Title
Changing Ocean Biological Systems (COBS): how will biota respond to a changing ocean?

Acronym COBS

Abstract
Climate models all project concurrent alterations to multiple oceanic properties, due to the effects of anthropogenic climate change. These projections are supported by a growing body of ocean observatory evidence demonstrating simultaneous shifts in life-sustaining properties such as temperature, CO_2, O_2, and nutrients. Hence, a major challenge for marine sciences is to determine the cumulative effects of such interactive and widespread alterations of oceanic conditions on organisms, communities and ecosystems. This challenge is multi-faceted, and research must advance in parallel to tackle three major themes: effects of multiple environmental drivers on the performance of individual organisms; community and foodweb responses to complex ocean change; and timescales of biological responses to climate change.

Consequently, we urgently need to develop a new generation of studies based on methodology that will allow us to progress from:

- ***Single to multiple environmental drivers***
- ***Organismal to community and ecosystem level responses***
- ***Transient acclimation physiology to long-term adaptation and evolution.***

This proposed SCOR working group will build strong transdisciplinary linkages to facilitate the design and development of a framework of experiments, observations, and conceptual/mathematical models to evolve each of these themes. This multi-thematic approach will provide a platform for the next generation of scientists to conduct rigorous inter-related research and to further refine this approach as new technologies emerge. The working group will also target how to develop powerful tools to convey the major research findings of this complex topic as directly and simply as possible for decision-makers in the marine realm.

Background and Rationale

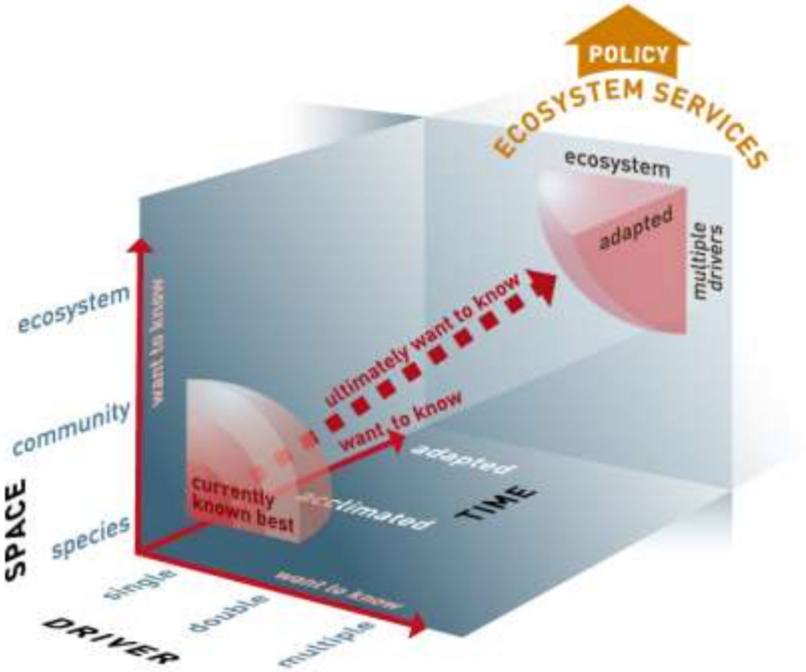

Figure 1 Present state of knowledge on Changing Ocean Biological Systems: most information on the impacts of ocean change presently available is on acclimated single species/strains under the influence of a single driver (lower left corner). Red arrows indicate the direction where we must expand our understanding. Assessment of impacts on ecosystem services, leading up to science-based policy advice, requires information on adapted responses to multiple drivers at the ecosystem level (upper right corner). From Riebesell and Gattuso (2015).

