OPINION PIECE

Multinational, integrated approaches to forecasting and managing the impacts of climate change on intertidal species

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ABSTRACT: Marine biodiversity and ecosystem functioning are facing unprecedented pressures in the Anthropocene, with climate change being a primary stressor. To understand the biological response mechanisms along coastlines, the international scientific community requires coordinated action, integrating obervations through observatory networks and spatially extensive experiments using standardized approaches over broad geographic scales. Currently, however, a multinational, integrated approach is lacking, with little application of standard methodologies or data sharing across countries. Changes in the abundance, distribution and competitive dominance of rocky intertidal organisms are useful sentinels of climate change because these communities are easy to observe and long-term time series exist. Europe is in a prime position to lead by example, building on the extensive history of sustained observations and experimental research to establish an integrated network of studies and monitoring programmes. These will improve our understanding of how organismal responses translate into biogeographic range shifts, and generate more biologically realistic predictions of future climate change impacts with which to design mitigation, adaptation and conservation strategies.

KEY WORDS: Climate change · Intertidal · Long-term monitoring · Experiments · Species distribution models

1. INTRODUCTION

Rapid climate change is one of the most pervasive threats to the planet, with major consequences for biodiversity and ecosystem functioning (Poloczanska et al. 2008) and the supply of ecosystem services (World Economic Forum 2016). One of the greatest challenges is to anticipate, quantify and manage future impacts by developing rigorously derived metrics to measure changes in biodiversity and species distributions, providing a tangible approach to inform policy and preserve marine resources. This is of particular

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relevance given that investment in long-term ecological studies is declining, despite their acknowledged role in understanding and predicting responses to global change (Clutton-Brock & Sheldon 2010).

Regional species pools change on historic (century), ecological (multi-decadal), and socio-economic (annual to decadal) timescales due to range shifts, extinctions or bioinvasions as climate change challenges organisms to acclimate, adapt or move at an unprecedented pace, whilst coping with additional regional-scale stressors. Despite the wealth of data available, our ability to predict with a degree of certainty how marine biodiversity will be reshaped and to characterize resultant socio-economic impacts depends on a still-growing research area.

An area of growing interest is to assess how processes linked to climate change affect changes in organismal temperatures at the local scale, quantifying underlying physiological and behavioural mechanisms (Queirós et al. 2015). This is a complex but paramount issue for ectotherms: body temperature closely reflects that of the substratum, with daily microclimate variations and resultant thermal stress being particularly marked in the intertidal, meaning species live close to their thermal tolerance limits (Somero 2002). Many intertidal species actively select thermally benign microhabitats as a means of thermoregulation to dampen thermal stress (Seuront & Ng 2016). Biological traits such as shape, size and colour, and behavioural adaptations such as aggregation and body orientation may also impact the heat budget, with metabolic sustainance of an energetic pathway associated with coping with thermal (and other) stress determining an organism's ability to survive. The combination of processes occurring at different spatiotemporal scales therefore describes the specific thermal regime experienced by individuals, complicating the effects of climate on the biogeographical distributions. In addition, success of competitive haplotypes that result in improved adaptation of populations may occur. These and other individual-level behavioural and physiological responses can be difficult to represent within large-scale predictive frameworks (Queirós et al. 2015), making it critical to understand how organisms respond to changes in environmental variables, and at what scales they affect population biology and ecology (Kearney 2006). In this context, we illustrate the need for a multi-faceted approach, combining experimental work on individual organisms with field observations of populations across large spatiotemporal scales. The use of these data, represented in species distribution models, are then well placed to help address the fundamental question of how coastal marine species and biodiversity will respond to climate change.

Future changes in planning and environmental management of marine systems must be taken into account against the backdrop of global climate change. One legislative instrument that has explicitly incorporated this need is the European Marine Strategy Framework Directive (MSFD) (EC 2008), the pillar of marine environmental management for the European Union, the largest marine territory in the world. The MSFD requires member states to develop operational indicators to support the protection of marine biodiversity, the first descriptor of 'Good Environmental Status' for habitats within 'prevailing climatic conditions' (EC 2008). However, an integrated approach to data collection and indicator development that supports cross-scale understanding is not currently being implemented within the MSFD or any other multinational legislation. Here we outline existing programmes and suggest the strategic development of a sustained multidisciplinary, integrated observational and experimental coastal biodiversity network to strengthen a multinational approach to tracking, understanding, forecasting and managing climate change impacts on intertidal species.

