Studying Worldwide Impacts of Calcification Trends on CHanging Climate

SWITCH

Working Group proposal submitted to SCOR, May 2023

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1. Summary/abstract

Ongoing fossil fuel burning affects the flow of carbon between the air, ocean, soils and biosphere and results in global warming, rising sea levels and acidifying and deoxygenating oceans. Climate models predict the consequences of rising greenhouse gas concentrations and guide measures to keep global warming under control[1]. The uncertainties associated with those models' outcomes are largely resulting from an incomplete understanding of the (biological) feedbacks within and between the various carbon sinks and sources[2,3]. Among such feedbacks, those in the ocean may have a particularly large effect on carbon cycling due to the size of marine carbon reservoir. In particular:

An integrated understanding of marine calcification is of crucial importance to understand the future of the marine carbon cycle and ocean-based solutions. This proposal aims at this by integrating across the regions, disciplines, combining observations, modelling and experimental approaches. This can only be achieved by an interdisciplinary and international collaboration, ideally as a SCOR working group.

Field studies and laboratory experiments have indicated different and even opposing trends in the response of marine calcifiers under multiple stressors[4,5]. This may well reflect the multiple, independent evolutionary developments of marine calcification[6]. This in turn, may mean that the mechanisms by which organisms form their calcium carbonate differs among taxa, and likely so does their sensitivity to carbon chemistry perturbations. **This working group is dedicated to compare calcifying organisms and integrate knowledge on the basic mechanisms that are responsible for $CaCO_3$ precipitation and the implications for the global carbon export.**

2. Scientific background/rationale

The oceans are the largest sink of active carbon and play a crucial role in modulating atmospheric CO_2 levels[6]. An important component of the cycling of carbon within the oceans is ocean carbon export, in which the poorly understood and constrained process of marine calcification plays an important role[7-11]. The relation between dissolved carbon and calcification works in both directions: calcification generates CO_2 and is also directly affected by the amount of dissolved bicarbonate/ carbonate in the ocean[12]. The uptake of carbon by calcifying organisms, the production of CO_2, the downward transport of the shells/ skeletons and the dissolution of the calcium carbonate are linked in the so-called carbonate counter pump (CCP; figure 1). The magnitude of CCP towards the CO_2 flux back to the atmosphere may be limited compared to continued CO_2 uptake by the ocean from the atmosphere, but the role of calcification may be exacerbated with reduced transport of organic carbon (the biological pump, or organic carbon pump) to the seafloor by so-called ballasting effect of $CaCO_3$ structures[13-15]. Furthermore, changes in the pelagic community composition due to multiple stressors may change the total amount of calcification and hence the strength of the CCP[4]. Ultimately, this will affect the overall carbonate budget[16], as is reflected in outcomes of models[9,17,18] estimating a reduction in marine CO_2 uptake ranging from ~6 to ~35 Ct carbon by the end of the next century. The variability in these estimates is mainly caused by an uncertainty in the response of (pelagic) calcification to increased dissolved carbon dioxide[4]. Such changes might also have important repercussions on the Marine Carbon Dioxide Removal (mCDR) strategies, most notably on the ocean alkalinity enhancement (OAE).

