



LabexMER

"A changing ocean"

LabexMER - Axis 2

Research project 2012-2014

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TABLE OF CONTENTS

1. Axis 2 : Complexity and efficiency of the biological pump	3
1.1. Scientific context, scientific questions, 10-years vision	3
1.1.1. Scientific context	3
1.1.2. Scientific question	4
1.2. Objectives for the next three years and specific actions	4
1.2.1. Objective 1: Investigate the geochemical and ecological controls on the quantity, quality and characteristics of biogenic materials ...	4
1.2.2. Objective 2: Determine the fate of biogenic materials sinking as aggregates and fecal pellets	7

1. AXIS 2 : COMPLEXITY AND EFFICIENCY OF THE BIOLOGICAL PUMP

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List of participating laboratories:

- DYNECO;
- LPO;
- LEMAR.

1.1. SCIENTIFIC CONTEXT, SCIENTIFIC QUESTIONS, 10-YEARS VISION

1.1.1. SCIENTIFIC CONTEXT

Concentrations of total dissolved carbon dioxide are about 20% higher in the deep ocean than in the surface ocean and ocean sediments contain up to several weight percent organic carbon. Were it not for these things, the amount of CO₂ present in the Earth's atmosphere would be significantly higher for the total amount of carbon present in the surface Earth-ocean-atmosphere system. The set of processes that transports particulate organic carbon (POC) to the deep sea and sediments is collectively known as the "biological pump" and includes the primary production of POC, the packaging of POC, via coagulation or other processes, into large, rapidly sinking particles versus its entrainment into marine food webs. With a quantitative understanding of these processes, we could better evaluate the role of the biological pump in the oscillation of atmospheric CO₂ concentrations from 280 ppm to 190 ppm over interglacial and glacial cycles and how the biological pump will respond to (or could be harnessed to sequester) the CO₂ added to the atmosphere by humankind.

At present, there is no consensus on the mechanisms that control the efficiency of the biological pump, something which varies dramatically, both spatially and temporally, at different scales (Boyd and Trull, 2007). Contributing to this lack of understanding is the fact that the complexity of these mechanisms, which reside at the intersection of ocean dynamics, biogeochemistry and ecology, has not yet been successfully incorporated into ocean models which could then be used to test hypotheses and validate experiments. In this project, we will address the complexity involved in the production and export of biogenic materials by working at different scales (from individual particles and organisms up to ecosystems) and combining field studies, experimental and modeling approaches (micro- and mesocosms, Dynamic Energy Budget, inverse modeling, virtual reality). The target to study processes on a scale between field observations and individual laboratory organisms is supported by the program EQUIPEX to establish the necessary experimental infrastructure to perform these tasks. The end goal is to make significant headway with the challenging endeavor of incorporating complexity at the individual level into ecosystem scales models.

Individual life history traits have been poorly accounted for in models, although they play a fundamental role in the quality of the biogenic matter produced by phytoplankton and bacteria, which in turn strongly affects the transfer of carbon to higher trophic levels and to the deep sea. The trade-offs between growth rate, susceptibility to grazing, and sedimentation losses; and the stoichiometric mismatch between phytoplankton and zooplankton in terms of their biomass carbon to nutrient (P, N, Si, Fe) ratio will mainly determine the proportion of production channeled into higher trophic levels. Functional diversity of primary producer communities, arising from individual life histories, affects the resource use efficiency and thereby the amount of carbon which can be fixed by phytoplankton (Striebel et al. 2009). It is known well known that trace metals (Fe, but also, Cu, Mn, Zn, Co, Cd,...) strongly impact the functioning and efficiency of the biological pump (Boyd et al., 2007; Blain et al., 2007; Maldonado et al., 2006; Peers and Price, 2004; Saito et al., 2008), although their sources, sink and internal cycles are still poorly quantified. In light of this, our first objective will be to investigate the ecological controls on the quantity, quality and character of biogenic materials produced in relation to primary production, and

how this quality impacts the export of carbon to the deep sea. This will be achieved through a combination of field work, laboratory and field mesocosm experiments in which we can manipulate the life history traits of organisms, and/or the complexity of the food web.