Theme 1: From single to multiple drivers

Experiments manipulating climate-related variables have provided valuable insights into the wide range of biological responses to projected alteration of oceanic conditions, for example ocean acidification (Gattuso and Hansson, 2011; Hutchins et al. 2013) or warming (Boyd et al., 2013). The design and interpretation of these single-driver manipulation experiments, in which a range of altered conditions – such as 550, 750 or 1000 μatm pCO_2 - are compared and contrasted with a control treatment (present day 400 μatm CO_2) – have been relatively straightforward. Since 2010, increased awareness across the marine science community of the complexity of the many concurrent changes to future ocean conditions (Doney, 2010) has resulted in more studies manipulating several environmental drivers concurrently. For example, one third of the 225 papers at the 2012 SCOR-sponsored symposium on "The Ocean in a High-CO_2 World" which reported on the biological response to Ocean Acidification (OA) also manipulated at least one other property (Cooley, 2012). Cooley reported a wide range of permutations of multi-driver perturbation experiments, for example pH and temperature, or CO_2 and nutrient manipulations. Figure 2 provides estimates of the number of studies which looked at multiple drivers (acidification plus at least another one) and how this trend has developed with time.

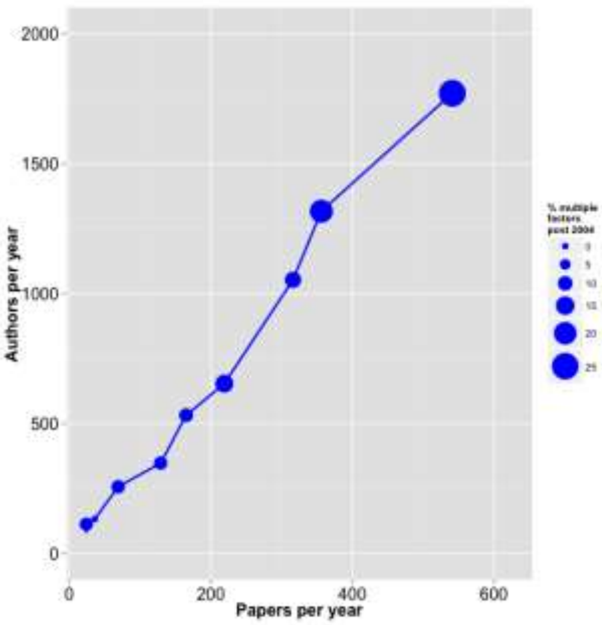

Figure 2 Increase in the number of papers focusing on both ocean acidification and other environmental drivers. Data courtesy of Jean-Pierre Gattuso, from a bibliographic database arranged with the Ocean Acidification International Co-ordination Centre (OA-ICC).

There has been a growing realisation that the experimental outcomes of such multi-driver experiments may not simply be additive and some are therefore highly non-linear, so their interpretation is exponentially more challenging than for single driver experiments (Figure 3).

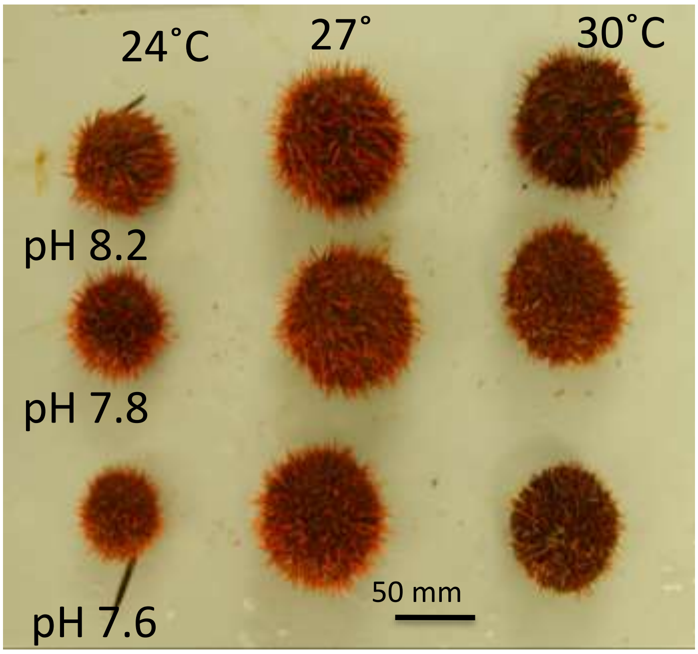

Figure 3 An example of the complex interplay of multiple environmental drivers on marine life. Temperature and pH both had a significant effect on growth of this sea urchin. Acidification reduced body size and warming mitigated this effect. Image - courtesy of Maria Byrne (University of Sydney, Australia).