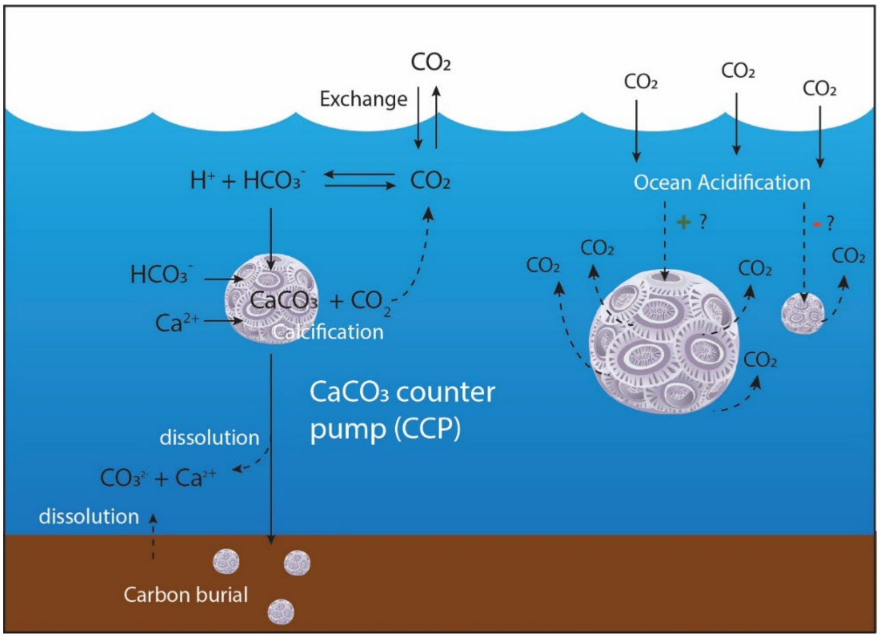

Figure 1: the role of the $CaCO_3$ pump and counter pump in exporting marine inorganic carbon. The production of pelagic shells (here conceptually depicted by coccolithophores) and subsequent sinking, transports carbon to the deep. In the surface, the process of calcium carbonate precipitation produces CO_2, shifts the alkalinity and alters the uptake rate of atmospheric CO_2. On their way to the seafloor, as well as within the sediment, part of the precipitated shells dissolve and return inorganic carbon to the marine inorganic carbon inventory. The effect of adding CO_2 to the ocean surface (ocean acidification) is indicated right: the effect may be positive, with additional CO_2 production, or negative and reduces the CO_2 production. The same basic mechanisms apply to (shallow) benthic calcifying organisms (corals, bivalves, gastropods, etc.) and other pelagic calcifiers (foraminifera, pteropods), but those are omitted here for clarity.

In (sub)polar regions, shells produced by coccolithophores, foraminifera and pteropods have the collective power to transport organic and inorganic carbon from the surface downward and subsequent long-term burial at great depths[19,20]. Since the downward flux is larger than the rate at which the alkalinity can 'replace' the carbon by upwelling, calcification can act in these regions as an alkalinity trap, which potentially a global impact on carbon cycling[21]. Other reports have identified region-wide variability in the ratio of downward inorganic to organic carbon fluxes and a seasonal variability therein[22].

Ocean acidification can either stimulate[23,24] or hamper calcification[25-34]. Atmospheric CO_2 uptake lowers the saturation state of surface seawater and is traditionally used as an explanation for reduced calcification by a decrease in the availability of carbonate ions. A lower saturation state will also make $CaCO_3$ structures prone to dissolution. This can happen at the seafloor due to shallowing of the lysocline[35,36] or through a lowered energy cost for bioeroding organisms to reach undersaturation[37,38]. In addition to a lowered saturation state, the total amount of dissolved inorganic carbon (DIC) increases with ongoing CO_2 uptake and calcifiers that manipulate the pH of the calcifying fluid may benefit from the increased carbon availability. For the latter category of organisms this would imply a trade-off since (increased) proton pumping costs energy and may explain the CO_2 optimum often seen in the response of marine organisms[39], but with clearly identified variability and diverse responses (figure 2).