It is well recognized that interaction between sinking particles (aggregates, fecal pellets) and the organisms that inhabit the mesopelagic layer (100 – 1000 m) strongly determines the depth at which carbon and associated biogenic elements will be remineralized (Ragueneau et al., 2006; Buesseler et al., 2007). However, these interactions are yet poorly known. They depend in part on the quality of the sinking particles, something which evolves with depth due to remineralization processes, and in part on the ecological structure of the mesopelagic zone. Therefore, our second objective will be to determine the fate of biogenic materials sinking as aggregates and fecal pellets by studying degradation processes inside sinking particles and the interaction between these particles and mesopelagic organisms. Degradation experiments will follow stoichiometric changes during degradation (C, N, Si, P...), while interactions with the mesopelagic organisms will be explored through laboratory experiments and the development of a virtual plankton + particles model.

Through this unique combination of suspended field mesocosms, novel experimental setups, and innovative modeling approaches (inverse modeling, DEB, virtual reality), we will be able to improve the parameterization of complexity in ecosystem models and large scale marine biogeochemical models.

1.1.2. SCIENTIFIC QUESTION

In this axis of the Labex, two main scientific objectives will be focused :

1. investigate the geochemical and ecological controls on the quantity, quality and character of biogenic materials produced in relation to primary production, and how this quality impacts the export of carbon to the deep sea
2. determine the fate of biogenic materials sinking as aggregates and fecal pellets by studying degradation processes inside sinking particles and the interaction between these particles and mesopelagic organisms

1.2. OBJECTIVES FOR THE NEXT THREE YEARS AND SPECIFIC ACTIONS

For each of the two main scientific objectives, specific actions have been identified. In the following road map document, they will be briefly described. When funding from the Labex is anticipated, it will be mentioned. Despite specific actions are listed and described, an objective of the Labex is to stimulate discussions and thus, to generate new ideas and new projects that were not foreseen at its beginning. Furthermore, the Labex will be used as a label to help innovative projects to successfully obtain the means necessary for their realization. A strong and firm goal is that at the end of the first three years, **one or two ANR-type projects will have been worked out**. These projects will be focused on the specific scientific questions of the axis and should stimulate collaborations within the axis but also among different axes (especially between axes 1, 2 and 6).

1.2.1. OBJECTIVE 1: INVESTIGATE THE GEOCHEMICAL AND ECOLOGICAL CONTROLS ON THE QUANTITY, QUALITY AND CHARACTERISTICS OF BIOGENIC MATERIALS ...

Action 1: Investigate interactions between zooplankton, phytoplankton, viruses and bacteria and their role in controlling organic matter production and fate

A large mesocosm experiments will be undertaken in the Bay of Hopavågen in Norway (part of the HYDRALAB IV set of European facilities). Three different phytoplankton populations (diatom, coccolithophorid, dinoflagellate) will be incubated in tanks with natural microbial and microzooplankton populations and in tanks with that plus copepods. The goal of this work is to identify differences in the biological pump in the different treatment in terms of overall levels of primary

production and in terms of differences in where this production ends up (in the food web versus incorporated into large particles which rapidly sink out of the system). Following on from the mesocosm experiment will be laboratory experiments in rolling tanks to further investigate interactions between zooplankton, phytoplankton, viruses, and bacteria and their role in controlling organic matter production and the formation, sinking, solubilization, fragmentation and remineralization of marine snow (i.e., the overall capacity and export efficiency of the biological pump).

The mesocosm experiment will be held in summer 2012 and it is expected that the ensuing data analysis and preparation of papers will last until the end of 2013. New work on the interactions of zooplankton, phytoplankton, viruses and bacteria in the formation and sinking of marine snow would be undertaken in late 2013. The results of the mesocosm experiment will determine the details of the work to be done and the partners of the Labex it would be interesting to involve.

No Labex funds have been requested for the mesocosm experiment. However, a request to the axis for a PhD student will be made in Autumn 2013. This person will play a central role in the to-be-planned experimental work to be undertaken as the mesocosm data analysis and paper writing gets wrapped up.

