Convocatoria 2019 - «Proyectos de I+D+i»

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IMPORTANT – The research proposal cannot exceed 20 pages. Instructions to fill this document are available in the website. If the project cost exceeds 100.000 €, this document must be filled in English.

IP 1 (Nombre y apellidos)**: Martí Galí Tàpias**
IP 2 (Nombre y apellidos)**: Yohan Ruprich-Robert**

TÍTULO DEL PROYECTO (ACRÓNIMO): Exportación, remineralización y advección de partículas orgánicas en la capa mesopelágica del Atlántico norte **(OPERA)**
TITLE OF THE PROJECT (ACRONYM): **O**rganic **P**article **E**xport, **R**emineralization and **A**dvection in the North Atlantic mesopelagic layer (**OPERA**)

Index

1. PROPUESTA CIENTÍFICA - *SCIENTIFIC PROPOSAL*

1.1 Introduction and state of the art

General context, motivation and aim

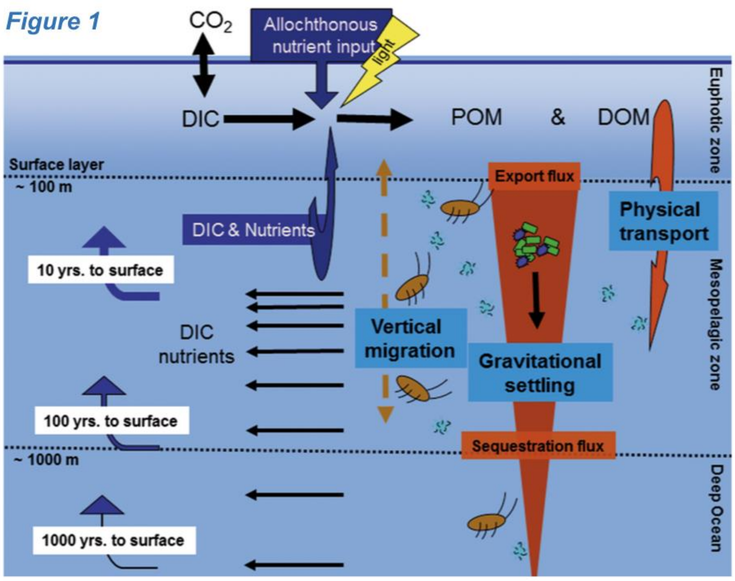
The mesopelagic layer of the oceans, also known as the Twilight Zone, extends between ~200 and 1000 m depth and is one of the vastest contiguous ecosystems on Earth[1,2]. It plays a pivotal role in global biogeochemical cycles and climate[3,4], and hosts a massive biomass of zooplankton and small fish[2,5]. However, scientific understanding and predictive capacity of biogeochemical processes in the mesopelagic zone are still in their infancy[1,6–9], primarily as a consequence of the dearth of observations[9,10]. This lack of quantitative understanding has societal and economic costs. Most prominently, it introduces uncertainty in estimates of oceanic carbon storage[4] (which inform policies for the reduction of carbon dioxide emissions), and might soon hamper sustainable management of mesopelagic biological resources (threatened by imminent exploitation[11]).

Mesopelagic functioning depends on the biological transformation and physical transport of organic matter produced mostly in the overlying sunlit layer of the ocean[1–3,7,12–14] (Fig. 1). So far, attempts to balance mesopelagic carbon budgets have failed as estimates of organic carbon consumption generally exceed inputs, sometimes by an order of magnitude or more[1,6,14,15]. Poor observation estimates of particle transformations and fluxes[6,9], especially those associated with *small particles*[15–18] (with size ranging 1-50 µm), stands out among the commonly invoked explanations for the mesopelagic carbon budget imbalance. Particle transformations and transports occur in a wide range of spatio-temporal scales that are technically impossible to fully observe. In this context, ocean biogeochemistry models informed by the available observations are the best tool at hand to gain detailed understanding of mesopelagic carbon budgets.

Advances in observation of ocean particles with autonomous robots (biogeochemical Argo floats) and recent developments in the representation of small particles in a state-of-the-art ocean biogeochemistry model PISCESv2[19] now enable comprehensive estimates of mesopelagic *particulate organic carbon* (POC) cycling pathways. **The aim of the OPERA project is to quantify mesopelagic POC budgets and constrain their sources of uncertainty**. By exploiting synergies between observations and models, we will tackle the poorly understood **biogeochemical cycling and advective transport of small particles in the North Atlantic**, a region that features wide latitudinal, seasonal and interannual variations in ocean dynamics. The relatively abundant observations of ocean circulation, biogeochemistry and ecosystem functioning make the North Atlantic an ideal testbed for our project.

Biogeochemical functioning of the mesopelagic layer

Every year, phytoplankton growing in the sunlit surface ocean produce ~50 PgC (50 x 10^{15} gC) globally. Approximately 20% of this *net primary production* (NPP), ~10 PgC per year, enters the mesopelagic zone[9,20,21]. This vertical flux, termed *export production*, comprises a wide variety[22] of sinking and suspended detritus, globally termed *particulate organic matter* (POM), and to a lesser extent, dissolved organic matter[12] (DOM). The vertical flux of organic matter attenuates rapidly with depth in the mesopelagic zone. Globally, only around 10% of the exported production (~1 PgC) can sink deeper than 1000 m, where it can be sequestered for centennial timescales, and a portion of it eventually settles onto deep ocean sediments[3,20–22].



