SCOR Working Group Proposal

Title

Integration of international ocean acidification research at CO_2 seeps.

Acronym:

InterSEEP

Summary

Ocean acidification (OA) is caused by the uptake of anthropogenic carbon dioxide (CO_2) and its effects on ocean chemistry are well understood. Most OA research has been conducted in laboratories and mesocosms, which isolate organisms from their environment, so the effects of OA on marine communities, species interactions, food web structure, and on ecosystem services are poorly known. Over the past 10 years, the study of shallow marine CO_2 seeps has emerged as a powerful tool to address this knowledge gap, to assess effects of OA on coastal ecosystems. This research community remains fragmented internationally, with a lack of capacity to study CO_2 seep systems in developing nations, so the time is right to form an international forum to exchange knowledge and coordinate efforts.

This working group will coordinate interdisciplinary international studies using natural gradients in seawater pCO_2 worldwide to analyse current data available, plan *in situ* observations, agree a set of standard techniques for work in seeps, and establish a foundation for long-term capacity building. A new global research community will be formed for the exchange of scientific information, to share new technologies/facilities, and to coordinate programs that no single nation can achieve alone. InterSEEP will also strengthen the voice of shallow CO_2 seep researchers worldwide during the UN World Ocean Decade, providing syntheses for policy makers and a legacy through training scientists worldwide.

Scientific Background and Rationale

Atmospheric pCO_2 will almost certainly double from pre-industrial levels by 2100, higher than at any time during the past few million years.[1] CO_2 emissions have caused a 26%

increase in [H+] in surface ocean waters since the early 1900s, with a projected drop in seawater pH of up to 0.5 units by 2100.[1] Additionally, increased air-sea heat flux and altered circulation patterns have led to significant warming of the global ocean, while extreme warming of seeps has also intensified in many regions.[1,2] The combined stressors of ocean acidification (OA) and warming are a major threat to marine ecosystems and the goods and services they provide (e.g., food provision and security, coastal defence, mitigation of climate change-blue carbon).[3] However, current understanding of how marine ecosystems will respond to climate change remains severely limited, which restricts our ability to predict and manage for further change.[4] Currently, the only forum that attracts OA scientists to meet on a regular basis are the symposia on The Ocean in a High-CO_2 World every four years, and that this frequency of meeting is not often enough to achieve needed planning and coordination in the CO_2 seep community. This proposal aims to bring together the resources of the global community of CO_2 seep scientists to address important OA research issues, and is explicitly linked to the UN Sustainable Development Goal (# 14.3), which aims to better understand the impacts of climate change on marine ecosystems.

The vast majority of our current understanding of how marine biota will respond to climate change stems from experiments conducted in tanks and mesocosms.[5,6] While these controlled manipulations are useful, they suffer from a lack of realism, as natural populations are influenced by abiotic and biotic processes that operate over multiple spatial and temporal scales.[5] Conversely, the majority of research on the impacts of climate change stems from long-term time series, which document ecological change, but do not generally elucidate underlying causative mechanisms.

Researchers around the globe have begun utilizing existing natural gradients in climate variables to conduct ‘space for time’ substitution experiments to examine how increased temperature and pCO_2 will likely influence ecosystem services for mankind[7–9]. This approach offers increased realism and inference because (i) marine communities found under the different environmental conditions are naturally assembled, complex and shaped by species interactions; (ii) environmental variables (both climate and non-climate related) exhibit ‘real’ variability patterns; and (iii) populations and communities have been exposed to the different environmental conditions for periods of time (decades to many centuries) that far exceed that of laboratory experiments. Recent work using spatial gradients (usually latitudinal) in temperature has shown that continued ocean warming will likely lead to changes in primary productivity, decreased resilience to physical disturbance and increased grazing pressure within many habitat types.[10] Similarly, research using CO_2 seeps as natural analogues has shown that OA will likely cause shifts in the relative abundance of calcifying organisms and changes in community structure and biodiversity.[7–9] Furthermore this kind of ecosystem can be found around the globe

(Fig. 1). There are other natural analogues for ocean acidification, like upwelling areas, but this proposal is focused on seeps as they allow the study of chronic exposure to high CO_2/low pH conditions. The benthic communities within them are exposed to this form of CO_2 injection for decades which cannot be reproduced in the lab or in upwelling zones.

