Marine ecosystem reorganisation under climate change

Abstract

Marine ecosystems are responding to climate change[1], yet our ability to predict future ecosystem reorganisation is hindered by the lack of a standardised, integrated, comparative analysis. To date, global analyses of climate impacts are based on meta-analyses and include biases such as a focus towards terrestrial systems, the use of data derived from the published literature rather than primary data, a reliance on studies of individual species, and a focus on individual metrics of climate change (e.g. phenology, distribution) in isolation from other drivers of change. We will provide the first global integrated view of marine biological impacts of climate change by conducting standardised, robust, whole-system analyses across multiple taxa, trophic levels and regions. This proposed SCOR Working Group brings together climate change ecologists with expertise in a diverse suite of marine ecosystems, strong statistical skills, and access to key marine biological datasets from around the globe. We will: (1) provide unbiased estimates of impacts of climate change; (2) determine the fate of species that do not appear to respond to climate change in conventional ways; (3) determine impacts of climate change at the ecosystem level; and (4) understand how interactions with other human stressors drive ecological change. Our comparative analyses will overcome many of the existing limitations of current meta-analyses, leverage new understanding of the importance of climate change in marine systems (e.g. velocity of climate change), and produce a unique global synthesis. Most importantly, we will provide the understanding of ecosystem reorganisation under a changing climate needed by policy and decision makers.

Rationale and Background

Scientific and societal importance: Global emissions of greenhouse gases are tracking beyond the highest scenarios considered by the IPCC. Recent analyses by ourselves and co-authors suggest that marine systems are responding as faster than terrestrial systems despite less ocean warming, based on a meta-analysis of observed impacts[1]. This is because the rate that species need to respond to cope with a changing climate, the velocity of climate change (geographic shifts of temperature isoclines over time) and seasonal climate shift (shift in timing of seasonal temperatures) is greater in the ocean than on land[2]. However, there remains major gaps in our understanding of marine climate change, with <0.3% of the 28,671 biological changes synthesised in the IPCC 4th Assessment Report from marine systems[3,4]. We need to fill these knowledge gaps and incorporate our new understanding of velocity of climate change and seasonal shift so we can predict how ecosystems will reorganise. This understanding is the pre-requisite for incorporating impacts of climate change into our current frameworks for marine fisheries, conservation and multiple use management.

Currently global assessments of climate change are based on meta-analyses of the available published literature and have demonstrated ecological responses across species, regions and biomes consistent with those expected under anthropogenic climate change[1,5–7]. However, these analyses, including those in IPCC Assessment Reports, have not analysed primary datasets and are thus limited in their ability to answer critical questions. For example, a global meta-analysis of marine impacts of climate change led by us[1] has shown that most studies are based on single species and thus could over-estimate the pervasiveness of impacts due to publication bias; that no studies analysed distribution change and phenology concurrently; that no studies analysed the viability of species not responding to climate change in terms of phenology or distribution change; that 95% of studies analysed only one taxonomic group in isolation; that only 15% of studies consider other human stressors (e.g. fishing) in their analyses[1,8]; and that statistical shortcomings of the original work is perpetuated into the meta-analysis. Using published studies to analyse climate change fingerprints therefore severely restricts our understanding of climate impacts and the capacity to investigate ecosystem reorganisation. We must therefore conduct standardised, robust, analyses on primary data that includes multiple taxa, trophic levels and regions and analyse these time series at the species level across multiple trophic levels and multiple responses to climate change to achieve a more robust understanding of impacts of climate change for marine biodiversity.

Timeliness: Given the rigorous meta-analyses[4,5,7,9] of impacts on terrestrial biology and the recent marine biological analysis[1], it is now time to take the next step and analyse primary data of multiple trophic levels from several well-studied systems in a uniform way to assess different aspects of climate change impacts (phenology, distribution, abundance, demography). In addition, application of the recently developed velocity of climate change and the novel index for seasonal climate shift[2], will allow us to better interpret whether biological changes are keeping pace with climate change.

Need for SCOR: SCOR provides a unique opportunity to fund global comparative analyses that national and regional funding bodies rarely support. The proposed work requires an international team and international databases for a global analysis of climate change impacts and for regional interpretation of results. It needs an international comparative approach because we are not just collating published data, but bringing together world experts in data analysis and climate change ecology that have access to data from key marine systems for an integrated analysis. SCOR has the track record and international profile that has attracted a group of leading researchers to this proposal and encouraged researchers to make their time and data available for this global analysis. This work also follows nicely on from historical work on SCOR WGs focused on time series and particular ecosystem components (e.g. phytoplankton, zooplankton, micronekton). The new understanding and analyses in this project will be incorporated into assessments for IPCC and IPBES (Intergovernmental Panel for Biodiversity and Ecosystem Services).