In consequence, **around 90% of the export production flux is consumed by mesopelagic organisms following two main pathways** (Fig. 1). A major fraction undergoes degradation and remineralization through the action of bacteria and detritivorous zooplankton, consuming oxygen and releasing CO_2 and inorganic nutrients[3,7,21]. Another fraction, generally smaller, is assimilated by zooplankton and transferred up the detrital food web[2,7,23], ultimately sustaining higher trophic levels of the ecosystem. The three competing pathways that define mesopelagic ecosystem functioning (respiration, trophic transfer and physical transports) redistribute inorganic and organic carbon, nutrients and trace elements among ocean basins through intermediate and mode waters. Slight changes in the balance between these competing pathways carry important consequences for global climate and upper ocean productivity[3,4,20].

Historically, our understanding of the mesopelagic layer has revolved around the concept of the *biological carbon pump*, the ensemble of biology-mediated processes that transfer organic carbon from the productive sunlit surface layer (*euphotic layer*) to the deep ocean[3,23]. This approach has placed emphasis on understanding ecological and physical factors that control *export efficiency* (the fraction of surface NPP exported to the mesopelagic) and *transfer efficiency* (the fraction of export production that reaches sequestration depths), both of which vary widely across ocean biomes and along the seasonal cycle[8]. Central to this approach is the hypothesis that "*carbon export from the euphotic zone and its fate within the twilight zone can be predicted knowing characteristics of the surface ocean ecosystem*"[24]. But, is this the case?

Mesopelagic carbon budgets: a test for our understanding

While global NPP estimates are reasonably well constrained, **the grand numbers of mesopelagic metabolism reported above suffer from large uncertainties**, frequently in the order of 50-100%[8,9,21]. These uncertainties, which arise from limitations in both observation and modeling abilities, have decreased little over the last decades[9,21] and remain a major enigma in marine biogeochemistry. Studies conducted in contrasting ocean biomes have found a large mismatch[6,14], of up to an order of magnitude, between traditional estimates of organic matter inputs (gravitational particle sinking) and outputs (bacterial and zooplanktonic respiration). To date, only one study has succeeded at balancing regional-scale mesopelagic carbon budgets[7] over a short period under simplifying assumptions. Yet, the authors acknowledged that the overall balance resulted from large compensating imbalances in the upper and lower mesopelagic. In short, **the inability to close mesopelagic carbon budgets indicates that the classical picture of the biological carbon pump is incomplete**. Proposed explanations for the difficulties in balancing mesopelagic carbon budgets invoke uncertainties in both sources and sinks[6].

Regarding the **sources**, various approaches indicate that POM input mechanisms other than gravitational particle sinking have been overlooked[9]. Gravitational sinking has traditionally received most of the attention due to the strong relationship between particle size, density and sinking speed dictated by physics (Stoke's law). This relationship implies a prominent role for large and dense particles produced during the peak and collapse of phytoplankton blooms in productive ocean areas. Historically overlooked mechanisms include, at least, vertical mixing[9], small- and large-scale subduction[9,25], and the vertical migrations of zooplankton and mesopelagic fish at both seasonal and diel periodicity[9]. These sources, collectively termed as *particle injection pumps,* could augment export production estimates by 50% globally[9].

Regarding the **sinks**, several studies pointed out that the respiration and growth rates of mesopelagic heterotrophic bacteria are poorly constrained[1,6]. Fresh POM inputs from the euphotic layer, with relatively labile composition, become more refractory as bacterial degradation proceeds[20,21]. Progressive POM degradation decreases bacterial growth efficiency[1], increasing the amount of bacterial respiration needed to produce a certain bacterial biomass. Zooplankton that feed in the mesopelagic zone also play a pivotal role[7,14] on the budget of mesopelagic POC. On the one hand, small particles and loose aggregates that pass through their guts are repackaged into compact and fast-sinking fecal pellets, accelerating carbon transfer to depth. On the other hand, sloppy feeding fragments aggregates into small particles reducing their sinking velocities and enhancing both their solubilization and respiration by bacteria[1,7].

In addition to "local" processes, the role of **horizontal POC advection** (which can contribute to either sources or sinks) has been historically neglected due to shortcomings in observation and modeling. Yet, its potential importance was already hypothesized 3 decades ago[21] and is supported by recent studies[13]. Finally, it is increasingly acknowledged that POC cycling processes do not necessarily operate at steady state[6,9] over the seasonal scale. However, the steady state hypothesis is commonly used when fitting empirical functions to vertical POC fluxes[21,22], leading to apparently contradictory findings[26] in the mesopelagic zone.

Overall, recent studies[9,13,15,16,18,20] highlight the **need to understand what controls the fate of organic particles within the mesopelagic** by (i) performing year-round 3-dimensional observations of mesopelagic particles and (ii) using these observations to evaluate and improve numerical models.