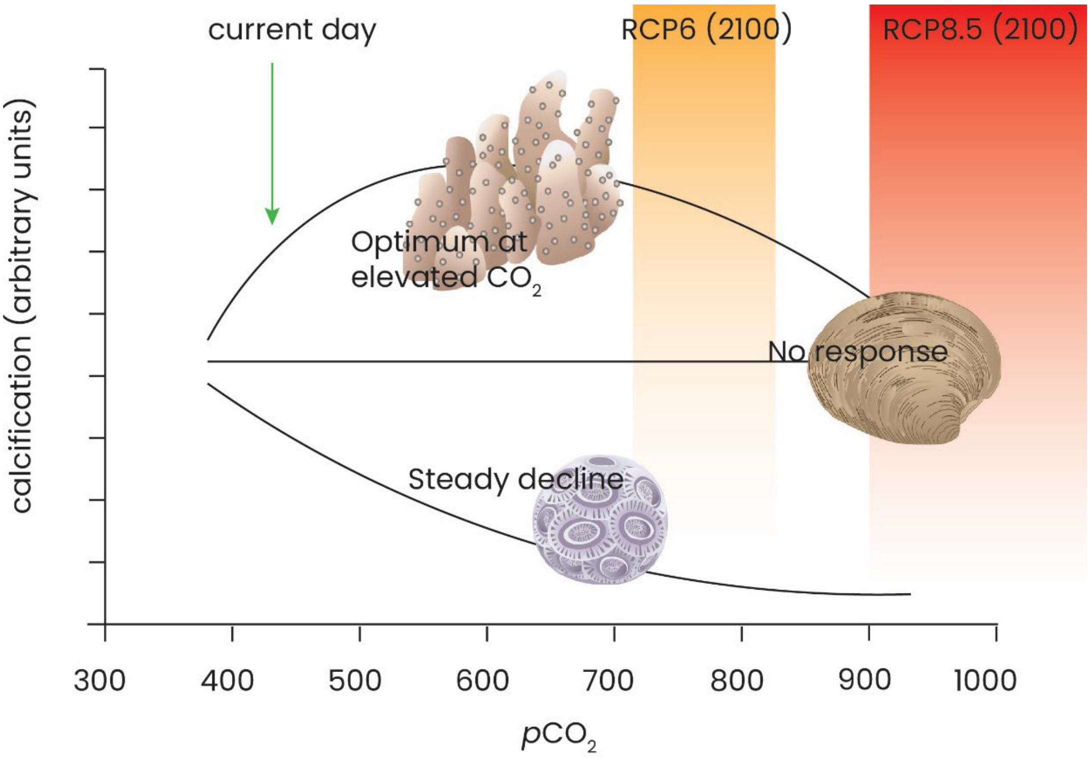

Figure 2: Hypothetical responses of three calcifiers to elevated CO_2 concentrations. Some species have been reported to have an optimum CO_2, higher than then that of the current day, at which they calcify most. Other species decrease their calcification when subjected to higher carbon dioxide levels and calcification in some species do not respond (noticeably) to increased CO_2.

So far, there is no integrated framework for marine calcification and dissolution, their role in CCP and its response to multiple stressors. This WG specifically aims to 1) bring together biological knowledge on all major calcifying groups, identify 2) how and why different organisms respond differently to increased CO_2/ OA and 3) develop a framework for calcification that can be included in models for global carbon cycling as well as for considerations and modelling of OAE.

The activities of SWITCH will address these issues will be based on four overarching questions:

Q1 What are the common cellular mechanisms involved in calcification? Calcification mechanisms are taxon-specific and mostly depend on the degree of control that the organisms exert on this process. This process is also tightly linked to other physiological characteristics such as photosynthesis (in e.g. CCA and corals). However, it may be possible to identify common mechanisms promoting $CaCO_3$ precipitation. Such mechanisms likely include increasing pH at the site of calcification and facilitation of calcification by specialized proteins. The compilation of data on the calcification mechanisms across taxonomic groups and the identification of similar mechanisms is necessary to better understand and assess how small changes in OA can significantly affect some, and not other, organisms.

Q2 How to measure calcification? Comparison of calcification rates is challenging since they both can be expressed in many ways, often related to growth, extension, surface area and is often monitored differently across calcifying groups and studies. In addition, there is a variety in experimental procedures when studying CO_2-related changes and there is a large gap between these experiments and field studies (i.e. where co-correlating factors act simultaneously, but where organisms may be better adapted than in the laboratory).

Q3 How to measure dissolution? Similar to calcification, dissolution of various $CaCO_3$ structures is variable and lacks a (conceptual) framework that accommodates the biological diversity in shells and skeletons. Secondly, dissolution takes place in different environments (e.g. at the seafloor, in the water column, by bioerosion) that needs to be considered when formulating an overall response of dissolution due to changes in increased CO_2.