2. EXISTING PROGRAMMES

2.1. Sustained observations

Coordinated action is required to monitor changes in key environmental variables, species diversity, genetic diversity and species distributions. Europe has a rich historical legacy of studies documenting population demographics and biogeographic ranges across several degrees of latitude dating back to the mid-1800s (see Mieszkowska & Sugden 2016 for a review). In this context, the MarClim project can be used as an exemplar model study based on long-term monitoring. It was established in 2001 to rescue, archive and analyse historical datasets that were started in the 1950s (Crisp & Southward 1958) and establish a current time-series network of 100 sites covering England, Wales, Scotland and northern France. MarClim has been tracking the distribution and abundance of temperature-sensitive, climate indicator species and non-indigenous species of intertidal invertebrates and macroalgae in response to climatic fluctuations across half a century (Mieszkowska et al. 2006, Mieszkowska & Sugden

2016). MarClim has shown some of the fastest shifts in leading and trailing edges of biogeographic distributions globally, and is being used by scientific and policy communities to track impacts on biodiversity and ecosystem functioning (Burrows et al. 2017).

Sustained observations of rocky intertidal habitats have been carried out or are ongoing around the world; however, none have such extensive temporal coverage as MarClim. Studies have been undertaken since the 1930s along the coastlines of France, Spain and Portugal (e.g. Fischer-Piette 1936, Fischer-Piette & Crisp 1959, Ardré 1970). A South African initiative monitored rocky shore sites on a quarterly basis for 13 yr (Dye 1998), benthic macroalgae and invertebrates have been recorded across 2 decades along the coastlines of Norway (Brattegard & Holthe 2001) and Germany (Breuer & Schramm 1988), and the Partnership for Interdisciplinary Studies of Coastal Oceans was established in 1999 to conduct research within the California Current Large Marine Ecosystem to inform management and policy (www. piscoweb.org).

In addition to scientific datasets, citizen science programmes across the globe (e.g. LiMPETS, Shorekeepers, MARINe, Sea Watchers, Reef Life Survey, Capturing Our Coast) provide broad-scale, interannual data on the distribution of intertidal species. These datasets could also be incorporated into networks studying climate change impacts on coastal ecosystems.

The implementation of large-scale, global biological observing networks poses considerable challenges, including defining key variables and methodological standardization. To address these challenges, the Biology and Ecosystem Panel within the Global Ocean Observing System is working on the identification and definition of ecological Essential Ocean Variables (EOVs) that integrate biological observing in coordinated monitoring networks, emphasizing simplicity and societal relevance, and providing a unifying global standard observational framework (Miloslavich et al. 2018). In addition, the implementation of a truly multinational observing network of marine biodiversity will require sustained support to facilitate integration of existing programmes and the development of new ones to promote high spatiotemporal resolution observations. Developing new technologies for automated acquisition of biological data will be key to operationalize an integrated, global observing biodiversity network.

Freely available platforms such as the Ocean Biogeographic Information System are beginning to address data integration challenges, promoting stan-dardization of methodologies and providing open access to datasets from around the world. With an informed understanding of the quality checks and caveats, these platforms provide an invaluable means to explore macro-scale patterns of biodiversity and temporal changes in species distributions, although further development and integration is still required.

2.2. Mechanistic insights

Climate-driven arrivals, losses and range shifts of species can impact local biodiversity, modify biogenic habitats and alter species interactions (Benedetti-Cecchi et al. 2006, Sarà et al. 2018). A combination of laboratory and field experiments measuring *in situ* measurements of environmental and biological variables (Lima & Wethey 2009), combining the effects of climatic and non-climatic stressors on a wide range of species covering multiple trophic levels, and including species interactions (Wernberg et al. 2012) across several degrees of latitude across biogeographic ranges can decipher the complexity of interactions that shape observed patterns, provide mechanistic insights into how species respond and adapt, and into how interactions are modified by climate change.

2.3. Modelling approaches

Linking experimental and observational results with ecosystem-level changes requires quantitative integration of physiological and ecological processes into statistical ecophysiological and population dynamic models, using an analytical framework to predict shifts in distribution and abundance into a non-analogue climatic future (Kearney & Porter 2009). Models provide quantitative predictions on how life-history traits react within species-specific physiological boundaries to environmental variability, and how these scale up to determine species distributions along spatiotemporal environmental gradients (Sarà et al. 2018). Biologically relevant, quantitative, GIS-mapped outputs can be modelled along coastlines with time-steps matching species biology, allowing effective mitigation and adaptation strategies.

Simplistic, predictive, correlative 'static' bioclimatic envelope models (BEMs) have been largely superseded by more sophisticated dynamic models (Cheung et al. 2009, Elith & Leathwick 2009), which incorporate mechanistic effects of temperature on the

bioenergetics of individual organisms, as in individual-based models such as those based on dynamic energy budget (DEB) theory (e.g. Kooiman 2010, Sarà et al. 2013). DEB models incorporate experimentally determined information to powerfully account for the effects of geographical barriers on temperature tracking, and differences in the capacity of species with different lifespans and reproductive rates to colonize newly suitable areas. Key elements of future modelling will include relevant mechanistic processes and species interactions, incorporating even more biological realism into predictions.