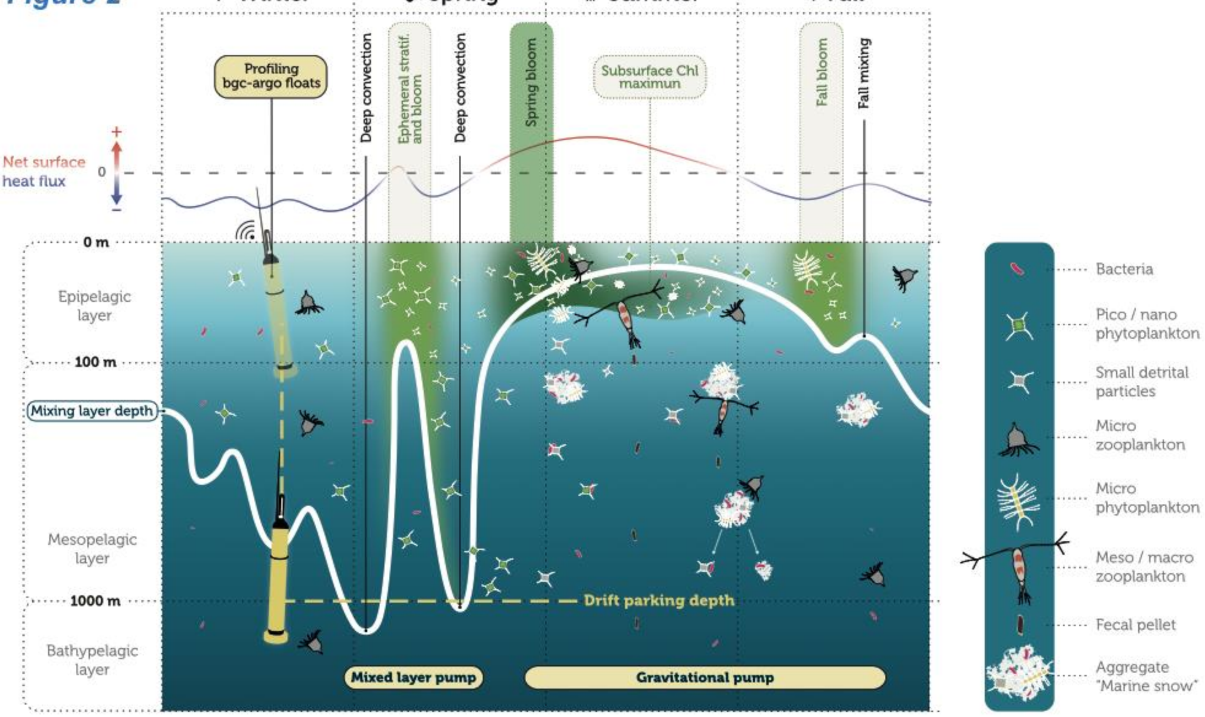
Important role of small particles: emerging views and observation techniques

Mesopelagic organic particle populations span a wide range in size[27] (from µm to cm) and sinking speed[15,17,18,27], and appear in a myriad of shapes and compositions that influence their reactivity towards bacterial degradation. For the sake of simplicity and tractability, particles are usually partitioned into a few functional classes: big particles (which sink at several tens or hundreds of meters per day) and small particles, including suspended particles and slow-sinking particles (e.g., less than 10 $m.d^{-1}$). The divide between the two classes is operationally placed between 50 and 100µm[15,18,28]. Big particles are generally assumed to carry most of the gravitational flux, whereas **small particles typically make up over 90% of the POC stock**. This scheme has an important corollary: small POC (sPOC) has a much longer residence time in the mesopelagic layer; thus, **with a similar reactivity**[29] **compared to aggregates, sPOC will support most of the mesopelagic respiration**.

Interestingly, studies performed during the last decade[15,17,18,27] reported a bimodal shape of the sinking POC flux size spectrum, with two marked populations of particles sinking at either <10 $m.d^{-1}$ or >100 $m.d^{-1}$. These studies showed that, **seasonally, slow-sinking particles can contribute up to 85% of the total POC vertical flux.** These observations, made in contrasting oceanographic settings with diverse techniques, are at odds with the classical paradigm[3,23]. Moreover, physical particle injection pumps are especially effective at injecting small particles in the mesopelagic layer[9], adding to the sinking sPOC input. For all the above reasons, better understanding of small particle dynamics is urgently needed.

In situ characterization of small particle stocks and fluxes can be achieved with several complementary techniques[15,18,27,30]. Yet, they are generally too expensive and time-consuming to allow for synoptic characterization of particle fields. In recent years, hundreds of bio-optical sensors deployed on autonomous profiling robots (**bgc-Argo floats**) have enabled observation of small particle stocks with high temporal and vertical resolution in extended regions. Unlike polar-orbiting satellites, bgc-Argo floats can take measurements all year-round between the surface and (at least) 1000 m depth at a frequency between 1 and 10 days (Fig. 2). This technology is compensating decades of seasonally biased sampling, powering scientific breakthroughs[10] and enabling large-scale assessment of mesopelagic particle dynamics[10,25].

Figure 2



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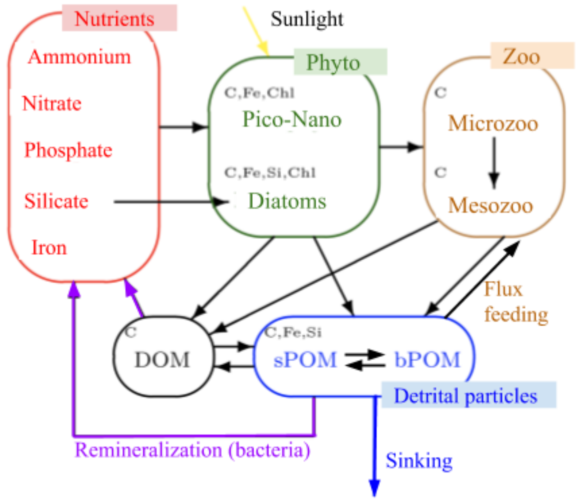
Bio-optical sensors (fluorometers, backscattering-meters, transmissometers) are accurate, robust and non-invasive[10]. When used in combination, they allow for a broad characterization of particle populations. The backscattering coefficient at 700 nm wavelength (**bbp700**) detects particles *mostly* in the 0.5-20 µm size range, and is therefore a good proxy for small (hence total) POC in ocean waters. Published comparisons between bbp700 and chemically-determined total POC yielded R^2 between 0.78-0.86[31,32] (care is needed to convert bbp700 to POC using appropriate factors). Moreover, the concentration of big POC (bPOC) can be semi-quantitatively inferred[10] using the bbp700 spike signal. By comparing bbp700 to fluorometric chlorophyll-*a* (chla), a common proxy for phytoplankton biomass, the presence of fresh phytoplanktonic material in sPOC and bPOC can also be determined. Only in the North Atlantic, 11700 co-located profiles of physical variables, bbp700 and chla have been acquired by bgc-Argo floats (Fig. 2) since 2011, of which 8400 in the subpolar gyre. Global bgc-Argo datasets are publicly available via the Coriolis Global Data Assembly Centre (Argo GDAC).

