OCEANOGRAPHY

A roadmap on ecosystem change

Global models highlight that environmental change in marine ecosystems is caused by multiple stressors. Now a study puts these projections into a biogeographical framework suitable for integration with wider biological understanding and more robust impact assessment.

John P. Dunne

Marine ecosystems supply irreplaceable economic and cultural value through coastal and maritime communities, livelihoods, tourism and more than 8% of global animal protein through capture alone[1]. Under human influence, these systems are undergoing changes in temperature, acidity, light, nutrients, and other environmental stressors with unknown impacts on living marine resources (LMRs). One of the greatest challenges in representing marine ecosystems is reconciling the vast experiential insight of observational oceanographers and marine biologists (on physiology, biodiversity and ecological function) with the idealized mathematical descriptions embedded in Earth System Models (ESMs). The diverse physiological and ecological sensitivities of LMRs and potential for threshold and multiplicative responses necessitate an integrative approach to robustly characterize the impacts of projected biogeochemical change on these resources. Writing in *Nature Climate Change*, Philip Boyd and colleagues[2] report an end-to-end statistical approach for province-level grouping of changes in multiple ocean biogeochemical stressors and subsequent regional application of direct biological observations for more robust assessments of ecosystem change.

Current ESMs project regionally intense environmental change across multiple stressors[3,4]. The challenges in interpreting how such changes will impact LMRs are manifold — ranging from biogeochemical response characterization to establishment of the significance of such multivariate changes to LMRs. The biogeochemical challenges include representation of the mean state, internal variability, and anthropogenic response in a self-consistent mathematical representation of ocean biogeographical provinces[5], which must account for features of circulation, seasonal stratification, ice cover, nitrate and iron limitation all characteristic of the real ocean. This diversity of interactions implies that different subsets of factors will have outsized or negligible influences depending on the oceanic regions and LMR, and that some model biases may lead to severe regional mischaracterizations.

At their best, current generation ESMs represent biome-level ecosystem biogeochemistry rather than local species-level biodiversity. At their worst, they misrepresent major spatial or temporal features of biomes and project widely divergent regional changes[3,4]. Thus, even as ESM representation of idealized diatoms or coccolithophores provides some insight into functional biogeochemical diversity, the representations do not suit most needs of LMR managers. While the quest to represent complex Earth system interactions and sensitivities with sufficient physical and biodiversity to meet the full spectrum of needs is critical and continuing[6], careful interpretation of current generation model response in relation to the richness of biological understanding available in field and laboratory studies can also shed some light. This interdisciplinary work requires a kind of 'roadmap' to engage the full intellect of the marine biological community across

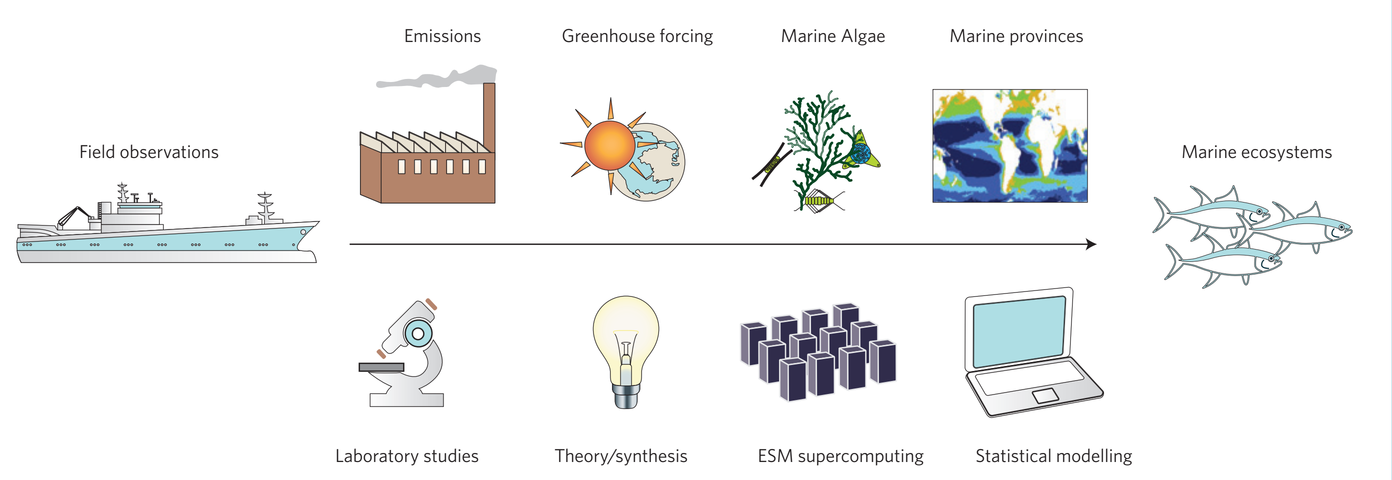

Figure 1 | A pictorial roadmap towards understanding environmental change impacts on marine ecosystems. Schematic of the design linking physical and biological field observations, laboratory study, theory, synthesis, full Earth System modelling with advanced supercomputers, and analysis through statistical modelling towards a robust biome-level understanding of marine ecosystem and LMR response under environmental change driven by human emissions of fossil fuels. Images from Istock/Thinkstock: Ship © Macrovector; microscope © Nikiteev_Konstantin; fish © LezusRocks.

the scope and capabilities of current generation ESMs, while quantitatively incorporating expert judgment to account for observational and model limitations.