Moreover, the results of the warming and acidification manipulation study on the sea urchin presented in Figure 3 highlight several important issues that have both direct scientific and wider policy ramifications. First, the effects of multiple drivers can offset or magnify one another, and so provide a different outcome than could be predicted from the results of a single-driver experiment. Second, the outcome of a multiple-driver experiment depends heavily on the selection and magnitude of the individual drivers being combined. Third, accurate communication and predictions of the collective effects of multiple drivers on marine life to policy makers requires consensus (in experimental trends) across a representative number of multiple-driver experiments.

Hence, to provide more reliable estimates of how marine biota will respond to the cumulative effects of multiple drivers requires that *we develop comprehensive approaches/studies that progress from single to multiple environmental drivers.*

Theme 2: From organisms to ecosystems

The findings from even sophisticated multiple-driver experiments on organisms, such as phytoplankton, that occupy a single trophic level in a foodweb cannot be used to predict how entire ecosystems will respond to complex ocean change (Boyd et al., 2010; Caron and Hutchins, 2013). The components within a foodweb, such as predators and their prey, may respond in very different ways to the same changing ocean conditions. For example, the physiology of microzooplankton (grazers) is more responsive than that of their prey (phytoplankton) to warming (Rose et al., 2009). Hence, as is evident for the previous theme, there has also been progress in the last five years in transitioning from an organismal to an ecosystem-level view of how marine life responds to global change (Brose et al., 2012). There has been increased use of mesocosms (large volume, 1000 L or more, enclosures, Figure 4) to examine marine pelagic ecosystems in coastal and most recently oceanic waters, which has provided valuable information on the responses of the organisms that occupy trophic levels across foodwebs (Calbet et al., 2014). These mesocosm studies provide unprecedented detail on how ecological and biogeochemical processes will be altered by ocean change. This approach has also opened the door for implementing experimental evolutionary biology approaches in natural systems (Scheinin et al. 2015). Other ecosystems, such as those in benthic nearshore waters (from the tropics to the polar oceans) have also been examined via mid-term (months) deployments of innovative large volume (1000 L) experimental chambers such as Free Ocean CO_2 Enrichments (FOCE) (Gattuso et al., 2014). Both mesocosms and FOCE enable multiple large-scale multi-disciplinary marine manipulation experiments that detail both ecological and biogeochemical responses to environmental change (Figure 1).

Figure 4 Large volume mesocosms of 20 m depth deployed in the Raunefjord, Norway to investigate the impacts of ocean acidification on pelagic communities (photo: Solvin Zankl, GEOMAR, 2015)

Although these large volume holistic approaches are advancing this theme, they do have limitations, such as the logistical challenges presented in manipulating more than a single driver (Figure 4). This illustrates the need to build strong cross-links with theme 1 which can more readily tackle the effects of multiple drivers. Thus, an approach such as modelling that facilitates integration of *organism to community and ecosystem levels responses* is urgently needed.

Theme 3: From Acclimation to Adaptation

Virtually all manipulation experiments, whether based on single- or multiple-driver experiments with organisms, communities, or ecosystems, have not considered the potential for adaptation to influence the outcome of the study (Schaum et al., 2014). In order to detect a measurable response to environmental manipulation, such experiments are primarily conducted using climate change projections for the year 2100, and thus represent a quasi-instantaneous alteration of environmental conditions, for example, increasing pCO_2 from present day (400 μatm) to 750 μatm (projected in some climate change IPCC scenarios for year 2100) on a timescale of hours to days. Such an experimental design cannot take into account the abilities of the study organisms to acclimate (days to weeks) or adapt (longer timescales) to alterations of oceanic conditions that occur incrementally over years or decades. Adaptation via micro-evolution for rapidly reproducing organisms such as microbes has been shown to occur on shorter timescales (<1000 generations, years) than previously thought (Lohbeck et al., 2013, Hutchins et al. in press), revealing the ability and indeed the need to consider evolutionary responses in global change experimental design (see Figure 1).

Hence, failure to more accurately mimic the ability of organisms to respond to environmental change in manipulation experiments may give a series of misleading experimental outcomes which could skew predictions of how organisms, communities and/or ecosystems will response to changing oceanic conditions. Thus, this third theme must be interwoven into themes 1 and 2, such that a subset of experiments considers *adaptation* in their design.