Model representation of mesopelagic particle transformations

The diversity of mesopelagic particle populations and cycling processes can hardly be represented in global biogeochemical models without incurring unaffordable computing costs. Thus, they have to be simplified with sensible parameterizations. In the majority of the models that participated in the 5th Climate Model Intercomparison Project, CMIP5, all detrital POC was lumped into just one size class[8]. As thoroughly argued in the previous section, this is insufficient to represent mesopelagic POC dynamics. In particular, this approach severely underestimates mesopelagic POC concentrations because all particles exported from the upper ocean are flushed towards the seafloor at high sinking speeds representative of aggregates (~100 m d^{-1}).

The PISCESv2 model used at BSC features two size classes of particulate organic matter, small (sPOM) and big (bPOM), nominally smaller/larger than 100 µm (Fig. 3). In PISCESv2, sPOM sinks at 2 $m.d^{-1}$, whereas bPOM sinks at variable speed between 30-200 $m.d^{-1}$. The two size classes carry organic carbon, macronutrients, iron and biominerals. They exchange matter through both biotic (mediated by zooplankton) and abiotic aggregation and fragmentation processes. The sPOM and bPOM stocks are connected to dissolved organic matter through DOM coagulation and bacterial POM solubilization. DOM and POM are remineralized by bacteria (implicitly represented in the remineralization equations), contributing to net respiration together with zooplankton. Although the two-class scheme brought significant improvements, PISCESv2 still underestimated mesopelagic POM concentrations[20], which prompted further development of the POM cycling parameterization.

Figure 3



Recently, Aumont et al. 2017[20] implemented a **reactivity continuum (RC) scheme by which POM is remineralized at variable speed "k"** (first-order kinetics) depending not only on temperature, but also on POM **reactivity** (lability). This scheme prescribes a maximum temperature-dependent k at the base of the illuminated layer, typical of freshly produced POM; k subsequently decreases with depth as fresh POM is rapidly consumed in the upper mesopelagic and refractory POM is left. The RC scheme enhances sPOC preservation, increasing mesopelagic POC concentration by two- to fourfold, which greatly improves the fit between modelled and measured POC profiles (reducing mean bias from 0.12 to 0.02 mmol.m^{-3} and achieving a correlation coefficient of 0.77). Indirect effects of the RC scheme propagate to nutrient regeneration, primary production and dissolved iron scavenging.

The ability to simulate realistic mesopelagic sPOC fields (see comparison in Fig. 5) enables examining the contribution of sPOC to mesopelagic respiration and the role of lateral sPOC transport. The potential importance of the latter can be glimpsed from a simple example. In PISCESv2 with the RC scheme, sPOC degradation k takes typical values of ~0.040 d^{-1} in the top 200 m of the ocean, ~0.003 d^{-1} in the upper mesopelagic (200-500 m), and ~0.001 d^{-1} in the lower mesopelagic (500-1000 m). Corresponding turnover times with respect to bacterial degradation are, respectively, ~25, ~300 and ~1000 days. With mean sinking speed of 2 m.d^{-1}, mesopelagic residence time with respect to sinking is 400 days. Assuming a homogeneous horizontal current of 5 km.d^{-1} in the mesopelagic layer, sPOC residence time with respect to lateral advection in a 100 km (1000 km) wide region is ~20 days (~200 days). Hence, sPOC residence time is theoretically more strongly controlled by lateral advection and bacterial degradation than by sinking, both at mesoscale and ocean basin scale. Hereafter, *PISCESv2 with the RC scheme will be referred to as PISCES*.

The North Atlantic as a testbed for mesopelagic C cycling

The North Atlantic is characterised by two wind driven circulation systems: the cyclonic subpolar gyre (SPG, spanning from 45ºN to 65 ºN) that is associated with a large scale upwelling and the anticyclonic subtropical gyre (STG, spanning from 15ºN to 45ºN) that is associated with a large scale downwelling (Fig. 4). The Gulf Stream forms the western border of the STG and, with its North Atlantic Current extension, it transports warm water masses northward from the STG to the SPG. Along the path of the SPG, surface water masses lose heat in contact with the relatively colder atmosphere, explaining the East-West gradient of the SPG sea surface temperature[33] (SST).

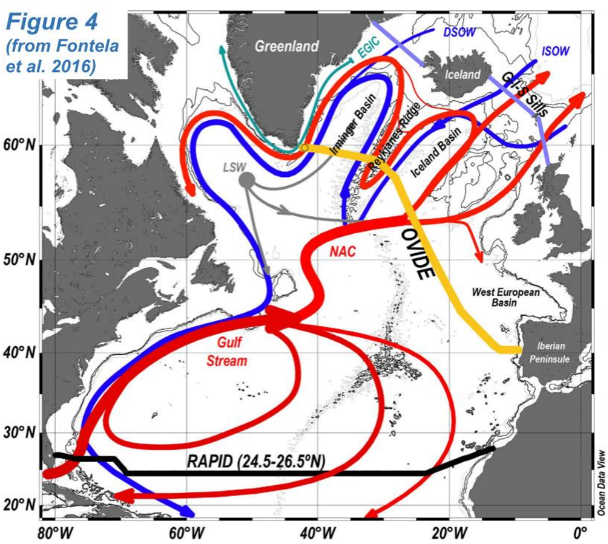


Figure 4 (from Fontela et al. 2016)

At interannual timescale, the variability of the North Atlantic is primarily controlled by direct responses to atmospheric wind changes. In particular, the first mode of variability of the North Atlantic - Europe atmospheric circulation, namely the North Atlantic Oscillation (NAO), largely explains the SST and current changes through turbulent heat fluxes and Ekman effect[34]. During a positive phase of the NAO (NAO+), the climatological winds are reinforced and shifted toward the North, cooling and increasing the mixed layer depth over the SPG and warming and extending northward the STG. The oceanic circulation also responds to the NAO with some delay. By cooling the SPG surface, NAO+ destabilizes the oceanic column, which increases deep oceanic convection in the

Labrador Sea and the density of the SPG inner core. Through geostrophic balance, the SPG intensifies along with the oceanic northward heat transport, eventually modifying the North Atlantic circulation and water mass temperature for several years[35].