Of the research focused on CO_2 seeps so far, there have been several high-impact publications.[9,11,12] We feel the time is ripe to create a holistic global synthesis of lessons learned to date and to map future strategies to maximize the use of natural analogues for ocean acidification. Therefore, we propose the creation of a global network of researchers working on CO_2 seeps to create open-access data resources, synthesize the impacts of variability in carbon chemistry, design global joint experiments, develop internationally agreed best practices for data acquisition and build capacity internationally, with an emphasis on developing countries. This proposal is designed to provide a unified forum for shallow CO_2 seeps researchers worldwide.

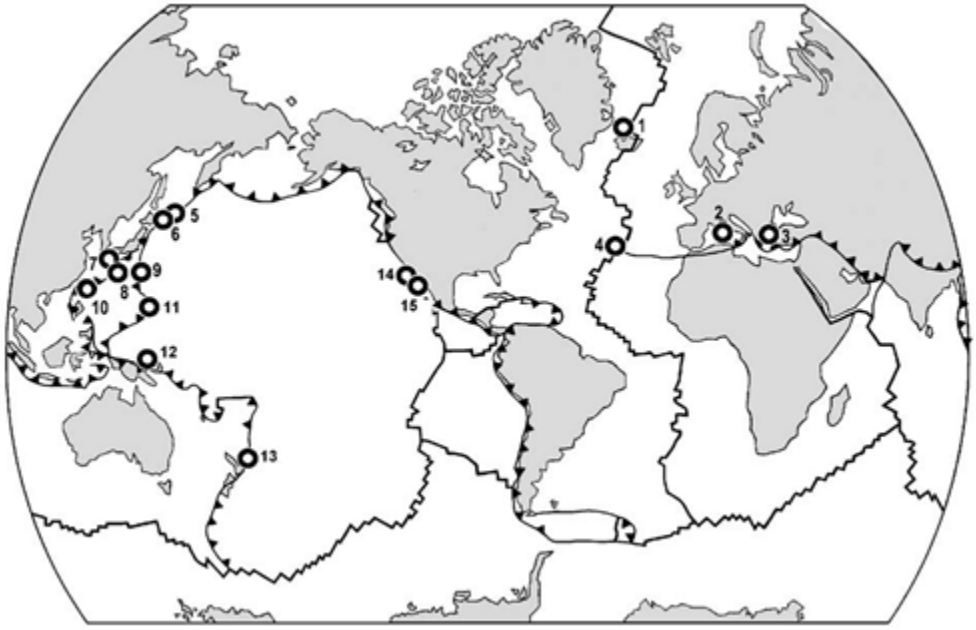

Figure 1, latest map from a peer reviewed publication with the location of shallow seeps.- Areas of shallow-water (<200 m) hydrothermal seeping with known data on biota up to 2005. 1 — Kolbeinsey, 2 — Tyrrhenian Sea (Capes Palinuro and Messino, Baia Pozzuoli, Aeolian Islands), Columbretes Islands 3 — Aegean Islands Santorini and Milos, 4—D. Joao de Castro Bank, Azores, 5— Ushishir Island, Kuril Islands, 6 – Kunashir Island, Kuril Islands, 7— Kagoshima Bay, 8 —Tokora and Iwo Islands, 9— Nishino-shima Sintoh, Ogasawara Islands, 10 — Kueishan Is., Taiwan, 11 — Esmeralda Bank, Mariana Islands, 12 — Matupi Harbour, New Britain Island and Tutum Bay, Ambitle Island, Papua New Guinea, 13 — Bay of Plenty, New Zealand, 14 — White Point, Palos Verdes, California, 15 — Punta Banda and Punta Mita, Baja California. From Tarasov[13]

Terms of Reference (ToR)

1. To create an open-access data resource based on research made at CO_2 seep sites globally.

2. Build, based on the observations made in the CO_2 seeps, on an emerging synthesis[7] of the impacts of carbon chemistry variability on marine ecosystems and the goods and services they provide.