Other support: Our institutions will provide in-kind support for WG members' time. Supporting funds have already been secured to run the proposed regional meetings within Australia (CSIRO), South Africa (Department of Agriculture, Forestry and Fisheries) and the UK (The Climate Change Consortium, Wales). Funding is currently being sort to support regional meetings in the US.

Terms of Reference

The proposed WG will answer the following questions:

1. *How pervasive are impacts of climate change?* Analysis of primary data will overcome the problem of publication bias, which artificially inflates the reported proportion of species responding to climate change. We will thus provide unbiased estimates of the proportion of species responding to climate change, and how this might differ among taxa and systems.
2. *What is the fate of species that do not appear to display conventional responses to climate change such as shifts in distribution and phenology?* Some species are able to make compensatory demographic changes that enable them to persist in sub-optimal habitats[16], at least until threshold environmental change is reached; others may simply not be able to keep pace with a changing climate, while others may exhibit large lags in response time. Analyses will be undertaken to identify species falling into these categories and for apparent 'non-responders' determine whether compensatory changes in demography or abundance are occurring.
3. *How do impacts of climate change manifest at the ecosystem level?* Previous syntheses of climate change responses generally lack an ecosystem perspective. Analyses of collated primary datasets will allow us to investigate effects of climate change on species interactions and food webs.
4. *How does climate change interact with other stressors to drive ecological change?* Oceans globally are exposed to multiple interacting anthropogenic stressors[11]. We will apply consistent analytical approaches that include multiple stressors so we can tease apart the role of climate from other stressors and identify key interactions.

Approach and WG Activities

We will undertake three tasks: (1) the collation of multi-system, multi-species and multi-metric marine biological and oceanographic time series datasets; (2) the development of a toolbox containing a suite of customised statistical tools for time series analysis; and (3) the comparative analysis of impacts of climate change across systems and trophic levels by applying the toolbox to the collated time series.

Task 1: Dataset collation. Our recent literature-based meta-database showed that the most robust data, in terms of quality and length of time-series, came from a limited number of datasets (e.g.

SAHFOS, CalCOFI and ICES). We have identified these primary datasets, along with other extensive datasets from around the globe, including areas under-represented in previous syntheses, as most suitable for analysis. These represent a wide range of marine species and habitats, from the poles to the tropics (Table 1). Primary datasets will be supplied by co-investigators, are freely obtainable, or have been made available by data custodians. Additional datasets will be included as access is negotiated. For example, negotiations are underway in Australia for access to >40-year datasets of marine turtle and seabird breeding and retrospective datasets of coral calcification rates.

Table 1 List of global primary datasets that will form the basis of the proposed analyses.

Datasets	Dates	Biota	Region
SAHFOS	1946 –	Chl a, phyto- zooplankton	NE Atlantic
ICES	1960s-	Fish, seabirds, phyto, zooplankton	NE Atlantic
MarClim	1950s-	Rocky intertidal	UK and Ireland
Seabird Monitoring Program	1960s-	Birds, cetaceans	NE Atlantic
CSIRO fish time-series	1970s-	Fish	Australia
AIMS	1986-2004	Coral (cover, composition); algal abundance, fish abundance, Chl a	Australia
Reefbase	1971-2000	Coral	Tropics
Reefcheck	1997-2004	Coral	Tropics
AGGRA	1997-2004	Coral (composition, disease, mortality, size); fish (biomass, density, abundance, size); algal abundance	Atlantic Gulf coast and Caribbean
CalCOFI	1950s-	Hydrography, biogeochemistry, zooplankton; fish, birds and mammals	West coast USA
PISCO	2000s-	Rocky intertidal	West coast USA
NansClim	1970s	Hydrography, biogeochemistry, phyto, zooplankton, fisheries	Southern Africa
SCAR-MarBIN	1960s-	Penguins* range of other data	Antarctic
Seabird.net	1960s-	Birds	Circumpolar
BODC	1961-	SST, hydrography, biogeochemistry	Global
Pacific CPR (Odate)	2000-	Plankton	North Pacific

Task 2: Toolbox development. We will develop a toolbox of robust statistical methods appropriate for the analysis of biological responses to climate change. Methods will emphasize approaches that allow direct use of all data. For example, generalised mixed-effects models[12] enable simultaneous analysis of data, including time-series, with different resolutions, durations or sizes, allowing quantification of effects of different climate and other human stressors consistently across datasets, taxa and regions[13]. This approach takes advantage of the hierarchical spatial structure of datasets, without losing information, as has often happened in literature-based meta-analyses[14]. The final toolbox will be an archive of the R code used for analyses, and include a comprehensive statistical guide for climate change ecologists, which we will make freely available outside the WG. This will be a lasting output and provide guidance for future analyses by the research community.