Biogeochemical regimes in the STG and the SPG biomes reflect the marked gradients in ocean physics[36]. Due to prevailing stratified conditions, the STG features low phytoplankton biomass and NPP rates, mostly fuelled by efficient microbial recycling of organic matter in the euphotic layer[3]. In consequence, the STG displays dampened seasonal and interannual variations. In contrast, the SPG undergoes intense vertical mixing in winter (reaching hundreds m depth and locally >1000 m depth), which replenishes each year the upper ocean with nutrients from deeper layers. As soon as light levels are sufficient, strong phytoplankton blooms dominated by large cells (diatoms) form through the spring[36], producing short and intense export of aggregates as blooms collapse. Variations in vertical mixing intensity, linked to the NAO, strongly affect the timing and (to a lesser extent) the magnitude of SPG phytoplankton blooms[36]. These contrasting physical and biogeochemical regimes result in different modes of POM supply to the mesopelagic zone. However, little is known about the interplay between POM sources, sinks and transport[13], and how they shape the structure and functioning of mesopelagic[37] ecosystems across North Atlantic biomes.

The North Atlantic is a region of global importance for its role in climate regulation and biological productivity. Although it currently supports around 15%[3,38] of global NPP, model projections converge to show wide reductions in NPP and export production in the SPG area due to increased stratification[8]. Better knowledge of mesopelagic dynamics is key to predict the response of North Atlantic ecosystems to global change.

1.2 Hypotheses and objectives

The OPERA project is structured around one overarching hypothesis (H1) and three derived hypotheses (H2-H4):

- **H1 (overarching hypothesis)**: Knowledge of biogeochemical transformations and physical transport of organic particles in the mesopelagic is crucial to understand and predict the fate of carbon exported from the upper ocean euphotic zone.
- **H2:** Small particulate organic carbon (POC) accounts for a major fraction of fluxes that contribute to mesopelagic POC budgets. This fraction varies according to dominant POC input mechanisms over the seasonal cycle in different North Atlantic biomes.
- **H3**: Advection of small POC makes a sizable contribution to mesopelagic carbon budgets by redistributing particles from source to sink areas in the North Atlantic ocean.
- **H4**: Interannual differences in oceanic circulation and vertical mixing in the North Atlantic Ocean impact the spatio-temporal distribution and transport pathways of mesopelagic POC.

The general objective of the OPERA project addresses H1 and is **to quantify POC budgets in the mesopelagic layer of the North Atlantic Ocean, and to constrain their sources of uncertainty, using the PISCES biogeochemical model and observational datasets including ocean color remote sensing and biogeochemical-Argo**. To achieve the general objective, four specific objectives (O1-O4) are devised:

- **O1**: To evaluate the impact of surface POC data-assimilation on the model's ability to reproduce mesopelagic POC dynamics in historical simulations. This objective addresses technical developments and production of reference simulations.
- **O2**: To calculate seasonal POC budgets at the regional (sub-basin) scale and to quantify the contribution of sPOC transformations. This objective addresses H2.
- **O3**: To quantify sPOC advection, the associated spatial and temporal scales, the dominant transport pathways, and the regions characterized by net horizontal import/export of POC. This objective addresses H3.
- **O4**: To assess the interannual variability in mesopelagic POC budgets with a particular focus on the variability driven by the North Atlantic Oscillation (NAO). This objective addresses H4.

Tasks to achieve objectives **O1-O4** will be executed in the corresponding work packages **WP1-WP4** (Section 1.4). The overarching hypothesis (**H1**) of the project will be addressed through the synthesis of results from WP1-WP4.

1.3 Background of the research team and ongoing activities relevant to the proposal

The Barcelona Supercomputing Center (BSC) combines unique high performance computing facilities and in-house research departments on computer, life, and Earth sciences, and computational applications, counting more than 640 researchers and students from 47 different countries. It has been accredited as one of the first eight Severo Ochoa Centers of Excellence. This award is given by the Spanish Government as recognition for leading research centers in Spain that are internationally well known in their respective areas.

The Earth Sciences Department of the BSC (ES-BSC), led by Prof. Francisco J. Doblas-Reyes, conducts multi-facet research in Earth system modeling. It is a main European actor in the development of climate predictions and climate services. The ES-BSC has a very dense international collaborative network counting 50 institutes worldwide, providing a very high quality and stimulating international research environment. It develops and conducts research with a multi-scale set of comprehensive climate numerical models. It is composed of four groups: 1) Climate Prediction group, 2) Atmospheric Composition group, 3) Earth System Services group, and 4) Computational Earth Science group. The OPERA project will be carried out in the Climate Prediction group in close collaboration with the Computational Earth Science group.

The Climate Prediction group (CP), led by Dr. Pablo Ortega and Dr. Markus Donat, undertakes advanced research to forecast climate variations from one month to several years into the future (also known as seasonal-to-decadal predictions) and from regional to global scales. It is a highly productive scientific entity that has published more than 85 research articles in peer-reviewed journals over the last 5 years, including 11 in prestigious high-impact journals. Since 2017, the CP group includes a team led by Dr. Raffaele Bernardello specifically dedicated to biogeochemistry research. Members of this team are currently leading/participating in two European H2020 projects, one national project and one project funded by a private entity.