Terms of Reference (TOR)

1) Assess the current status of emerging research themes 1-3 by reviewing the literature to assess the dominant research foci, their relative coverage, and identify any major gaps and/or limitations. Publish this review in an open-access peer-reviewed journal.

2) Raise awareness across different scientific communities (evolutionary experimental biologists, ecologists, physiologists, chemists, modelers) to initiate better alignment and integration of research efforts.

3) Co-ordinate thematic transdisciplinary sessions to attract and assemble experts from other fields such as paleoceanography and marine ecotoxicology to learn from the successful approaches their fields have developed to address multiple drivers.

4) Develop a multi-driver Best-Practice Guide (BPG, or other tools) as one potentially valuable way to help this research field move forward in a cohesive manner.

5) Mentor early career scientists in the design process for complex multiple driver manipulation experiments, familiarize them with BPG, and teach them practical methodologies for the analysis of their experimental findings.

6) Build an interactive website on 'multiple drivers and marine biota' to ensure the long-term future and inter-connectedness of this international research community, and to provide educational information at a variety of levels.

7) Publish a series of short articles in both the scientific media and with scientific journalists to disseminate the challenges and opportunities surrounding multiple drivers and ecosystems.

8) Engage with policy-makers and science communication experts to produce a glossary of terms and an implementation guide for policy-makers to better understand the role of multiple drivers in altering marine living resources and ecosystem services.

Working plan

The TOR will each be fulfilled as action items between and/or during WG meetings. We will run each meeting alongside conferences that will be well attended by WG members including *Oceans in a High* CO_2 *World* (May 2016), the *Ocean Global Change Biology Gordon Research Conference* (GRC, July 2016, 2018), and other venues – AGU/EGU meetings to minimise travel costs.

Year 1

The proposed WG will focus on TOR 1/2 to develop the point of departure for this WG (i.e. assessment of the status of emerging research themes), and to build a research community (better alignment and integration of research themes).

Specifically we will use the IPCC AR5 2014 marine chapters as a platform to assemble this Review (TOR 1). To 'kick-start' this WG, the Chair will initiate this Review so that a draft can be circulated to stimulate discussion at our inaugural meeting.

Efforts to initiate better alignment and integration of research efforts will commence early in year 1 by surveying different research communities (outlined in Figure 1) through customized questionnaires such as SurveyMonkey (https://www.surveymonkey.com/) that have been used previously by Boyd/Hutchins. Surveys will enable the WG to identify which meetings different researchers attend (e.g., experimental evolutionary biologists), that will help to assess the suitability of conferences (GRC, EGU, AGU) to bring together many different marine scientists.

At our first WG meeting, the design of customized questionnaires (akin to those used for the IPCC ocean acidification special report, Gattuso et al., 2013) will be discussed so they can be circulated (via the Web) at the end of year 1 to identify experts from other fields (e.g. marine ecotoxicology) to learn from their approaches to multiple drivers (TOR 2/3).

Year 2
We will build on our initial activities, in particular to co-ordinate thematic transdisciplinary sessions (TOR 3) and to develop a Best-Practice Guide (BPG, and/or other tools) for COBS. These discussions will commence at the 2nd WG meeting (end of year 1). We will target transdisciplinary workshops such as GRC/GRS (Gordon Research Symposia for early career researchers) which regularly attract a diverse range of speakers from paleoceanography to ecotoxicology (TOR2).
Based on the experiences of Riebesell/Gattuso in preparing and updating the Ocean Acidification BPG (Riebesell et al., 2010), this WG proposes to proceed in a more innovative and flexible way – via wiki books (http://www.gms-books.de). This approach can involve many contributors, leading to a better product that could be launched initially with a few chapters and expanded later. Furthermore, updates would be relatively straightforward to implement.

The synthesis of these findings will help guide us as to the timeline for developing BGP wiki books that will commence towards the end of year 2.

Year 3
The main goals (in addition to adding further value to earlier TORs that will be fulfilled, partially or wholly in years 1/2) will be to run a 'hands-on' training workshop that targets primarily early career scientists (TOR 5) and to build the interactive website (TOR 6). This will be done in conjunction with the capacity building activity of the Ocean Acidification International Coordination Center which organizes several training courses worldwide annually.