Action 2: Impact of the presence of grazers on the silicification by diatoms

Hamm and collaborators in 2003 have demonstrated the efficiency of the frustule to protect diatoms from grazing by zooplankton by testing the resistance of the frustule to different mechanical constraints. Furthermore, this increased silicification appears to occur for diatoms growing in seawater that has contained copepods, even if the latter are absent (Pondaven et al., 2007). Starting from these recent studies, a series of microcosm experiments will be designed during spring 2012/2013 to test the impact of the presence of different types of grazers on the silicification of different species of diatoms. The objective will be to monitor the changes in the level of silicification of the frustule but also in the structure of the organic matrices of the frustule. In a second step, the impact of the higher silicification on the fate of the diatoms will be studied. Experiments on the impact of high silicification on grazer behaviors will shortly follow the first experiments while dissolution experiments should be undertaken during the fall. These aggregates versus grazer interactions require specific equipment that will be the basis for an ANR project proposed in 2013. No specific funding from the Labex will be requested for this action.

Action 3: Biodiversity and ecosystem productivity

One of the major concerns is a loss of biodiversity expected to result from global change and eutrophication, the two most large environmental hazards to most aquatic environments. Recently, more and more evidence is accumulating that diversity can influence important ecosystem functions such as resource use and production. It is therefore important to understand the mechanistic base of how diversity can influence ecosystem processes. A hitherto largely neglected aspect of phytoplankton resource partitioning is complementarity in the use of different spectral components of the photosynthetic active radiation (PAR). Complementarity effects within phytoplankton communities could then result from more diverse communities using a broader range of wavelengths and thereby increasing the effectiveness of light harvesting. We will study these hypotheses in theoretical models, enclosed marine phytoplankton communities exposed to different environmental conditions and with field data from investigations of marine lakes.

The experimental work planned in this action will be partly performed by a post-doc funded for 1 year (**starting in spring 2012**) by the Labex axis 2 and the University of Munich.

Action 4: The distribution of the pelagic habitats and biodiversity

Different hypotheses have been proposed to explain the pelagic microbial biodiversity and the species co existence, such as co-limitation in phytoplankton growth, pressure by zooplankton, time variability of physical and chemical parameters. Until now, this biodiversity is poorly represented by classical NPZD models, which takes into account a few integrated Functional Phytoplankton Types. The seminal work undertaken by Follows brings a new approach : it is based on the seeding of the ocean by several tens of virtual phytoplankton characterized by their traits randomly defined within a range of realistic parameters (growth, co-limitation, mortality/grazing, sedimentation). Follows has shown that the environmental and hydrodynamical conditions are able to discriminate "species" in time and space, as an emergent property of the virtual ecosystem (pelagic habitats). His work has been done at a global scale, at low resolution. Using this approach, the project aims at understanding the processes which drive the distribution of the pelagic habitats and biodiversity at meso- and sub meso-scale. In order to validate the simulations, this study will be focused on the Rade de Brest and Mer d'Iroise. Using the ROMS model, this study will be undertaken with a PhD, through a collaboration between LEMAR and DYNECO, as well as a collaboration with LOCEAN, Paris (M. Lévy), University of California (C. Edwards) and MIT (M. Follows). The funding for the PhD should come from Région Bretagne through the GIS. A small participation of 7000 Euros of the Labex is required for several stays of the PhD student at Univ. California in order to implement the coupled model with C. Edwards.

Action 5: Size structuration and functioning of plankton ecosystem

We have chosen here a completely novel approach that is based on a continuum size structured model reproducing phytoplankton, zooplankton and detritus in quasi-continuous size classes (Armstrong 1999). Indeed this kind of model appears to be the most powerful tool to get quantitative and qualitative information about sinking particles. Within a given habitat, the body-size distribution is a function of resource allocation among a group of organisms (Mc Arthur 1960) and is hence an index of the organization of ecosystems. A continuum size structured model has been developed by F. Poulin with this philosophy (Poulin and Franks, 2010) and is now working in a 1D configuration with a single nutrient (nitrate). Our focus is to refine the description and our understanding of the production of particles in the euphotic zone. *Our first objective* will be to add biogeochemistry, implementing Si-cycle with diatoms, C-cycle, and also to add the aggregation of phytoplankton and the production of size-resolved faecal pellets. Validation of the model will be achieved by taking advantage of the mesocosms experiments in the Labex described previously in this objective (see Actions 1 and 2), and data set from the CCE-LTER and Calcofi programs (P.Franks research team). *The second objective* of this axis focuses on the fate of the biogenic materials sinking off the euphotic zone (see below). The modeling studies planned in this objective will require a robust description of the physical and biogeochemical nature of the particles entering the mesopelagic layer. A post-doc position may be needed to work on this topic. The funding is not yet defined and part of it may be requested to the Labex, if necessary.