3. To produce a peer-reviewed perspectives article on future seep research, identifying what kind of research is needed and in which locations. Emphasis will be given to a) benthic and pelagic diversity, abundance and biomass; b) sea food quality; and c) resilience of coastal habitats to ocean acidification and temperature increases.

4. To share knowledge and transfer skills for surveys and experiments, laboratory analysis and data management, in order to build capacity in developing countries.

5. To develop a document of internationally agreed best practices for data acquisition, standardized output formats and archiving for surveys and experiments that harness the advantages of CO_2 seep research and outreach.

Working plan (logical sequence of steps to fulfil terms of reference, with timeline)

Year 1.- February 2021

A kick-off meeting will be led by Ecuador to begin addressing TORs 1-5. The format will depend on social distancing and travel regulations in place at that time.

Goal for ToR 1 at this meeting.- Determine what data are currently available in what format, propose how to structure data, determine what data can be uploaded into the database, and design a Data Team.

One-day session. Participants will be contacted before the workshop and asked to complete a survey where they will state which data they could contribute and its structure.

The working methodology is:

1) Presentation of the Sustainable Development Goal 14.3.1 in order to have all participants aware of expected data quality and format to be used.

2) Presentation of the results of the survey of WG members on available data.
3) Form small groups, based on the expertise of the Working Group members, which will focus on each kind of data in order to propose specifics ways to structure the data.
4) Each group will present in 15 minutes their proposal for the data structure and will receive comments of all participants.
5) Designation of a Data Team within the members of the working group, which will be in charge of developing the dataset.
6) A summary of the proposed methodology.
7) Design a follow-up plan to develop the database.

Goal for ToR 2 at this meeting.- To create a draft with the structure of a synthesis paper.

One-day session. Before the Workshop, all participants will be asked to create a 10-minute presentation with their current work and results. The presentations will be held at the beginning of the day in order to show the state of the science on CO_2 seeps. The working methodology is:

1) Presentation of participant's research and results.
2) Presentation of general guidelines of the content of the synthesis paper.
3) Separate in work groups to modify/improve the proposed guidelines.
4) Presentation of work groups' ideas.
5) Brainstorming to define the structure and content of the synthesis paper.
6) Designation of a Synthesis Paper Coordinator.
7) Design a follow-up plan to develop the paper.

Goal for ToR 3 at this meeting.- Design research strategies, with general and specific objectives, plus methodology, for a peer-reviewed perspectives article.

One-day session. Based on the expertise and interest of each participant, the attendees will be separated in small work groups to design research strategies and perspectives with emphasis on each of the ToR's scopes. The working methodology is:

1) Separate in work groups to design research strategies for each experimental focus.
2) Presentation of work groups ideas.
3) Brainstorming to define final content of each approach.
4) Designation of 3 Research Strategy coordinators, one per topic.
5) Define collaborators for each Research Strategy.
6) Design a follow up plan to develop each Research Strategy.

Goal for ToR 4 at this meeting.- Planning of Capacity building event.

One-half day will be devoted to this goal, discussing the following topics:

1) Decide what capacity will be built at the following year's meeting.
2) How it will be test/use the best practices manual.
3) How funding will be raised for the event.

Goal for ToR 5 at this meeting.- To create a draft with the structure of the Best Practices handbook.

One-day session. Before the Workshop, all participants will receive a document with bullet points and a tentative structure of a Best Practices handbook, plus reference material. The working methodology is:

1) Presentation of general guidelines of the content of the Best Practices handbook.
2) Separate in work groups to modify/improve the proposed guidelines.
3) Presentation of work groups ideas.
4) Brainstorming to define final content of the Best Practices handbook.
5) Designation of Best Practices handbook chapter leaders and teams.
6) Design a follow-up plan to develop the Best Practices handbook.

Year 2.- February 2021

The second meeting of the group will be held in Dominica in February 2021. The meeting will address ToRs 2, 4, and 5. In particular, ToR 4 will be addressed through a special capacity building event to be done at the same time (see capacity building section below).