Q4 What is the net, global calcification response? This requires bridging the gap from laboratory-based CO_2 manipulation studies to field surveys (Q1-3). It also requires to relate insights from the smallest scale (e.g. identification of the genes involved in calcification) to estimates on region-wide $CaCO_3$ production (e.g. from sediment trap time series). The region- or basin-wide responses are ultimately a function of the mechanisms employed by pelagic and benthic calcifiers.

Q5 How does this affect model outcomes? With the answers to Q1-4, it will be possible to pinpoint the role and contribution of calcification and dissolution to the marine carbon cycle, with special emphasis on the current and future contributions under climate change. By extension, this focus of SWITCH will play a role in efforts of CO_2 uptake via OAE. This may draw down extra CO_2 from the atmosphere by increased total alkalinity and buffering, but increased calcification by marine organisms may partly offset the efficiency of OAE.

2. Terms of reference (ToR)

The five overarching questions each define their own ToR:

ToR1. Review mechanisms and patterns of calcification. Grouping organisms according to their responses to global change scenarios in a database. This will allow guide future research on critical unknowns in our understanding of calcification mechanisms. This will also help to identify 'response groups' that may be included in models.

ToR2. Review methods of measuring calcification in the laboratory and the field. Identify requirements regarding organism size, lifespan, time to observe changes in biomineralization, etc. This will provide guidelines for future research and allow integration of results. We aim to suggest realistic scenarios of climate changes that should be tested and will aid formulation of what data is required for modelling calcification in the context of CCP.

ToR3. Identify whether shells and skeletons all dissolve at similar rates and under similar conditions. Since a combination of mineral phases may also determine dissolution rates[40], it is necessary to investigate knowns and unknows of dissolution kinetics of biogenic $CaCO_3$ structures.

ToR4. Provide expert guidance in using general calcification sensitivities for implementation in global carbon cycle modelling and testing for the efficiency of the OAE mitigation efforts. Validate this by using models through testable hypotheses. This will be extended by including a synthesis of the dissolution kinetics.

ToR5. Foster a multidisciplinary scientific community with a focus on capacity building, global synthesis of calcification and dissolution responses to global ocean changes and continued collaboration on these processes in relation to marine carbon cycling.

4. Working plan.

The five ToR's directly translate into a working plan (WP1-5). The first the two ToR's will be tackled by a working plan that is extensive enough to have them divided over two approaches.

Working Plan-1a. We will review the literature and discuss taxon-specific calcification mechanisms and patterns to build a relevant and robust database for calcification and dissolution. The focus will be on the six groups of marine calcifying organisms that contribute most to the global cycling of carbon: foraminifera, coccolithophores and pteropods for the open ocean and corals, bivalves and crustose coralline algae for the (tropical) shallow benthic habitats. This will be the first of the two main topics to focus on in the first dedicated meeting in the Netherlands that will take place (beginning of year 1). Other calcifiers (sponges, bacterial mats., etc.) may be discussed and added to the database as the WG continues its activities beyond the first meetings.

Working Plan-2a. Based on the activities related to ToR1, we will identify uncertainties in mechanisms and the obtained rates and develop a framework to integrate insights from diverse scales. Acknowledging differences between taxa and scales should not prevent an overall, net estimation of calcification in a changing world. Drafting a 'route map' for such an integrated framework is the task of a dedicated thematic team, which will be reviewed and discussed by all WG members before being made public (planned for the second year). Likely, this will take place during a meeting aligned with an international conference attended by many of the (associate) members like EGU general assembly, AGU fall meeting or an Ocean Sciences meeting (to be determined). The choice for such a meeting (no 2 and 3 in figure 3) will also be based on the accessibility of researchers from developing countries, including those not formally part of the listed (associate) members. This will then also provide the opportunity to perform part of the capacity building (see 6) in these developing countries.