Task 3: Impacts analysis. Analyses will be undertaken at regional scales and combined to provide a global understanding of ecological change relevant to managers and policymakers. We will address our four Terms of Reference:

1. How pervasive are impacts of climate change? We do not know how many species are not responding to climate change. Studies that do report results for whole assemblages often find that some species have not responded in directions expected[15]. Using primary data, we will determine the proportion of species not responding to climate change across taxa and regions, thereby identifying hotspots of change and areas where few responses are expected, both spatially and taxonomically. Relationships between observed responses will be compared with the velocity that climate change is moving in space and time[2] to determine whether regions experiencing more gradual change (Fig. 1) have more species not responding to climate change. Moreover, we will run velocity estimates for different time windows to determine whether periods of acceleration or deceleration of climate velocity correspond with observed biological responses.

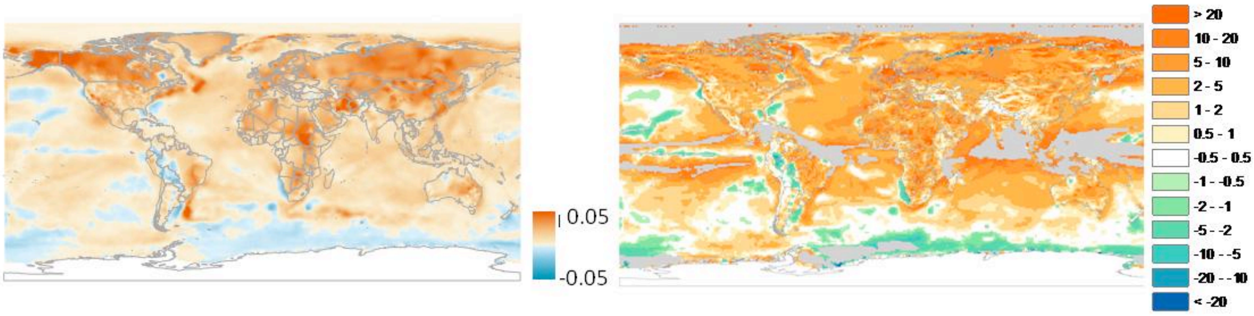

Fig. 1 (left) Trends in SST (HadISST1, °C.yr^{-1}), and (right) velocity of climate change in the oceans 1960-2009 (km.yr^{-1}) showing local reversals and areas of more rapid change[2].

2. What is the fate of species that do not appear to display conventional responses to climate change such as shifts in distribution and phenology? We will assess patterns in demography (e.g. growth, phenology, survival) through time to determine whether changes in demographic rates buffer some organisms from negative effects of climate change, as has been observed in some terrestrial (tundra) assemblages[16]. We will use the proportion of taxa responding to climate change and then compare rates of change in other patterns of demography for responders and apparent 'non-responders' to determine whether these 'non-responders' are compensating in different ways.

3. How do impacts of climate change manifest at the ecosystem level? Ecosystems are dynamic and shaped by physicochemical processes, species interactions, and external forces including climate[18]. Different components of the same ecosystem thus do not respond independently to climate change; instead responses may be idiosyncratic or influenced by interactions with other species[17,19,20]. For example, Beaugrand and Kirby[20] showed that fluctuations in the abundance of plankton and cod recruitment in the North Sea were not a result of the common influence of temperature on both trophic levels, but rather that cod recruitment was more strongly regulated by the indirect trophic effect of temperature on planktonic assemblages. We will determine the range of types and rates of responses of different taxa both within ecosystems and across regions. We will use causal modelling[21] and generalised mixed-effects models across multiple trophic levels and multiple climate and non-climate stressors (e.g. fishing, eutrophication) to determine types of control operating in different marine ecosystems[19,20]. By using this approach on a range of ecosystems and across multiple basins, we will generalise understanding of the complex direct and indirect trophic effects of climate change on the structure and functioning of marine ecosystems.

4. How does climate change interact with other stressors to drive ecological change? Other stressors will be considered in our analyses, as many marine species are exploited or subject to other human stressors such as eutrophication. Understanding consequences of multiple interacting anthropogenic stressors is vital to determine how marine managers must adapt regional stressors, such as fishing, to account for or manage climate change impacts[22]. We will use approaches such as mixed-effects models that incorporate both climate and non-climate stressors, and causal models that seek to explain complex patterns of causality among competing mechanistic hypotheses, to determine interactions of climate change with other stressors across taxa and ecosystems.