Goal for ToR 2 at this meeting.- Finalise the synthesis paper.

The document started during the previous year will be approved by all Working group members and submitted for review. A half-day session will be devoted to a final check of the synthesis paper.

Goal for ToR 4 at this meeting.- Conduct a training activity focused on the use of CO_2 seeps for ocean acidification studies (see capacity building section below).

Goal for ToR 5 at this meeting.- Review, based on field activities, the Best Practices handbook.

Two sessions, one before and one after the capacity building event, will be carried out to discuss the methods and content of the document. The Best Practices Handbook Chapter leaders and teams will review the work carried out and will propose improvements on the document.

Year 3.- February 2022

The closing meeting of the group will be held in Barcelona for face-to-face interactions, and dial in using Zoom. The meeting will address ToR 5 in detail.

Goal for ToR 5 at this meeting.- Final review of the content, structure and final agreement on the Best Practices handbook.

Two and a half day session. Before the Workshop, all participants will receive the latest draft of the Best Practices handbook. The working methodology is:

Day 1.- Mini symposia

1) Presentation of the current content of the Best Practices handbook.
2) Presentation of research results of the "road test" of the Best Practices handbook done at the Capacity building event, as well as research conducted by the participants in the previous 2 years.

Day 2.- Work groups and brainstorming

1) Separate in work groups to modify/improve the proposed methodologies.
2) Presentation of work groups' ideas in a plenary session.
3) Brainstorming to define final content of the Best Practices handbook.

Day 3.- Half day

4) Summary of the 2 previous days' work.
5) Discussion of a potential follow-up plan of InterSEEP.
6) Closing remarks of the Working Group.

Deliverables.

1. ToR 1

Open-access resource of temporal-space data variability created in the *Earth System Science Data* journal to secure accessibility. It will include gas parameters, water

parameters, substratum parameters, microbes, meiofauna, plankton, macroalgae, sessile and mobile macrobenthos, and demersal and pelagic fish.

2. ToR 2.

- Synthesis paper to be published in a peer-reviewed journal: reanalysis of datasets mentioned above, focusing on the most relevant aspect (building on preliminary work on the effects of ocean acidification on ecosystem functioning and services[7]).

3. ToR 3.

- A peer-reviewed perspectives article on future seep research with conceptual models of key future global experiments. A key legacy of this Working Group will be to create a roadmap of globally replicated experiments at CO_2 seeps a reality, focused on socially and economically important aspects of coastal services to mankind. The OA research community can use these perspectives as a basis to design and submit new research projects to funding agencies as Horizon Europe, a €100 billion research and innovation programme that will succeed Horizon 2020, the Environmental Restoration and Conservation Agency from Japan (ERCA), the Japan International Cooperation Agency and NOAA's Ocean Acidification Program, if possible.

4. ToRs 4-5.

- Road test our draft of the Best Practices Handbook during the Capacity Building activity in 2021. Then with input of all the participants finalize a guide of best practices on Ocean Acidification research in CO_2 seeps. In the OA and multiple stressors field there are set of best practices recommendations for laboratory studies that we as a community can augment for field-based approaches. Current CO_2 seep research is uncoordinated and uses disparate experimental designs that make comparisons of results and conclusions difficult. A best practice manual, tailor made for analogues of future ocean conditions, is crucial to be able to integrate results and draw conclusions of global significance.

Capacity Building

Our training activity will focus on the use of CO_2 seeps for ocean acidification studies, and will be held in February 2021.

The aim of the workshop is to provide an opportunity for training as well as data collection. A major goal of the workshop will be to educate a new cohort of young scientists from developing countries to the opportunities available to apply their techniques to natural CO_2 gradients to scale-up from laboratory studies and improve predictions about the long-term effects of CO_2 on coastal ocean system functioning.

The training activity will consist on theoretical and review lectures in the mornings about the chemical and physical effects of volcanic marine seeps, the use of natural analogues for high-CO_2 conditions, physiological experiments at CO_2 seeps and work to date on the use of low pH/low saturation states in natural settings. These will be followed by practical field sessions in the afternoons on the intertidal and subtidal coastal ecological shifts along CO_2 gradients, physiological in situ experimentation, pelagic sampling and boat-based water chemistry monitoring plus the deployment of a range of loggers to monitor the system. A total of 12 early-career scientists willing to work on those ecosystems back at their home countries are expected to participate.