Working Plan-2b. The WG will fully evaluate the analytical procedures when measuring calcification and dissolution in the laboratory, and in the field. Issues of adaptation, evolution and ecology will be discussed too to integrate differences in organism size, growth form, biomineral composition and taxonomic and environmental impact on the calcification mechanisms. Standard procedures to quantify changes in biomineral composition (density, mineral phase, deformations), recommendations for experimental durations and set-up of realistic acidification scenarios in the laboratory will be evaluated. Ideally, guidelines to make laboratory experiments relevant for realistic climate change scenarios will be proposed. This will be the second topic to focus on during the initial meeting.

Working Plan-3. Within SWITCH, we will discuss dissolution kinetics of the various shells and skeletons based on the mineral phase, chemical composition, porosity, morphology and presence of organic compounds. With a special emphasis on differences between taxa, this may lead to defining ‘response groups’ regarding dissolution differently from the current classification.

Working Plan-4. Models that include a carbon component need to be equipped with sensitivities, preferably region- and habitat-specific, of calcifying organisms. Within the plan related to T1, special emphasis will be on the identification of the ‘response groups’. The demise or persistence of certain groups as a function of ongoing acidification may compromise the use of a single, CO_2-calcification response in such models. Development of ‘response groups’ that may be particularly relevant for incorporation in biogeochemical models that are directly integrated in (global) climate models and can explore the consequences for the carbon pump as well as OAE mitigation scenarios.

Working Plan-5. Incremental improvement of models by incorporation of new experimental data and mechanistic understanding of carbonate biomineralization to predict changes in the global C-cycle due to changes in calcification. Testable hypotheses should be formulated based on predictions of the developed models.

These activities, partly overlapping in time, will take place over a four-year period (figure 3).

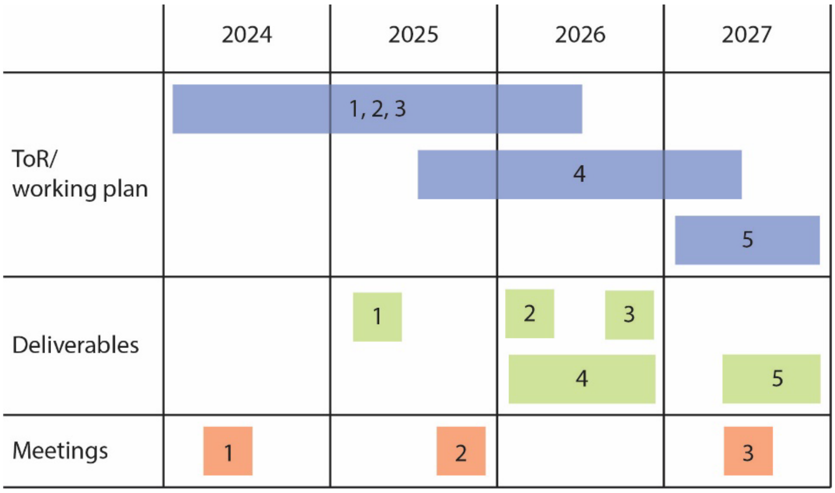

Figure 3: The four-year planning for SWITCH.

5. SWITCH Deliverables

The 5 ToR's and related working plans will result in five deliverables (D1-D5):

D1. A review paper on calcification across marine taxa, including a review on how to measure organismal- and community-level calcification. This will also contain a standard for measuring calcification (ToR1 and ToR2) and identified knowledge gaps.

D2. A database on current-day calcification, including experimental and field data. This will guide investigations of crucial, but missing, sensitivities of taxon-specific responses to ocean acidification (ToR2).

D3. A peer-reviewed paper on the status of dissolution of various marine calcifiers (ToR3). This will identify whether modeling of dissolution process needs to account for which $CaCO_3$ shells or skeletons are dissolving and under what conditions they dissolve (ToR3 and ToR4). Incorporating dissolution in models may severely affect the carbonate pump and climate interventions. As for D2, this deliverable will focus on missing knowledge and sensitivities and thereby recommend explicit follow-up studies.

D4. A set of practical recommendations to use the data and recommendations of D1-3 in biogeochemical and climate models. The working plan of this WG proposal will deliver key sensitivities in the marine carbon-climate feedback system (in particular, the CCP). This will build upon the web-based, freely accessible database (D2) that is open to future data on responses of calcification and dissolution to environmental conditions. This will ensure an ever-updated reference for modeling purposes.

