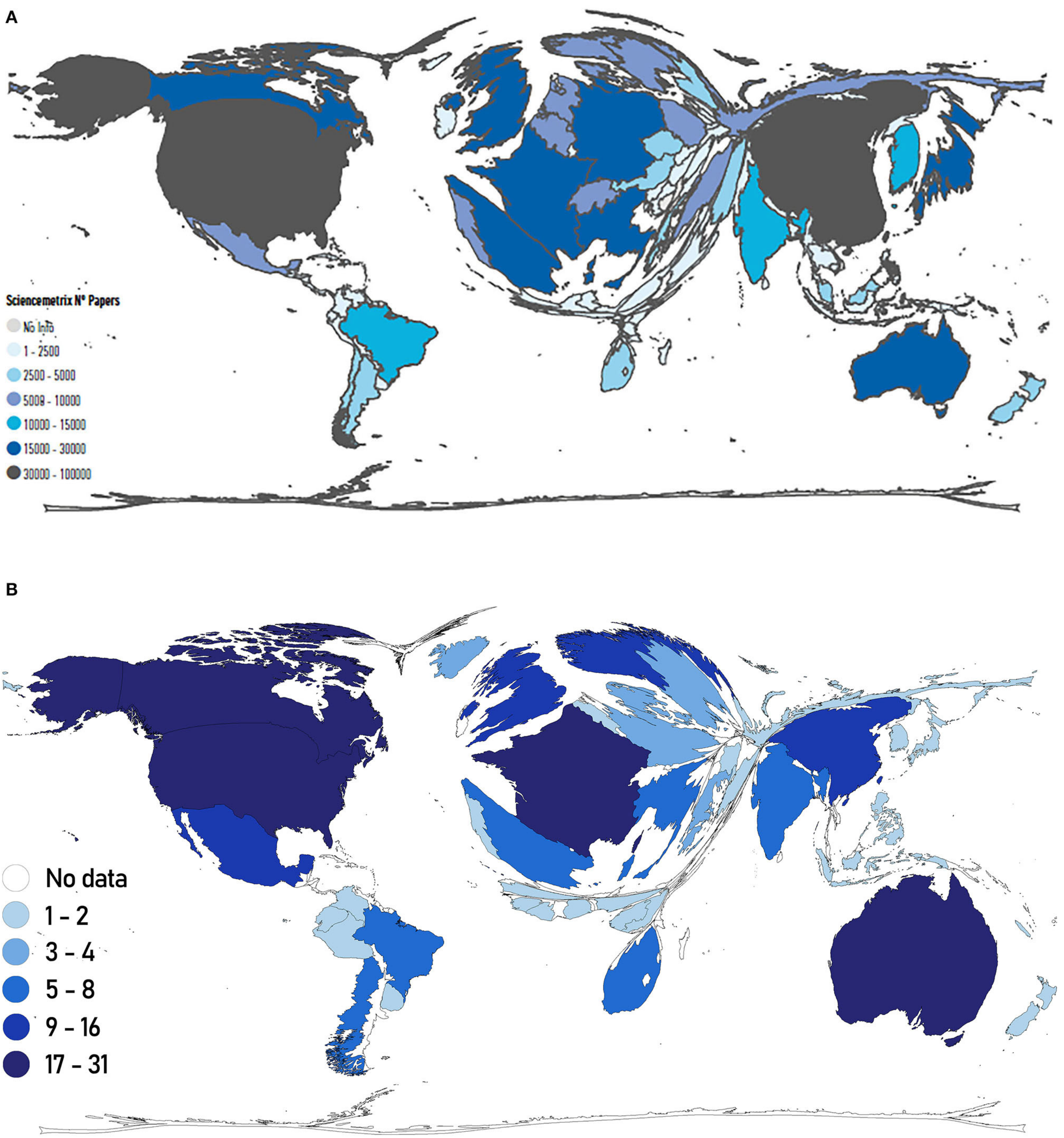

FIGURE 1 | Cartograms* depicting **(A)** Number of ocean science publications by country (from Figure 5.2 in IOC-UNESCO Global Ocean Science Report under the license: CC BY-NC-SA 3.0 IGO) and **(B)** indicative number of ecosystem modelers per country based on the author's networks and knowledge. * In these cartograms the countries are deformed and rescaled in proportion to their relative research production by **(A)** Publication and **(B)** Percentage of ecosystem modelers.

of physical-biogeochemical-ecological-social model assemblages make predictions in two directions; i.e., driven by physical changes but also driven by social changes, with feedback through the assemblage to the physics or chemistry. This important research gap is also highlighted by Claudet et al. (2019).