During this training course the participants will be trained in different aspects of OA research as:

- Standard measurements for carbon system parameters, including analytical chemistry techniques,
- The use of stable isotopes as a major tool in food web analysis in the framework of OA research,
- In-situ sample collection in a CO_2 seep for chemical and biological analysis,
- And the study of benthic community structure and functioning under the influence of high CO_2 conditions.

Upon completion of the training course, participants will have gained increased knowledge in the different issues involved in the training and experimental activities, and they will be able to:

1. Monitor basic carbonate chemistry, including detailed methodology for collecting samples, measurements of potentiometric pH and total alkalinity (TA), the use of certified reference materials, and specific challenges related to each method.
2. Understand what ancillary seawater measurements are needed, and at what accuracy to calculate all the parameters of the carbonate system in seawater (i.e.,

temperature, salinity, nutrients, barometric pressure), as well as to know what algorithms can be used as proxies for aragonite and calcite saturation state in field studies.

3. Collect and pre-treat seawater samples and biological samples for isotopic analysis, explore data management and interpretation.

4. Analyse the relationship between seawater carbonate chemistry and benthic community structure in enriched-CO_2 sites, in order to evaluate potential impact of high pCO_2 conditions on ecosystem functioning.

To fund this activity support proposals will be submitted to The Ocean Foundation (TOF), and to the International Atomic Energy Agency (IAEA) Technical Cooperation project INT7019 “Supporting a Global Ocean Acidification Observing Network – towards Increased Involvement of Developing States”; both of which support training initiative in OA research.

Working Group composition

Full Members

Name	Gender	Place of work	Expertise relevant to proposal
1 Cristina Linares	Female	Associate Professor at the Department of Evolutionary biology, Ecology and Environmental Sciences, University of Barcelona, Spain.	Her research focuses on the study of the structure and dynamics of coastal benthic communities and their response to global change
2 Jason Hall-Spencer CO-CHAIR	Male	Professor of Marine Biology. School of Biological and Marine Sciences, Faculty of Science and Engineering. UK.	Seamount ecology , fisheries , ocean acidification, aquaculture and conservation. Fieldwork sites are currently at volcanic CO_2 seeps in the Mediterranean and off Japan.

3 Katharina Fabricius	Female	Senior Principal Research Scientist, Australian Institute of Marine Science (AIMS), Australia.	Coral reefs processes (ranging from ecophysiology to macro-ecology), understanding the effects of cumulative impacts from chronic and acute disturbances, CO_2 seeps, ecosystem resilience.
4 Haruko Kurihara	Female	Assistant Professor, Department of Chemistry, Biology, and Marine Science, University of the Ryukyus, Japan.	Research focus on risk assessment and management of ocean acidification impacts on Japan's coastal habitats and fisheries
5 Rafael Bermúdez CO-CHAIR	Male	Researcher-Lecturer at Galapagos Marine Research and Exploration Program (GMaRE), Ecuador.	Research focus on the effect of Ocean Acidification in the biomolecular composition of primary producers and its concomitant influence in food webs.
6 Riccardo Rodolfo Metalpa	Male	Researcher at ENTROPIE - Écologie marine tropicale des océans Pacifique et Indien, Institute of Research for Development. France.	Research focus on coral reefs, global change, ocean acidification, coral calcification, coral physiology,
7 Salvatrice Vizzini	Female	Professor of Ecology, Università degli Studi di Palermo, Consorzio Nazionale Interuniversitario per le Scienze del Mare-CoNISMa, Italy.	Research activity is focused on the ecology of coastal environments with particular attention on trophic ecology using stable isotopes and fatty acids as trophic markers