The workshop will train researchers, and in particular early career researchers (ECRs), in the design of complex multiple driver manipulation experiments. It will also familiarize them with BPG, and assist with development of skills needed for analysis of their experimental findings. The WG will bring together a diverse range of skillsets (physiology, -omics, bio-statistics, evolution, food webs, ecosystems, mesocosm 'engineering', chemistry, remote-sensing and modellers) to build a workshop programme. To make the most of the assembled interdisciplinary talents, the WG will seek co-funding from national and foundation science funding agencies to expand the scope of this workshop and maximise the participation of ECRs. We will align this workshop with a WG meeting to further enhance the interactions between the WG, other experts and the workshop participants. Our ability to raise additional funding will also determine whether we run this workshop once or twice during the WG's four-year tenure.

The interactive website (TOR 6) will ensure the long-term future and inter-connectedness of this international research community, and provide educational information from school-leavers to postgraduate. It will also provide live links to prior TOR's such as 1 (the state-of-the-art review) by updating bibliographies of new research, emerging policy documentation, and be a repository for topical popular articles.

In addition, the website will list international contacts and national programmes that are aligned with this research network, publicise up and coming events, workshops and conferences, and ensure that these activities and the capacity build during the lifetime of the WG continues to thrive beyond this WG.

Year 4 and looking beyond the lifetime of the COBS WG

The final TOR's will be fulfilled in year 4, and together with some of the prior TOR's will provide a range of flexible tools and approaches that up-and-coming ECRs (from TOR 5 workshops) as well as established scientists can build upon, ensuring the longevity of this research theme, that will be required for at least a decade (Riebesell and Gattuso, 2015).

We will publish articles (research and popular) in both the scientific media and with scientific journalists to disseminate the issues surrounding multiple drivers and marine ecosystems. Articles will include a thematic section in an open-access journal such as *Marine Ecology Progress Series*. Popular articles will be contributions to the media, as well as the product of discussions/advocacy with journalists at magazines including *Scientific American*. The website will integrate these approaches and make further links to a new generation of scientists and environmentalists who increasingly use social media to disseminate their research and scientific opinions.

The website will help to build strong relationships with policy-makers and science communicators to produce a glossary of terms and a practical implementation guide for policy-makers (similar to the IOC/UNESO ocean fertilization guide) to better understand the role of multiple drivers in altering marine ecosystem services. 8 TOR will link to IPCC AR6 (due 2020) individual chapters, and assist with Executive Summaries and other IPCC products.

Deliverables

TOR 1 and 2: Communicate this state-of-the-art as a Synthesis paper to an open-access journal (end of year 1). This Review paper will contribute to IPCC AR6 cycle.

TOR 2 and 3: Co-ordinate thematic transdisciplinary sessions at international conferences to attract and assemble experts from fields such as paleoceanography and marine ecotoxicology. Produce a short popular article on this topic in an open-access journal (end of year 2)

TOR 4: Produce a BPG or equivalent tool(s) for COBS such as wiki books in conjunction with Copernicus/EGU (end of year 4)

TOR 5: Establishment of a new training course for young scientists moving into this field, with the intention of this becoming an annual or semi-annual event for the foreseeable future (years 3, 4, and beyond).

TOR 6: Build and maintain an interactive website focused on new approaches to multiple-driver research themes for document and methods collation, open forum discourse, and communication and outreach activities. Actively seek web co-ordinators and a host institution beyond the life of this WG.

TOR 7: Publish a transdisciplinary thematic series in an open-access journal such as MEPS. Publish a range of articles in both the popular scientific media and with scientific journalists to disseminate the challenges and opportunities surrounding multiple drivers and marine ecosystems.

TOR 8: Policy outreach via the production and dissemination of a clearly written, non-technical guide for marine resource managers and policy managers that includes a glossary of terms and a practical set of recommendations for predictive management of marine multi-driver impacts.

Capacity Building (How will this WG build long-lasting capacity for practicing and understanding this area of marine science globally)

Given the need for long-term (i.e., well beyond the lifetime of a 4 year WG) and sustained international research into how biota will respond to a changing ocean, we have in part detailed some of our longer term aspirations in our working plan under the section "Year 4 and looking beyond the lifetime of the COBS WG".