Time-scales and Products

We propose to run 3 intensive, in-person, 5-day meetings over 3-years, as well as 2 regional meetings in each of Europe, Australia, South Africa and North America. Regional meetings (regionally funded) will reduce the overall cost of the research and allow a focus on regional datasets and analysis with results feeding back into the main project. Regional meetings will also enable the membership of the WG to be expanded by including additional participants, particularly graduate students and early-to-mid career researchers, and it is anticipated that this inclusivity will also facilitate access to further datasets. Full members from outside these regions will also be able to link in via video-conferencing. Progress inter-sessionally will be monitored monthly via Skype.

Table 3 Timelines and products

Workshop	Workshop aims	Task	Inter-sessional tasks and products
Mar 2013 UK	• Set up website for collation of datasets and identify other datasets to include • Refine hypotheses • Initiate toolbox development • Initial analyses of individual datasets	1 1 2 3	• Continued analysis of datasets • Paper: based on initial analyses
Oct 2013 Regional meetings*	• Compilation of initial results of primary analyses and paper outlines • Further development of statistical toolbox • Regional analyses	3 2 3	• Impacts analysis on questions 1-4 • Paper: Statistical toolbox for climate change analysis
June 2014 Australia	• Impacts analysis on TORs 1-4	3	• Impacts analysis and paper writing • Papers: TORs 1-4
Nov 2014 Regional meetings*	• Impacts analysis on TORs 1-4 • Regional analyses	3 3	• Impacts analysis and paper writing • Papers: TORs 1-4
June 2015 US	• Impacts analysis on TORs 1-4	3	• Impacts analysis and paper writing • Papers: TORs 1-4

*Regional meetings will link via twice daily video conferencing

This first comprehensive global synthesis of climate change impacts using primary data will have a broad, global impact. Addressing the TORs will result in a suite of multi-authored papers in high-impact journals. A key outcome of the proposed project is to inform climate change policy. Findings will therefore be presented at international meetings aimed at policymakers (e.g. Greenhouse 2014 (AUS), Coastal Futures 2015 (UK) and Advancing Science, Serving Society 2015 (US)). An online description of the project will provide regular updates on progress and outputs.

Members

We have deliberately chosen a mix of male and female, and early, mid- and later-career researchers.

Full Members	Sex	Affiliation	Contribution & expertise
1. Anthony J Richardson+	M	University of Queensland, **Australia**	WG Co-Chair, IPCC AR5 contributing author, plankton ecology, statistical analyses
2. Pippa J Moore+ (Early career scientist)	F	Aberystwyth University, **UK**	WG Co-Chair, coastal ecology, ecosystem processes
3. Elvira Poloczanska	F	CSIRO, **Australia**	IPCC AR5 lead author, coastal ecology
4. Dawit Ghebrehiwet+	M	Department of Agriculture, Forestry and Fisheries, **South Africa**	Fisheries ecology
5. Sanae Chiba +	F	Japan Agency for Marine and Earth Science and Technology, **Japan**	Plankton ecology, phenology
6. Omar Defeo	M	Universidad de la República- Facultad de Ciencias, **Uruguay**	Marine policy, fisheries, sandy beach ecology
7. David S Schoeman	M	University of Sunshine Coast, **Australia**	IPCC AR5 contributing author, sandy beach ecology, statistical analyses
8. William Sydeman+	M	Farrallon Institute, **USA**	IPCC AR5 contributing author, seabird ecology, Californian Current system
9. Michael T Burrows	M	Scottish Association for Marine Science, **UK**	IPCC AR5 contributing author, coastal ecology, ecosystem modeling, spatial statistics
10. Nick Dulvy+	M	Simon Fraser University, **Canada**	Fisheries ecology
Associate Members			
1. Ove Hoegh-Guldberg	M	University of Queensland, **Australia**	IPCC AR5 coordinating lead author, coral reefs
2. Gregory Beaugrand+	M	CNRS, **France**	Plankton ecology, statistical analysis
3. Carlos Duarte	M	Mediterranean Institute for Advanced Studies, **Spain**	IPCC AR5 contributing author, stability and dynamics of aquatic habitats
4. Chris Brown	M	University of Queensland, **Australia**	Ecosystem modelling, statistical analysis
5. Tony Koslow+	M	Scripps, **USA**	Plankton ecology, Californian Current system
6. Keith Brander+	M	Technical University of Denmark, **Denmark**	Fisheries ecology, climate impacts
7. Mary O'Connor	F	University of British Columbia, **Canada**	IPCC AR5 author, coastal ecology, metabolic theory

+ denotes data contributor

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