8 Sam Rastrick	Male	Associate Research Professor, Research Group of Benthic Habitats and Shellfish, Institute of Marine Research, Norway.	Research focus on the use of physiology to explain the ecological distribution, both temporal and spatial, of species important to both ecosystem function and services.
9 Sylvain Agostini	Male	Assistant Professor. Shimoda Marine Research Center, University of Tsukuba, Japan.	Research activity is focused on the eco physiology of hermatypic corals in temperate and tropical zones.
10 Vanessa Yepes-Narvaez	Female	Marine and Coastal Research Institute INVEMAR, Santa Marta, Colombia.	Ecology, taxonomy, distribution and population genetics of marine deep and shallow bryozoans in the Atlantic Ocean

Associate Members

Name	Gender	Place of work	Expertise relevant to proposal
1 Christopher Cornwall	Male	Victoria Wellington University, Wellington, New Zealand	Research focus on examine how macroalgal dominated ecosystems function today and how this will be altered by future ocean acidification in the context of variability in the

			environment (e.g. pH, water motion and light)
2 Derek Manzello	Male	Researcher, Ocean Chemistry and Ecosystems Division, NOAA's Atlantic Oceanographic and Meteorological Laboratory, USA	Research focus on how climate change and ocean acidification will, and already are, affecting the construction (coral growth, calcification) and breakdown (bioerosion, dissolution) of coral reefs, as well as the associated ramifications this has for ecosystem function
3 Marco Milazzo	Male	Professor of Ecology, Università degli Studi di Palermo, Italy	Research interests on impacts of humans on marine ecosystems, biological invasions, and marine reserves.
4 Lucia Porzio	Female	PostDoc at Stazione Zoologica Anton Dohrn, Italy	Research focus on the study of anthropogenic pressures and the impacts they cause on macrophytes and on their biodiversity.
5 Yu-Shih Lin	Female	Assistant professor, Department of Oceanography, National Sun Yat-Sen University	Biogeochemistry and isotope geochemistry in CO_2 vents
6 Melissa Chierici	Female	Principal scientist at the IMR in Tromsø, Norway	Chemical oceanography focusing on carbon cycle, biogeochemical processes, ocean acidification, sea ice chemistry, water mass distribution, polar ocean.

Working Group contributions

Cristina Linares.- Associate professor from a developed country. Expertise on the study of the structure and functioning of temperate benthic ecosystems and their response to

global change and CO_2 seep research affecting mesophotic communities in Columbretes Islands (NW Mediterranean Sea)

Jason Hall-Spencer.- Senior researcher from a developed country. Expertise on laboratory studies, mesocosms and CO_2 seep research in the Mediterranean, the Azores, Papua New Guinea, China and Japan. Helped organise a previous training workshop on seeps in Italy

Katharina Fabricius.- Senior researcher from a developed country, ongoing collaborative research in developing countries. Coral reef ecologist, with strong focus on using field settings as natural laboratories. Her interdisciplinary CO_2 seeps project in Papua New Guinea has involved ~50 collaborators from over 20 nations to date.

Haruko Kurihara.- Assistant professor from a developed country. Research focus on risk assessment and management of ocean acidification impacts on Japan's coastal habitats and fisheries

Rafael Bermúdez.- Junior Professor from a developing country. Expertise on food webs under ocean acidification conditions. Researcher at the newly found seep at Galapagos. organized previous training on seeps in Ecuador.

Riccardo Rodolfo Metalpa - Researcher from a developing country. Working on coral reefs and other calcifier organisms at CO_2 seep from 2008. Laboratory mesocosms, CO_2 seep and extreme environments in the Med, Papua New Guinea and New Caledonia.

Salvatrice Vizzini.- Senior researcher from a developed country. Expertise on effects of ocean acidification on trophic interactions and benthic communities and processes in CO_2 seeps. Organised previous training on seeps in Italy.

Samuel Rastrick.- Associate research professor in marine ecophysiology form a developed country. Expertise in laboratory, mesocosm and natural analogue studies e.g. CO_2 seeps in Mediterranean, Japan and the Caribbean. Develops traditionally laboratory based methods for use in the field. Chairs an international WG exploring using natural analogies to investigate CC in Arctic ecosystems. Organised previous training on seeps in Dominica.