D5. A white paper for policy makers (ToR4 and ToR5). The working plan of this WG proposal will deliver key sensitivities in the marine carbon-climate feedback system (in particular, the CCP). For mitigation purposes (e.g. using OAE) such insights may be crucial, especially if our sensitivity studies find that increased the efficiency of alkalinity enhancement might be reduced through increased calcification, making insights directly relevant for future mitigation uses.

6. Capacity building

The four-year activities of SWITCH and the deliverables (D1-D5) are foreseen to have a wider and longer-lasting impact, integrating the knowledge based in the developing countries in the forefront of development. It is our vision that physiological, biochemical and ecological knowledge is of vital importance to global carbon and climate models across various regional scales of various basins. Bridging this gap is one of the fundaments of this proposal and may at the same time, fully develop into education/ outreach activities and capacity building (CB), which will be possible though an international network of collaborators in this proposal. More specifically:

We aim to pass the collected insights, expertise and outcomes to new scientists through collaboration with topic-specific summer schools, with WG members delivering lectures. We will organize a training workshop in conjunction with a WG meeting to be held in a developing country. The content of the workshop will support a synthesis science behind the importance of marine calcification with the integrated observation and modelling interface. This will give an early-career research (ECR) from the developing countries an opportunity to present their research and be actively involved in networking. Alongside, we will develop training material and organize webinars. Furthermore, an active participation and networking will be further supported though a quarterly online webinar on the relevant topics, with the inclusion of ECR and the network of developing country scientists. Timely knowledge and CB are especially significant for the developing countries related to the ocean-based mCDR solutions, which are at the forefront of development and application. Our CB will thus be extended to share the timely knowledge that will support active participation of developing countries in such mCDR developments. With our partners, we will produce informative, user friendly products encompassing the web portal and interactive data access and visualization applications online.

This is further supported by the interaction with ongoing programs (IMBeR, SOLAS) in which members are participating already (see under 8). We are envisioning fostering a strong collaboration with these programs to establish the links between developing countries and ECR networks to have a n enhanced participations and capacity building.

Need and timeliness for a SCOR WG

With the commitment to keep global warming within 1.5-2.0 °C, negative emissions will likely be part of the strategy to mitigate the ongoing rise in atmospheric CO_2 levels. Many recently proposed/ developed techniques make use of the ocean as an effective climate solution. However, the effects of mCDRs are virtually uninvestigated, but will need to be included when calculating the net effect of climate interventions. Capturing inorganic carbon in the form of $CaCO_3$ and subsequent long-term storage could reveal marine calcifiers as an important 'blue carbon' player. A much better understanding of the global carbon cycle, especially of the calcification and CCP that represent the most uncertain feedback loops, is timely and critical because even a small change in calcification rates may affect atmospheric CO_2. SWITCH explicitly considers this potential of marine calcification. To fill this gap in our knowledge, it is necessary to gather and integrate the perspectives of the biological, biogeochemical, climate sciences across spatial and temporal interface. SWITCH brings a new perspective in such synthesis to bridge scales at which calcification and its response to climate change is studied. This spans a large range of processes from genes, subcellular to organismal, population and biogeochemical processes related to ocean export fluxes and feedbacks. This gives this WG a unique standing to deliver timely and robust products with wide-net distribution and archiving. These products can be used by a significantly larger communities that are involved with the ocean-based solutions and climate interventions, such as many start-ups, and organizations (IMBeR, SOLAS, etc.).

7. Working Group composition

SWITCH consists of 10 full members and 10 associate members, with a gender balance of 11 F to 9 M). It also includes 6 early career scientists and a good geographical balance, including members from Asia, Africa and Latin-America. The expertise within the group covers all required competences as listed in the ToRs and the associated work packages.