The combination of training workshops for early career scientists (TOR 5), online publication of a COBS BPG as wiki books (TOR 4), and of succession planning (TOR 6) beyond the lifetime of the proposed COBS WG will ensure the following:

a) A new generation of scientists, from an wide range of countries, with comprehensive skillsets to further evolve the field of COB, and to meet the challenges that lie ahead in better understanding how ocean biota will respond to changing ocean conditions.
b) A series of interactive guidelines (wiki books on a multiple drivers BPG) that can be readily updated and accessed on line by the emerging international community of both established and emerging early career researchers.
c) An interactive website that will continue to act as a repository for new information and emerging initiatives that the international community can focus on.

The wide range of products from this WG from popular articles (TOR 7) to tools for policy analysts (TOR 8) will raise awareness on this issue from schools through to Governments. Such enhanced awareness will provide a platform for further engagement with a new generation of scientists, and the publications from the COBS WG will act as benchmarks that will be updated and improved over the coming decade.

The provision of synthesis products (TOR 1 and 2) will feed into landmark widely-read publications such as IPCC AR6 (due in 2020) and beyond 2020 provide a "point of departure" for other IPCC cycles. The outreach fostered by this WG will also provide important links into emerging and multi-faceted organisations such as Future Earth.

Working Group composition

Full Members

Name	Gender	Place of work	Expertise relevant to proposal
1 Philip Boyd (chair)	Male	Institute for Marine and Antarctic Studies,Australia	Phytoplankton and multiple drivers
2 David Hutchins	Male	University of S. California, USA	Global change and ocean biogeochemical cycles
3 Jean-Pierre Gattuso	Male	University of Paris, France	Foodweb responses to ocean acidification and warming
4 Ulf Riebesell	Male	IFM-GEOMAR at University of Kiel, Germany	Pelagic foodwebs and mesocosm enclosures
5 Christina McGraw	Female	University of New England, Australia	Chemical engineering and experimental design
6 Sinead Collins	Female	University of Edinburgh, UK	Experimental evolutionary biology
7 Aurea Ciotti	Female	Centro de Biologia Marinha (CEBIMAR), Universidade de São Paulo. Brazil	Detection of phytoplankton functional types from Space
8 Marion Gehlen	Female	CNRS-LSCE-IPSL-CEA, France	Biogeochemical modeler, co-chair e Marine Ecosystem and Prediction Task Team
9 Jorge Navarro	Male	Marine Science Institute, Austral University of Chile, Chile	Climate change and marine bivalves
10 Kunshan Gao	Male	Xiamen University, China	Multiple drivers and their interactive effects on ocean biota

Associate members

Name	Gender	Place of work	Expertise relevant to proposal
1 Hans-Otto Pörtner	Male	Alfred Wegener Institute, Germany	Animal physiology and multiple drivers, IPCC AR5 Co-ordinating lead author
2 Graham Bell	Male	McGill University, Canada	Evolutionary rescue and climate change
3 Gorann Nilsson	Male	Biosciences, Univ. of Oslo, Norway	Fish dynamics and climate change
4 Marcello Vichi	Male	Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy	Climate change modelling
5 Uta Passow	Female	Univ. California Santa Barbara, USA	Climate change and the oceans biological pump
6 Katharina Fabricius	Female	Australian Institute of Marine Sciences, Australia	Natural laboratories to study multiple drivers (vent systems)
7 John Havenhand	Male	University of Gothenburg, Sweden	Biostatistics and experimental design
8 Haruko Kurihara	Male	University of the Ryukyus, Okinawa, Japan	Impact of ocean change on marine invertebrates
9 Sam Dupont	Male	University of Gothenburg, Sweden	Coastal communities and multiple drivers
10			

Working Group contributions

Together, the full members bring a wide range of expertise that ranges from multiple driver lab and field manipulation studies, evidence of biological responses to a changing ocean (from satellites), environmental sensor design, experimental evolutionary biology, and mathematical modelling.

Philip Boyd (Australia, Chair). Boyd is a Professor in Marine Biogeochemistry whose research focusses on the influence of multiple drivers on pelagic ecosystems. He was a lead author on the Ocean systems chapter of the IPCC AR5 report and will chair the 2016 Gordon Research Conference on Ocean Global Change Biology.