Sylvain Agostini.- Assistant professor from a developed country in Asia. Expertise on the ecological and physiological effects of ocean acidification on corals and other marine organisms. Researcher at the CO_2 seeps in Japan.

Vanessa Yepes-Narvaez.- Junior researcher from a developing country. Research focus on ecology, taxonomy, distribution and population genetics of marine deep and shallow bryozoans in the Atlantic Ocean with emphasis in seep sites in the Caribbean sea.

Relationship to other international programs and SCOR Working groups (max. 500 words)

The Ocean Foundation (TOF) is a community foundation with a mission to support, strengthen, and promote organizations dedicated to reversing the trend of destruction of ocean environments around the world. In parallel, the International Atomic Energy Agency (IAEA) has the Technical Cooperation project INT7019 "Supporting a Global Ocean Acidification Observing Network – towards Increased Involvement of Developing States"; InterSEEP aims to partner with TOF and the IAEA in order to promote Ocean Acidification research on natural CO_2 seep systems on developing countries as a model for predictive future ocean scenarios. InterSEEP also aspires to become a Special Hub (in contrast to Regional Hubs) within the Global Ocean Acidification Observing Network (GOA-ON) in order to promote OA research in Seep sites around the globe.

This proposed group fits perfectly within SCOR's scope on Ocean Carbon Working Groups. It is novel as it focuses on observations of biological responses of Ocean Acidification using the complex marine communities found around natural seeps. InterSEEP is also a timely update to the Working Group 104 "Coral Reef Responses to Global Change: The Role of Adaptation" which published its last report 20 years ago. Additionally, InterSEEP will potentially expand the application of the newly developed tool, created by the Working Group 149, for experiments related to Ocean Acidification and multi-stress factors in laboratory experiments, in order to use it in natural field seep conditions. Additionally the group will link with the Integrate Marine Biosphere Research (IMBeR) in order to help in answering some of the tasks of their Ocean Acidification group as for instance the promotion of international experiments. Also will contact the International Oceanographic Data and Information Exchange group (IODE) of the Intergovernmental Oceanographic Commission" to help in the diffusion of the scientific outcome of the group. Furthermore, following the steps of SCOR/InterRidge Working Group 135 on Deep Sea Hydrothermal systems, InterSEEP will bring together CO_2 seep researchers worldwide to address important issues to improve and coordinate global research.

Key References

1. Boyd, P. W. *et al.* IPCC WGII AR5 Chapter 6. (2014).

2. Oliver, E. C. J. *et al.* Longer and more frequent marine heatwaves over the past century. *Nat. Commun.* 1–12 (2018).

3. Gattuso, J.-P. *et al.* Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. *Science (80-.).* 349, aac4722 (2015).

4. Riebesell, U. & Gattuso, J. Lessons learned from ocean acidification research. *Nat. Clim. Chang.* 5, 12–14 (2015).

5. Wernberg, T. *et al*. A decade of climate change experiments on marine organisms: Procedures, patterns and problems. *Glob. Chang. Biol.* 18, 1491–1498 (2012).

6. Kroeker, K. *et al*. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* 13, 1419–34 (2010).

7. Hall-Spencer, J.M. & Harvey, B.P., (2019) Ocean acidification impacts on coastal ecosystem services due to habitat degradation. *Emerging Topics in the Life Sciences* 3, 197-206.

8. Pessarrodona, A. *et al*. Carbon assimilation and transfer through kelp forests in the NE Atlantic is diminished under a warmer ocean climate. *Glob. Chang. Biol.* 24, 4386–4398 (2018).

9. Hall-Spencer, J. M. *et al.* Volcanic carbon dioxide seeps show ecosystem effects of ocean acidification. *Nature* 454, 96–9 (2008).

10. Vergés, A. *et al.* Long-term empirical evidence of ocean warming leading to tropicalization of fish communities, increased herbivory, and loss of kelp. *Proc. Natl. Acad. Sci.* 113, 13791–13796 (2016).

11. Fabricius, K. E. *et al.* Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. *Nat. Clim. Chang.* 1, 165–169 (2011).