Full members

Name		Gender	Place of work	Expertise
1.	Lennart de Nooijer (Chair)	M	The Netherlands	Foraminifera
2.	Nina Bednaršek (co-chair)	F	Slovenia	Pteropods, OA
3.	Steeve Comeau	M	France	Corals
4.	Tatiana Ilyina	F	Germany	Carbon modelling
5.	Carmel McDougall	F	Scotland	Molluscs
6.	Karin Kvale	F	New Zealand	Coccolithophores, modeling
7.	Justin Ries	M	USA	Ocean Acidification
8.	Nyssa Silbiger	F	USA	Bioerosion, synthesis
9.	Takashi Toyofuku	M	Japan	Foraminifera
10.	Oliver Voigt	M	Germany	Sponges, genetics

Associate members

Name		Gender	Place of work	Expertise
11.	Linda Barranco	F	Chile	Ocean acidification
12.	Carla Berghoff	F	Argentina	Marine biogeochemistry, C sequestration
13.	Muhammad Dosoky	M	Egypt	Corals
14.	Valeria Ibelu	F	Turkey	Marine chemistry
15.	Yi-Wei Liu	F	Taiwan	Biomineralization
16.	Fanny Monteiro	F	UK	Carbon modeling
17.	Rajani Panchang	F	India	Pteropods, Indian ocean
18.	Olivier Sulpis	M	France	Dissolution, modelling
19.	Sylvie Tambutté	F	Monaco	Corals
20.	Vengatesen Thiyagarajan	M	Hong Kong	Bivalves

Working group contributions (full members)

Lennart de Nooijer (Chair), Royal NIOZ, Texel, The Netherlands.

Biogeochemist, expertise in biomineralization, bio-erosion and trace element incorporation in biogenic calcium carbonate. Experience with applying such element/ isotope calibrations downcore to reconstruct past climate change.

Nina Bednaršek (Co-chair), [1]Cooperative Institute for Marine Resources Studies, Hatfield Marine Science Center, USA and National Institute of Biology, Marine Biological Station, Slovenia.

Biological Oceanographer with an expertise in marine calcification, pelagic calcifiers, pteropods, miultiple stressors across regional and temporal scales. Her research involves integrating modelling, experiments and observations and synthesis science (meta-analyses and threshold analyses).

Steeve Comeau, Sorbonne Université Laboratoire d'Océanographie de Villefranche (LOV).

Is an expert in carbonate chemistry, calcification mechanisms and community metabolism. His research involves the use of a variety of experimental approaches (multi-stressors, manipulations of the carbonate chemistry) and tools (isotopes, raman spectroscopy, etc.) to understand the effects of climate change on the calcification mechanisms of corals and coralline algae.

Tatiana Ilyina, Max Planck Institute, Hamburg, Germany.

Her research interests are ocean biogeochemistry, in particular the carbon cycle, its variability, predictability, and relation to Earth's climate and ocean acidification.

Karin Kvale, GNS Lower Hutt, New Zealand.

Biogeochemical modeller and coccolithophore model developer with expertise in the calcium carbonate counter pump and its interactions with climate and the biological carbon pump.

Carmel McDougall, Scottish Oceans Institute, University of St Andrews, Scotland.

Molecular biologist, expertise in molluscan biomineralisation, transcriptomics, comparative biology. Experience with assessing transcriptomic responses to ocean acidification/ocean warming. Has also worked with calcifying annelids and CCA.

Justin Ries, NorthEastern University, USA.

Works on the interplay between ocean acidification and biomineralization and has revealed that variable responses of marine calcifying organisms to elevated CO_2 levels.

He holds several patents for methods that sequester CO_2 emitted by fossil fuel-fired power plants.

Nyssa Silbiger, Biology department, California State University, Northridge, USA.

Ecologist and applied biogeochemist with expertise in accretion and bioerosion rates of coral reefs and rocky intertidal ecosystems.

Takashi Toyofuku, Japan Agency for Marine-earth Science and Technology, JAMSTEC, Japan.

Research focusses on culturing benthic foraminifera and in-situ (fluorescent) observations on calcifying organisms. His unique live imaging approach and expertise in biomineral formation make him an ideal core member of SWITCH.