3. LINKING APPROACHES VIA A COMPLEMENTARY FRAMEWORK

It is challenging to draw generalities about climate impacts on species and diversity distributions from such diverse lines of evidence. A new generation of interdisciplinary studies combines field and laboratory studies with modelling, scaling up detailed understanding of stressor impacts at the individual level to regional impacts on species distributions, biodiversity, and economic implications. These approaches benefit from observations integrated through large-scale observatory networks, providing time series to validate the skill of macro-scale modelling projections (Queirós et al. 2015). Furthermore, distributed experiments using standardized approaches over wide geographic scales (Fig. 1) could enhance complementary framework applications and the ability to represent population-level adaptational processes affecting species biogeography. Such data are, however, rarely available.

To date, few studies have looked at the physiology and trophic interactions of foundation species or integrated detailed, species-level experimental information (Queirós et al. 2015). Only long-term experimental investigations of trophic interactions relevant at the community level will elucidate patterns in rocky shore diversity and the key mechanisms of maintenance otherwise threatened by global changes; however, the application of sophisticated tools to monitoring species-level responses is rapidly increasing.

Recent developments in time-series analysis and multivariate species distribution models provide novel opportunities to reveal how historical processes modulate population responses to present-day perturbations (Staniczenko et al. 2017). Hybrid datasets combining observational data with distributed experiments have been proposed to leverage scope and attribute causality, combining the large scope of observations with the strong causal inferential strengths of manipulative experiments (Benedetti-Cecchi et al. 2018).

A further step towards the integration of empirical data and models is offered by macro-scale modelling, involving mathematical representation of individual, population and/or ecosystem processes to assess changes in system properties and test responses to scenarios of change or management (Queirós et al. 2016). By using information derived from survey and experimental work within modelling frameworks, climate change responses and effects of novel future stressor combinations can be assessed beyond the information contained in historical datasets, providing anticipatory information to marine adaptation and mitigation policies at policy-relevant spatiotemporal scales. Such predictive, spatially explicit products can be used to assist management of coastal ecosystems, identify areas where species are at risk of being lost due to future climate change and addi-
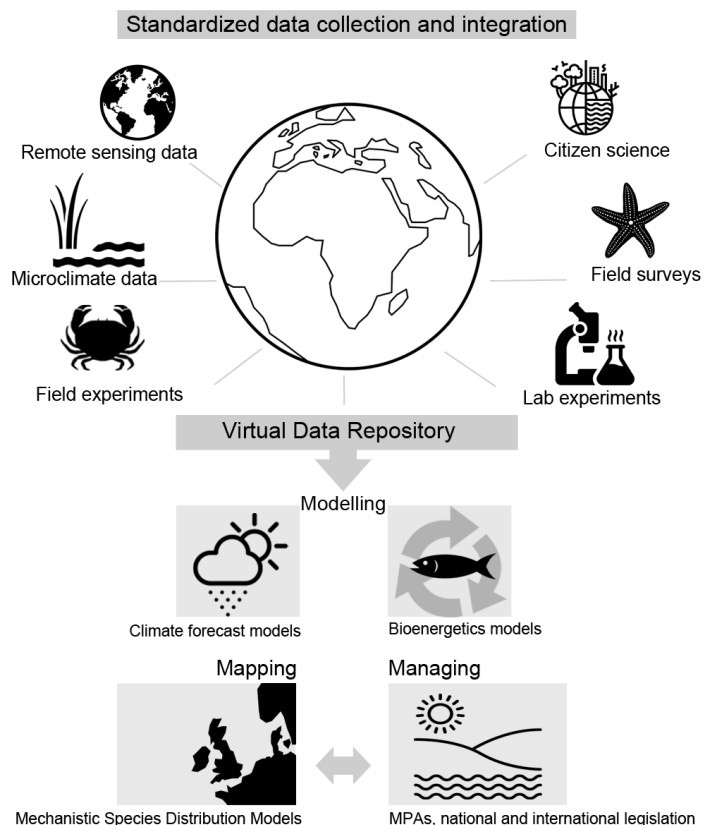

Fig. 1. Proposed international network integrating research on the impacts of climate change from the organismal level to the biogeographic level, to assist effective adaptive management of coastal eco-systems, including marine protected areas (MPAs)

tional stressors, and provide quantitative information to assist with the designation and ongoing adaptive management of marine protected areas (Fig. 1).

4. CONCLUSIONS

A multi-faceted approach, combining experimental work on individual organisms, high-resolution field observations of populations across large spatiotemporal scales and mechanistic species distribution models based on life-history traits and species interactions is required to address the fundamental question of how coastal marine species will respond to climate change. The analysis of hybrid datasets with emerging techniques in time-series analysis and macroecology is a powerful approach combining the experimental ability to establish causality with the broad scope allowed by observational studies. Such toolkits are necessary to develop biologically realistic models to forecast the impacts of future climate change, and facilitate adaptive management of coastal ecosystems.

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