12. Munday, P. *et al*. Behavioural impairment in reef fishes caused by ocean acidification at CO_2 seeps. *Nat. Clim. Chang.* 4, 487–492 (2014).

13. Tarasov, V. G., *et al*. Deep-sea and shallow-water hydrothermal seep communities : Two different phenomena ? *Chem. Geol*. 224, 5–39 (2005).

ANNEX 1.- Five more relevant publications of the Full Members

Cristina Linares.-

1. Exploring the oxygen and carbon isotopic composition of the Mediterranean red coral (Corallium rubrum) for seawater temperature reconstruction (2016)
   S Chaabane, ML Correa, P Montagna, N Kallel, M Taviani, C Linares, *et al.*
   Marine Chemistry 186, 11-23

2. Experimental evidence of the synergistic effects of warming and invasive algae on a temperate reef-builder coral (2015)
   DK Kersting, E Cebrian, C Casado, N Teixidó, J Garrabou, C Linares
   Scientific reports 5, 18635

3. Persistent natural acidification drives major distribution shifts in marine benthic ecosystems (2015)
   C Linares, M Vidal, *et al.*
   Proc. R. Soc. B 282 (1818), 20150587

4. Harvesting effects, recovery mechanisms, and management strategies for a long-lived and structural precious coral (2015)
   I Montero-Serra, C Linares, M García, *et al.*
   PloS one 10 (2), e0117250.

5. Rapid recovery from injuries in the temperate long-lived coral *Cladocora caespitosa* (2015)
   C Casado, DK Kersting, E Cebrian, N Teixidó, J Garrabou, C Linares
   Marine Biodiversity 45 (1), 135-137

Jason Hall-Spencer.-

1. Ocean acidification can mediate biodiversity shifts by changing biogenic habitat (2017)
   JM Sunday *et al.* including JM Hall-Spencer
   Nature Climate Change, 7, 81-85

2. Effects of ocean acidification on marine photosynthetic organisms under the concurrent influences of warming, UV radiation and deoxygenation. (2019)
   K Gao *et al.* including JM Hall-Spencer
   Frontiers in Marine Science 6, 322 doi: 10.3389/fmars.2019.00322

3. Changes in the biochemical and nutrient composition of seafood due to ocean acidification and warming (2019)
   AJ LeMasson, JM Hall-Spencer *et al.*
   Marine Environmental Research, 143, 82-92

4. Changes in fish communities under ocean acidification conditions (2020)
   C Cattano *et al.* including JM Hall-Spencer
   Science of the Total Environment 725, 138501
   doi.org/10.1016/j.scitotenv.2020.138501

5. Decreased motility of flagellated microalgae long-term acclimated to CO_2-induced acidified waters (2020)
   Y Wang et al. including JM Hall-Spencer
   Nature Climate Change (*in press*)

Katharina Fabricius.-

1. Classification and regression trees: a powerful yet simple technique for ecological data analysis (2000)
   G De'ath, KE Fabricius.
   Ecology 81 (11), 3178-3192

2. Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations (2011)
   KE Fabricius, C Langdon, *et al.*.
   Nature Climate Change 1 (3), 165

3. Declining coral calcification on the Great Barrier Reef (2009)
   G De'ath, JM Lough, KE Fabricius
   Science 323 (5910), 116-119

4. Declining coral calcification in massive Porites in two nearshore regions of the northern Great Barrier Reef (2008)

TF Cooper, G De'Ath, KE Fabricius, JM Lough
Global Change Biology 14 (3), 529-538

5. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef (2005)
   K Fabricius, G De'ath, *et al.*
   Marine pollution bulletin 51 (1-4), 384-398

Haruko Kurihara.-

1. Ocean acidification impacts in select Pacific Basin coral reef ecosystems (2019)
   M Lebrec, S Stefanski, R Gates, S Acar, Y Golbuu, A Claudel-Rusin, H Kurihara, *et al*.
   Regional Studies in Marine Science, 100584

2. Effects of CO_2-driven ocean acidification on the early developmental stages of invertebrates (2008)
   H Kurihara
   Marine Ecology Progress Series 373, 275-284

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