The Computational Earth Science group (CES), led by Kim Serradell, provides guidance to the scientists with their technical work issues and develops a framework for the most efficient use of HPC resources. Support includes optimization of the tools developed by scientists, development of automatic tools to compile, launch, monitor and post-process climate simulations and handle the large amount of data produced, as well as installation and upgrade of a variety of scientific software.

The OPERA research team blends therefore expertise in biogeochemical oceanography (M. Galí, J. Llort - CP), physical dynamics of Atlantic variability (Y. Ruprich-Robert - CP), data assimilation techniques (V. Lapin - CP) and model evaluation (J. Vegas-Regidor - CES), ensuring that both scientific and technical objectives will be achieved.

Dr. Martí Galí: During his 12 years' experience in marine biogeochemistry, Dr. Galí has combined experiments, observations and models. His previous work, mostly devoted to organic sulfur compounds, reveals a solid understanding of plankton ecosystems, biogeochemical cycles and their response to physical forcing. Since 2018 he leads the ORCAS project in the CP group, which strives to improve biogeochemical models of mesopelagic POC cycling.

Dr. Yohan Ruprich-Robert has a broad expertise on climate variability and predictability as well as excellent skills in numerical modeling. Thanks to his individual MSCA fellowship INADEC, he develops since 2018 a new line of research in the CP group on the origins and impacts of the North Atlantic decadal variability, with the long term goal of better predicting decadal variations of the Earth system.

Dr. Joan Llort is an oceanographer specialised in the coupling between ocean dynamics and marine biogeochemistry. He obtained a PhD in the University Pierre et Marie Curie, in France, and continued developing his research career at the Institute for Marine and Antarctic Studies in Australia. He has extensive experience in modeling using PISCES and demonstrated expertise on bgc-Argo floats. He is currently developing in the CP group a new line of research on prediction of mesopelagic biomass.

Dr. Vladimir Lapin: Trained as an applied mathematician, Dr. Lapin has an extensive background in data assimilation and numerical climate modeling. His experience includes developing a new high-resolution model of ocean tides during his fellowship at the University of Leeds and implementing the sea ice component of ICON-ESM at MPI-M. He currently leads the research efforts to incorporate nudging and ensemble Kalman filter data assimilation in the community model EC-Earth in the CP group.

Javier Vegas-Regidor is working in the CES group and has been in charge since 2016 of the development of diagnostics for the entire ES-BSC. He is also part of the core development team of ESMValTool, a community diagnostic and performance metrics tool for evaluation of CMIP models.

In addition, to fulfill the project objectives, the current working team will be reinforced with a research engineer that will be hired for the 3-year length of OPERA (Section 1.7) and by the training of a PhD student in relation to this project (cf. Section 3 - Training Capacity). OPERA will also benefit from the collaboration with other members of the CP and CES groups, in particular Dr. Raffaele Bernardello and Dr. Valentina Sicardi, experts on biogeochemistry and oceanic modeling.

Ongoing projects in ES-BSC in line with the research proposed in OPERA:

- ORCAS (2018-2021): Organic carbon sequestration in the ocean: constraining model predictions with novel high-resolution observations. Funding: "Junior Leader" fellowship program, "la Caixa" Banking Foundation. Principal Investigator: Martí Galí.
- INADEC (2018-2020): Impacts of the North Atlantic Decadal variability on European Climate: mechanisms and predictability. Funding: European Marie Skłodowska-Curie Actions individual fellowship. Principal Investigator: Yohan Ruprich-Robert.
- DeCUSO (2018-2020): Decadal predictions of carbon uptake in the Southern Ocean and impact of the biological carbon pump uncertainty. Funding: Spain's Agencia Estatal de Investigación (MINECO). Principal Investigator: Raffaele Bernardello.
- TRIATLAS (2019-2023): Tropical and South Atlantic climate-based marine ecosystem prediction for sustainable management. Funding: European Commission H2020 program. BSC Principal Investigator: Pablo Ortega (Climate Prediction group co-leader).
- CCiCC (2019-2023): Climate-Carbon Interactions in the Coming Century. Funding: European Commission H2020 program. BSC Principal Investigator: Raffaele Bernardello.

The tools and findings resulting from ongoing ES-BSC projects will leverage the ambitious OPERA research plan. In ORCAS we have setup a water column (1D) simulations framework that facilitates quick comparison between PISCES and bgc-Argo data and parameter sensitivity tests. Within ORCAS we have also setup a bgc-Argo data processing pipeline to perform data cleaning, binning, regridding and calculation of climatologies. In DeCUSO, the transport matrix method[39] has been implemented to greatly accelerate the spin-up of biogeochemical models (e.g., PISCES) through a matrix representation of mean ocean transport fields. In INADEC, the additional atmospheric forcing methodology that will be used in OPERA has been implemented in the same coupled ocean-atmosphere version of NEMO that we will use.

The OPERA team at BSC will also be strengthened through collaboration with researchers in top institutions at national and international levels, who will provide complementary expertise, participate in the OPERA workshop and host BSC team members, as explained below:

Dr. Olivier Aumont is a research scientist from IRD working at LOCEAN in Paris. With a genuine interest in marine ecosystems and biogeochemical cycles, he is the creator and main developer of PISCES biogeochemical model that is used in several Earth System Models and operational modeling platforms of the ocean. He currently participates in the EU-funded project SUMMER (see below).

Dr. Stephanie Henson is Honorary Associate Professor at UK's National Oceanography Centre and the University of Southampton, where she leads a research group in global biogeochemical oceanography. She has made significant contributions to the understanding of the physical processes that alter phytoplankton populations and the biological carbon pump. Dr. Henson is co-PI of the NERC-founded project COMICS (Controls over Ocean Mesopelagic Interior Carbon Storage; 2017-2021), in which ES-BSC member Dr Bernardello is involved as external collaborator.