David Hutchins (USA). Prof. Hutchins has expertise in how global change affects marine biology and carbon, nutrient and trace metal biogeochemistry. His most recent work has examined evolutionary responses of phytoplankton to ocean acidification and warming, and he served as chair of the first Ocean Global Change Biology Gordon Conference in 2014.

Jean-Pierre Gattuso (France). Is a field leader in the study of multiple drivers and their effects on coastal marine communities using innovative experimental systems. He led the seminal European Project on OCean Acidification (EPOCA) for four years.

Ulf Riebesell (Germany). Prof. Riebesell's research aims to address physiological, ecological, biogeochemical and, in recent years, evolutionary responses to ocean change. He combines approaches ranging from single species lab experiments to large-scale mesocosm studies on natural plankton communities.

Christina McGraw (Australia). Dr. McGraw is a chemical engineer who is a field-leading innovator in the design of experimental manipulations uystems (ocean acidification under trace metal clean conditions. She is currently working on the design of novel sensors for multiple driver research.

Sinead Collins (UK). Dr. Collins is one of the pioneers of experimental evolutionary global change biology. Her expertise thus crosses disciplinary boundaries from evolutionary biology to marine science.

Aurea Ciotti (Brazil) Dr. Ciotti is a field-leading optical oceanographer who studies the remote sensing of phytoplankton communities in order to better assess how changing ocean conditions are altering community structure. She is a member of the International Ocean-Colour Coordinating Group.

Marion Gehlen (France). Dr. Gehlen is a renowned modeler focusing on global ocean biogeochemical processes in a changing climate. She is currently co-chair (along with Katja Fennel (Canada) of the Marine Ecosystem and Prediction Task Team.

Jorge Navarro (Chile). Professor Navarro is a leading researcher on the impact of ocean changes on commercial bivalves such as mussels. His multi-driver research has targeted larval to adult bivalves to assess which part of the life cycle is most susceptible to changing ocean conditions.

Kunshan Gao (China). Prof. Gao is recognized as the leading authority in China on ocean acidification and primary producers, including both microplankton and macrophytes. His recent work has focused on understanding the responses of phytoplankton to multi-variate climate change processes.

Relationship to other international programs and SCOR Working groups

The proposed working group will provide much needed linkages across a range of national programmes that are focusing on various aspect of multiple drivers, such as those investigating ocean acidification (BIOACID, Germany, www.bioacid.de/ ; UK Ocean Acidification Research Programme (UKOA) www.oceanacidification.org.uk/), the wider ramifications of aspects of multiple drivers on biogeochemistry (US Ocean Carbon Biogeochemistry, www.us-ocb.org/) or ecology (Japanese NEOPS (The New Ocean Paradigm on its Biogeochemistry, Ecosystem, and Sustainable Use), ocean.fs.a.u-tokyo.ac.jp/index-e.html). Other invaluable relationships will be formed with organisations such as the Ocean Acidification International Coordination Center, whose prior experience in running training workshops will help our proposed WG to excel in achieving our TOR #5.

At the international level, our SCOR working group will also liaise with other initiatives such as the recently established Gordon Research Conference (and Gordon Research Symposium for early career scientists) on Ocean Global Change Biology (for details of the inaugural July 2014 meeting see https://www.grc.org/programs.aspx?id=15855; for the 2016 GRC and GRS see https://www.grc.org/conferences.aspx?id=0000771). Several of the proposed full members of this WG are active participants in organizing the 2016 meeting.

Proposed full members also have strong linkages to other international programmes that have begun to focus some of their efforts on the field of multiple environmental drivers and marine biota. These include SOLAS (Surface Ocean Lower Atmosphere Study) which has identified "Multiple stressors and ocean ecosystems" as one of eight themes as part of their 2015-2025 research plan (http://www.solas-int.org/about/future_solas.html). Boyd has strong links with the SOLAS programme. Multiple drivers has also been the focus of the IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) programme which is holding a workshop on "Marine and human systems - Addressing multiple scales and multiple stressors" In late 2015 (http://www.imber.info/). Both Gattuso and Riebesell have long established links with the IMBER programme.

Key References

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Appendix
For each Full Member, indicate 5 key publications related to the proposal.

Philip Boyd

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