Action 6: Ocean acidification and trace metals sensitivity of phytoplankton

The increase of anthropogenic atmospheric CO₂ and its solubilisation in the ocean will modify the chemical carbonate equilibrium (Sabine *et al.*, 2004) which leads to seawater acidification (Caldeira and Wickett, 2005). Ocean acidification has negative consequences on the primary production by affecting the functioning and growth of the two major phytoplankton functional groups in the ocean carbon cycle, the micro algae (eukaryotes) diatoms and coccolithophorids. In the context of global climate change, shifts in micronutrients (metals) supply in seawater can also profoundly impact primary productivity and biological processes, hence CO₂ budgets. Notably it is realized that, zinc (Zn), cobalt (Co) and cadmium (Cd) can alter growth, dominance, productivity and metabolism of the two major phytoplankton groups (Saito *et al.*, 2008). However the combined effect of ocean acidification and shifts

in the ratio of the three micronutrients has been hardly studied so far (Buitenhuis et al., 2003). Hence we propose to test the sensitivity of marine biomineralizers to future climatic scenarios under variable micronutrients involved in the cellular metabolism of carbon and partial pressure of CO₂ that leads to ocean acidification. This will help at further understanding and predicting consequences of these changes on the biological carbon fixation and on the production of biogenic particulate matter.

A postdoc position is required to develop this work for at least one year. Two options are proposed, a full funding from the Labex to hire a postdoc in 2012; or a co-funding between the Labex and the Région Bretagne (or CG29) to hire a postdoc in 2013. The second option is obviously the preferred option.

Action 7: A field study to investigate the impact of trace metals on the complexity and efficiency of the biological pump

The North Atlantic plays a key role in the Earth climate and the thermohaline circulation. A very recent study within the central Iceland Basin during late July to early September 2007 provided strong evidence that iron limitation within the post-spring bloom phytoplankton community contributed to the observed residual macronutrient pool during summer (Nielsdottir et al., 2009). Low atmospheric iron supply and suboptimal Fe:N ratios in winter overturned deep water were suggested to result in the formation of this seasonal high-nutrient, low chlorophyll (HNLC) condition, representing an inefficiency of the biological (soft tissue) carbon pump in the region. To better understand and quantify trace metal limitation in the Subpolar Gyre is of particular importance (Marinov et al., 2008; Sarmiento and Orr, 1991). In 2014, we propose to perform a multi-proxy approach along the OVIDE section. This multi-proxy approach will be carried out by analysing a large panel of trace metals (Fe, Al, Zn, Mn, Cd, Cu, Co, Ni), as well as other tracers for the quantification of specific oceanic mechanisms such as, (i) long-term mixing rates of deep waters or shelf-to-open ocean mixing rates (e.g. natural and artificial radionuclides, Key et al., 2004), (ii) Boundary Exchange processes (e.g. Nd, Lacan and Jeandel, 2001, 2005; Jeandel et al, 2011), (iii) downward flux of organic carbon or the dissolution of this carbon in deep waters (e.g. ²³⁴Th, biogenic particulate barium, Buesseler et al., 2004; Jacquet et al., 2008). This project will be a French contribution to the international GEOTRACES programme. A two-year post-doc position is needed to work on this topic. The funding is not yet found but a co-funding ANR/Labex is planned to be asked.