Dr. Xabier Irigoien is Ikerbasque Research Professor and Scientific Director at AZTI-Tecnalia. He has made key contributions to the understanding of planktonic trophic webs, factors affecting fish recruitment, and estimation of mesopelagic fish biomass. His team coordinates the EU-funded project SUMMER (Sustainable Management of Mesopelagic Resources; 2019-2023) and participates in MEESO (Ecologically and economically sustainable mesopelagic fisheries; 2019-2023).

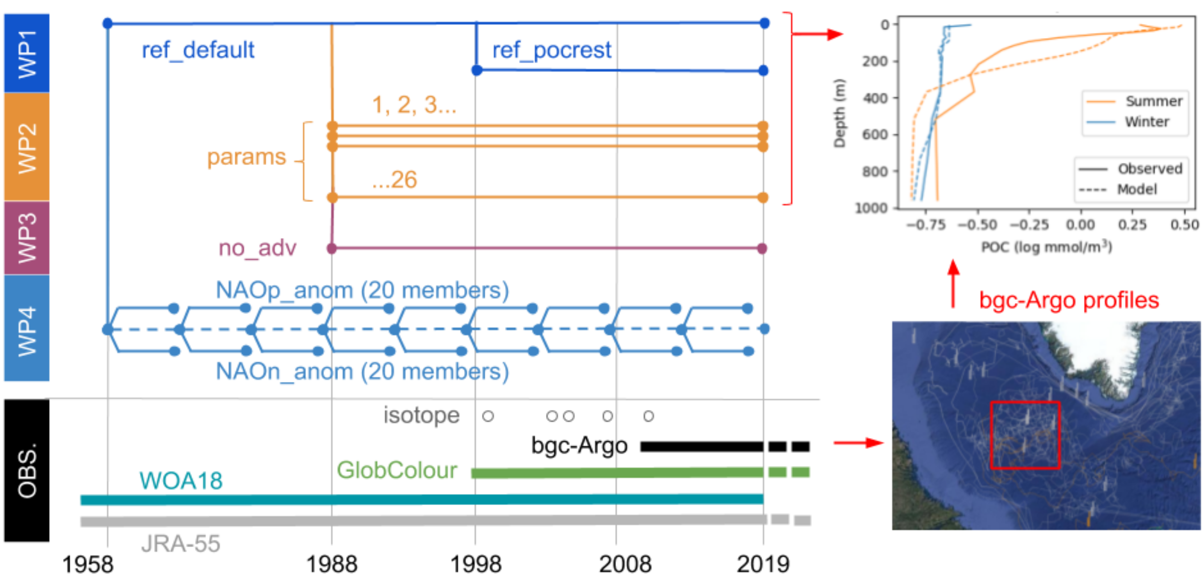
1.4 Methodology and work packages (WP)

WP1: Historical simulations and setup of data assimilation and evaluation/analysis tools
Galí (25%), Ruprich-Robert (25%), Llort (25%), Lapin (60% from his 0.5 EDP), Vegas-Regidor, (60% from his 0.5 EDP), RE1 (20%). Coordinated by Galí and Ruprich-Robert.

WP1 addresses Objective 1 and focuses on the production of NEMO4-PISCES historical simulations matching the last 60 years of biogeochemical observations (Fig. 5), and on the setup of PISCES diagnostics and evaluation tools that will enable analyses in WP2-4. All simulations will be launched using the *autosubmit*[40] software, which provides seamless simulation management and ensures reproducibility. We will setup two model configurations that will provide the templates for simulations carried out in WP2-4: one with the default PISCES configuration and parameter values (**ref_default**; task 1.2), and another where surface POC simulated by PISCES will be constrained to follow satellite-retrieved POC (**ref_pocrest**, task 1.3). The purpose of surface POC restoring is to correct potential model bias and/or to align model interannual variability to observations[41]. This development will allow us to evaluate how errors in simulated surface-ocean POC impact mesopelagic POC and, more importantly, to focus on the POC uncertainty arising from model representation of mesopelagic processes in WP2-4.

In WP1, the **ref_default** and **ref_pocrest** simulations will be subsequently evaluated against a wide array of observations. Comparison to monthly global climatologies of nutrients and dissolved O_2 will be used as a standard model skill metric over the entire simulation period (1958-2019). Simulated POC and chlorophyll-*a* will be compared to Bgc-Argo data both with and without climatological averaging. By comparing PISCES sPOC against climatological bgc-Argo sPOC over the 2010-2019 period we will evaluate the model's' skill at reproducing mean patterns; by comparing PISCES sPOC against non-climatological bgc-Argo profiles we will evaluate the models' ability to capture sPOC seasonal and interannual variability. These two evaluation frameworks are complementary because, despite the remarkable amount of available profiles, bgc-Argo data do not provide full coverage, resulting in uneven weighting of observations over seasons and regions. In case the **ref_pocrest** scheme is clearly superior at reproducing sPOC mean and variability, it will be used instead of the **ref_default** setup in all posterior analyses involving comparison with bgc-Argo observations (Fig. 5).

Figure 5



Tasks 1.1 - Design of model output and diagnostics for evaluation and budget calculations (led by M. Galí). New **diagnostics** will be implemented to enable PISCES to output all the terms (sources, sinks and horizontal transport) of mesopelagic sPOC and bPOC budget equations[19] between the base of the euphotic layer and 1000 m depth (10-day resolution). In addition, 3D fields of the concentrations of PISCES tracers (nutrients, O_2, phytoplankton and zooplankton biomass, DOC, sPOC and bPOC) and derived variables (chlorophyll-*a*) will be saved at monthly resolution prior to 1998, and at monthly and 10-day resolution afterwards. Outputs will be saved over the multiyear periods relevant for each planned analysis.