Boyd *et al.*[2] take an innovative approach to build and use such a roadmap (Fig. 1), through application of a statistical tool (principle component analysis with factor rotation) to cluster biogeochemical impacts on 15 stressors into 6 global patterns and assess their relative contributions over 14 biogeographical provinces. This biome-level grouping of systems among the potential biogeochemical stressors facilitates comprehensive assessment of regional change. The fundamental advantage of this approach is in maximizing the information on ESM biome-level biogeochemical change in which the authors have more confidence, while minimizing reliance on model-dependent regional phytoplankton physiology and biodiversity representations in which they have less confidence. Boyd *et al.* then exercise this roadmap with a suite of observationally motivated interpretations of these biome-level changes through key phytoplankton taxa including coccolithophores, diatoms, and cyanobacteria. Their results are generally grim news for diatoms, but highlight a potentially growing niche for coccolithophores, despite decreasing rates of calcification.

The roadmap provided by this study[2] certainly has impressive potential to expand the community of observational and laboratory scientists directed at regional assessment, however, much work still remains. From the current examination of an individual model response for one scenario at a single centennial timescale, future investigation of ensembles of models with several scenarios on a continuum of timescales is needed to assess the sign and magnitude of change from the current generation of models. Advanced statistical approaches that mechanistically determine the physiological impact of multiple stressors[7] are needed for robust synthesis of multi-stressor, single-species response. Incorporation of more realistic biodiversity at the phytoplankton level is necessary to begin validating ecosystem models against observations. Most challenging, these comparisons must move beyond phytoplankton to the broader ecosystem context[8] to turn the breadth of biogeochemical understanding into relevant and actionable information for managers[9].

This work by Boyd *et al.*[2] is an innovative and threshold advance in integrative marine ecosystem study to address the challenges of environmental change. Just as a new generation of ESMs has recently emerged with the Fifth Coupled Model Intercomparison Project[10], an expansion of interdisciplinary engagement in analytical tools demonstrated by Boyd *et al.*[2] will be required to fully assess LMR impacts. This nexus of field and laboratory observations, theory, modelling, statistics, and knowledge synthesis across the physical, biological, and mathematical sciences has unveiled new challenges and opportunities to understand our environment, its sensitivity and resilience, and the role of humans. ❐

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ATMOSPHERIC CHEMISTRY

Climate's chemical sensitivity

Constraining climate sensitivity is a top priority for climate science. Now research shows that the details of how stratospheric ozone is represented in models can have a strong influence on warming projections.

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To predict how climate will change we need to know just two things: the future forcings on the Earth system, and the feedbacks that will ensue. The first requires forecasts of socioeconomics, technology, and human behaviour to be translated into changes in the planetary energy budget; for example, via changes in anthropogenic emissions and atmospheric composition. The second requires understanding of how processes interact to either amplify or damp climate response to the forcing, together with the timescales over which they operate. This response is encapsulated by a parameter called the climate sensitivity. Warmer air can (and generally does) accommodate more water vapour molecules. As water vapour is a greenhouse gas, any warming is amplified: this represents a positive feedback — it increases climate sensitivity. Several other feedbacks operate in the Earth system, including those associated with sea ice and clouds; most are positive. Negative feedbacks appear to be less common. Writing in *Nature Climate Change*, Peer Nowack and co-authors[2] report a large negative feedback, which causes a significant (in the order of 20%) reduction in climate sensitivity, resulting from a more comprehensive model representation of stratospheric ozone chemistry.

Quantifying climate sensitivity could hardly be more important. Equilibrium climate sensitivity (ECS) is defined by the surface warming in a world with doubled pre-industrial atmospheric CO_2 levels, once the system has returned to equilibrium. Current estimates of ECS are wide[1]: 1.5–4.5 °C. If Earth's climate sensitivity is high, then rapid and severe cuts in emissions are needed to have any chance of avoiding dangerous climate change[3].

Climate sensitivity can be estimated in a variety of ways, from both observations and models[1]. One commonly employed method involves subjecting a range of climate models to an abrupt quadrupling of atmospheric CO_2, and following their simulated surface temperature response over at least the next century[4]. Different representations of key Earth system processes, such as convection, cause each model to have an individual response to the atmospheric forcing. These result in different simulation of feedbacks, and consequently some models project more warming than others. Together with poorly