Oliver Voigt, Palaeontology and Geobiology, LMU Munich, Germany.

Biologist, expertise in biomineralization of calcareous sponges, especially by means of transcriptomics, proteomics, DNA analysis and RNA in situ hybridization.

8. Relationship to other, international programs

Connection with IMBeR

Our goals and deliverables are in close overlap with the following IMBeR's activities: 1) *Grand Challenge I* on the 'Understanding and quantifying the state and variability of marine ecosystems', identifying how multiple stressors can impact essential biological and biogeochemical processes directly involved in carbon dynamics. 2) Proposed synthetized efforts related to the modelling can support the activities within the *Grand Challenge II* on the 'Improving scenarios, predictions and projections of future ocean-human systems at multiple scales. Finally, sensitivity testing of OAE support the activities in the *Innovation challenge 5* on the 'Interventions to change the course of climate impacts?, explicitly testing for the interventions in the simulation models across the scales, thereby reducing the risk of where climate interventions would be inappropriate or inefficient. Nina Bednaršek, who chairs IMBeR's IC5, will be closely integrating across the both programs for successful deliveries of the goals and objectives.

Other international programs that will be directly connected to SWITCH include the EXPORTS program (https://oceanexports.org/), the Global Ocean Acidification Observing Network (GOA-ON; http://www.goa-on.org/) and the NF-POGO Alumni Network for Oceans (NANO) DOAP-Project: A global study of coastal Deoxygenation, Ocean Acidification and Productivity at selected sites (2017-underway) PI: Subrata Sarker https://nf-pogo-alumni.org/projects/global/. Various full and associate members of SWITCH are involved in these larger projects.

Sylvie Tambutté is involved in DOE-BES-CSGB-Geosciences, Coral Biomineralization. PI: Pupa Gilbert, Grant period September 15, 2021 – September 14, 2024, (DE-FG02-07ER15899), a project devoted to biomineralization and climate change. And Venegasten Thiyagarajan participates in the AUSTRALIAN RESEARCH COUNCIL (ARC) DISCOVERY INDIGENOUS GRANTS (IN). Title: Oyster adaptation to climate change via transgenerational plasticity. Amount:

2,857,701 (period: 2022-2025). Nina Bednaršek has a Slovenian Research Agency (j1 2468) funded project on the ‘Biomarkers of stress in marine calcifiers due to multiple stressors.

In addition, the members host a NERC starting grant (Fanny Monteiro) on coccolithophore calcification (http://gotw.nerc.ac.uk/list_full.asp?pcode=NE%2FX001261%2F1&classtype=Science+Topic&classification=Climate+%26+Climate+Change) and are members of the steering committee of the OA Mediterranean-Hub of Global Ocean Acidification Observing Network (GOA-ON) and the program 'Evaluating the Impact of Ocean Acidification on Seafood – a Global Approach Funding body: International Atomic Energy Agency (IAEA). Funding body: IAEA. Project ID: CRP K41018 (latter two Valeria Ibello). Nyssa Silbiger is involved in the Kavli Frontiers of Science Symposium (Indonesia and Israel).

9. Selected relevant publications of members

Lennart de Nooijer, chair

De Nooijer, L.J., Toyofuku, T., Kitazato, H., 2009. Foraminifera promote calcification by elevating their internal pH. Proceedings of the National Academy of Sciences 106: 15374-15378.

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Nina Bednaršek, co-chair

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Steeve Comeau

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Tatiana Ilyina

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Nyssa Silbiger

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Carmel McDougall

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McDougall, C., Degnan, B.M., 2018. The evolution of molluscan shells. WIRES Developmental Biology e313. (Invited review).

Justin Ries

Ries, J.B., 2011a. A physicochemical framework for interpreting the biological calcification response to CO_2-induced ocean acidification. Geochimica et Cosmochimica Acta 75: 4053-4064.

Ries, J.B., 2011b. Skeletal mineralogy in a high-CO_2 world. Journal of Experimental Marine Biology and Ecology 403: 54-64.

Takashi Toyofuku

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