Ryabinin et al. (2019) suggest that activities in coastal seas are becoming more interdependent, and suggest that they require real-time decision-making and anticipatory planning. Unfortunately, models with sufficient scope (across scales and ecosystem components) cannot currently support this in real time, though near real-time physical-biogeochemical models are now becoming more common. Development versions of models with sufficient scope and resolution do exist, but still require refinement to address constraining computing capacity (which could be addressed by new morphing model approaches Gray and Wotherspoon, 2012 or larger computing infrastructure). Such models are also significantly constrained by the lack of suitable data (especially reliable and instantly accessible data) and other relevant information (see priority 5). Ryabinin et al. (2019) also suggest that the Ocean Decade might engage the unconnected modeling groups and industries to design the multi-scale ocean observation and prediction system of the future. This would be ideal and will be assisted by the ecosystem modeling community's historical openness to working together, embracing a diversity of approaches and not being drawn into unproductive "my model is better than yours" mantras that competitive funding can unintentionally incentivize.

7. Capacity Building, Accelerated Technology Transfer, Training, Education, and Ocean Literacy will be imperative to the success of the Ocean Decade (Claudet et al., 2019). To meet the capacity shortfall already felt globally by bodies attempting to deliver sustainable ocean use, this capacity development requirement needs to be taken on board by the ocean modeling community, supported by funders. To obtain the widespread use of ecosystem models (and its products) to deliver new kinds of modeling and the model ensembles suggested above, we will need many more modeling-literate scientists, managers and users. However, as the cartogram in the IOC/UNESCO Global Ocean Science Report (IOC-UNESCO, 2017) shows, there is a very significant problem with the distribution of general science capacity across the world (**Figure 1A**), which is even more desperate if we look at a cartogram of the ecosystem modeling capacity (**Figure 1B**). Therefore, a concerted effort to train more modelers, and to make models more understandable to all scientists, managers and policy makers is of the utmost importance (Fulton et al., 2015).

DISCUSSION

The Ocean Decade starts in 2021. Its scope is necessarily ambitious and requires cooperation, collaboration and a common vision among researchers from all disciplines, policy, management, stakeholders and the public. This includes ecosystem modelers. As an essential component of the Ocean Decade, how can we do our part to address the priorities to conserve and sustainably use the ocean and its resources to help ensure its success? Questions we need to address include:

i To connect to policy and management, how do we:
- Improve (and explain) our models to enhance policy makers' confidence in the models and their predictions?
- Make models ready-to-use for managers?
- Deal with and communicate uncertainty?

ii To include the technical advances needed, how do we:
- Effectively couple models to better capture reality?
- Deal with multiple spatio-temporal scales, given that some of our drivers are local, while others are regional or even global?

iii To enhance research and modeling capacity, how do we:
- Build the capacity required, and determine where it is needed?
- Better engage with and co-design our models with a broader set of knowledge holders, whether industry, the Ocean Observation community, traditional owners/indigenous communities, and policy and decision makers?
- Work together to achieve the ensemble of well-parameterized, calibrated and validated ecosystem models needed to address the questions asked of us in the Ocean Decade?

We therefore challenge all ecosystem modelers to achieve a fully operational ensemble of ecosystem models for all marine ecosystems and the global ocean by the end of the Ocean Decade. We believe that if we work together, we can.

AUTHOR CONTRIBUTIONS

JH conceived and lead the study. AB, VC, MC, KM, EF, CP, Y-JS, JS, and MT-T contributed to the ideas and discussion. JS created **Figure 1B**. All authors contributed to the article and approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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