1.2.2. OBJECTIVE 2: DETERMINE THE FATE OF BIOGENIC MATERIALS SINKING AS AGGREGATES AND FECAL PELLETS

Action 1: development of a virtual plankton model of the mesopelagic domain

Organisms in the mesopelagic layer play a tremendous role in modifying the quantity (Steinberg et al., 2008a) and the quality (Ragueneau et al., 2006) of biogenic particles produced in surface waters. Individual traits and interactions among individuals must play a key role (Stemmann et al., 2008) and as stated earlier, simple NPZD can not adequately account for the influence of biodiversity and of interactions across different organization levels, on biogeochemical fluxes. In this action therefore, we will develop an autonomy-based modeling approach (Woods et al., 2005; Hölker et al., 2005) in the mesopelagic domain, which will allow us to account for the complexity of ecosystems. Each phenomenon (aggregating, grazing...) involved in this open ecosystem will be modeled as an autonomous situated entity (structural coupling). The first steps towards this original development have been undertaken within the VICOFLUX project. In 2012, a Ph.D. will start at LabSTICC-CERV to develop the virtual model simulating the interaction between zooplankton and sinking particles. This will require strong interactions with scientists at LEMAR. Experimental work undertaken in Action 2 will be used for the latter. The financial demand to the Labex, therefore, targets (1) ½ a Ph.D. (the other half will be demanded to the Region Bretagne by the LabSTICC-CERV) and (2) a post-doc, closely associated with the international chair of excellence, specializing in zooplankton ecology, hopefully in the mesopelagic zone (for the latter, the funding will come from the chair, not from the axis).

Action 2: biogeochemical processes inside sinking particles

Large particles are the main vector of organic matter to the deep ocean as they sink fast enough to avoid degradation/dissolution in the surface waters. Still as the key processes governing aggregation are not yet identify, the formation of large sinking episode is still hard to predict using the actual model. The impact of the formation of large particles, be it aggregates or fecal pellets could strongly impact most parameters governing degradation (food web and biochemical degradation/dissolution). Before understanding how aggregation and incorporation to fecal pellets can impact biogeochemical cycles of C and Si, it is necessary to identify the main characteristics of the micro-environment encountered by phytoplankton when incorporated to aggregate and fecal pellets. Due to the huge heterogeneity of these large particles, characterization of the micro-environment should be done not only in laboratory but also in field experiments, using microcosm and mesocosm experiments of EURO-BASIN (2012-2013) and of the action 3 of the objective 1. This action will benefit from the input of actions 1 and 2 of the objective 1 in term of particles formation and will focus on better understanding the degradation/dissolution/destruction of large particles during their descent to the deep sea. Due to the complexity and the constraints link to the manipulation of large particles, these experiments can not be envisaged before 2014. The funding of a PhD student partially through the Labex will be requested to start in 2014. This PhD student will work on the characterization of the micro-environment of the particles both in labs, in microcosms and mesocosms.

Action 3: The role of higher trophic levels and vertical migration on the production of particles and their fate in the water column

Understanding and predicting the effects that human activities and global changes have on marine ecosystems require to identify and characterize the dynamics of energy pathways in food webs (Shin et al., 2009). This is a major challenge for ecologists. Trophic relationships are indeed of critical importance as they control the amount of energy which is transferred from autotrophs to the top predators exploited by fisheries. Consequently, understanding the fluxes of energy through the food web is a prerequisite to understand and predict the dynamics of marine resources and ultimately to provide useful scientific basis for their management. Moreover, the characteristics of trophic webs largely determine the fate of the biogenic carbon, in particular its export below the euphotic zone, either by the sinking of particles or by the diel vertical movements of the organisms (e.g., Legendre and Rivkin, 2002). This is of fundamental importance for the climate system as the biological CO₂ pump in the ocean is one of the major sink of atmospheric CO₂. Within the framework of the ANR-CEPS program MACROES (P.I. O. Aumont), an end-to-end ecosystem model representing the full marine trophic food web has been constructed. This model is based on a classical NPZD model PISCES (Aumont and Bopp, 2006) and an ecosystem model APECOSM (Maury et al., 2007). We propose here to use this model to study the impact of the higher trophic levels on the production of particles, within and below the euphotic zone. No specific funding from the Labex will be requested.