Task 1.2 - Production of a global-scale simulation of ocean biogeochemistry (1958-2019) (led by Y. Ruprich-Robert). We will produce a global simulation of ocean biogeochemistry using NEMO4-PISCESv2 (1 degree resolution -ORCA1 grid-, 75 vertical levels) forced by the JRA-55 atmospheric reanalysis (1958-2019). We will follow the standard protocol[42] of the Ocean Model Intercomparison Project (OMIP-2Tier 2) to constrain ocean physics and biogeochemistry. The OMIP protocol requires that atmospheric forcing is repeated 5 times to equilibrate the ocean physics (NEMO) and the output from a sixth cycle is considered. Ocean biogeochemical fields (PISCES) are equilibrated using the ocean circulation from the third cycle, and then are coupled back to the physics for the following 3 cycles, while atmospheric CO_2 is prescribed according to historical observations. This simulation is the reference run with default configuration, named **ref_default** (Fig. 5).

Task 1.3 - Implementation of surface POC restoring (led by V. Lapin). A surface restoring scheme will be implemented to correct modelled POC over the surface mixed layer according to satellite-retrieved POC[31]. Restoring will be applied during the period 1998-2019 (Fig. 5) using monthly POC fields from the merged multisensor product Globcolour, taking into account data gaps at high latitudes in winter[41]. Total POC in PISCES results from adding 6 explicit tracers: 2 phytoplankton, 2 zooplankton and 2 detrital (sPOC and bPOC) size classes. Thus, total PISCES POC will be scaled to satellite POC preserving the proportion between the 6 modelled components. We will test 2 alternative restoring approaches to correct for either mean sPOC bias only or both interannual variability and mean state biases. The approach showing the best balance between faithfulness to reality and minimal intrusiveness will be adopted, and called **ref_pocrest**.

Task 1.4 - Evaluation of simulated biogeochemical fields (led by J. Vegas-Regidor). We will setup procedures to evaluate model output variables against their observational counterparts in a wide array of available datasets including, at least (Fig. 5):

- Monthly mean climatologies of nutrients (nitrate, phosphate, silicate) and dissolved O_2 from the World Ocean Atlas 2018 (WOA2018) which covers the period 1955-2018.
- Concentration of sPOC, bPOC and chlorophyll-*a* between 0 and 1000 m estimated from bgc-Argo bbp700 profiles (n=11700) at 2 levels of data aggregation: 10-day binned data (non-climatological), and monthly binned data (2010-2019 climatology).
- POC export at the base of the euphotic layer determined with isotope techniques[28] (Th^{234} disequilibrium) (n=723 globally, n=111 in the subtropical-subpolar North Atlantic), with no data averaging (direct matching).

All observations will be regridded or binned onto the NEMO4-PISCES model grid using tools already available at ES-BSC, including ESMValTool which will be particularly useful for task 1.4.

WP2: Biogeochemical controls on mesopelagic POC budgets and their uncertainty

Galí (40%), Ruprich-Robert (15%), Llort (20%), Lapin (20% from his 0.5 EDP), Vegas-Regidor, (40% from his 0.5 EDP), RE1 (30%). Coordinated by Galí.

In WP2 we will address Objective 2 (H2) by analyzing the **ref** simulations in contrasting North Atlantic biomes to obtain a comprehensive picture of mesopelagic POC budgets. We will disentangle the contribution of sPOC and bPOC to mesopelagic respiration, zooplankton growth and vertical POC flux. Previous research[7,9] and results from our ongoing ORCAS project indicate that the sPOC residence time in different mesopelagic depth horizons depends on the interplay between remineralization k, zooplankton flux-feeding and sPOC sinking speed. Thus, we will quantify the POC budget uncertainty by perturbing these parameters within a range of realistic observed values. These sensitivity tests will produce mechanistic understanding of the biogeochemical processes that control mesopelagic budgets and turnover times of both sPOC and bPOC over the seasonal cycle, paving the way for the analyses proposed in WP3-4.

Task 2.1 - Quantification of mesopelagic sPOC and bPOC budgets (led by M. Galí). We will firstly visualize, identify and analyze the main sPOC and bPOC budget terms (fluxes) diagnosed from **ref** PISCES runs (see tasks 1.1). Secondly, we will analyze the relative contribution of sPOC and bPOC to the total mesopelagic POC fluxes. Thirdly, we will analyze the link - taking into account potential temporal delay - between vertical mixing, euphotic layer processes (primary production and export) and mesopelagic POC consumption rates (e.g. by bacterial remineralization and zooplankton flux feeding) over the seasonal cycle. To perform these analyses we will integrate POC fluxes over different spatio-temporal domains, examining both (a) seasonal vertical profiles of spatially-aggregated fluxes, and (b) horizontal variations (maps) of fluxes integrated over defined vertical domains (euphotic layer, upper and lower mesopelagic layers). Spatial integration will be performed over 2 different scales: in the entire STG and SPG biomes[43]; and in smaller regions within each biome, defined on the basis of oceanographic and ecological features and the abundance of bgc-Argo data. For example, the Labrador Sea, Irminger Sea and Iceland basin within the SPG, and a rectangular region in the western subtropical N Atlantic (20-25N, 35-45W).

Task 2.2 - Analysis of parametric uncertainty (led by M. Galí). We will run simulations for the period 1988-2019 by perturbing 3 selected parameters (remineralization k, detritivorous zooplankton flux feeding, and sPOC sinking speed) by a factor of ½ or 2 in all possible combinations. This makes a total of 27 model runs (**params** simulations, Fig. 5) including the **ref** run computed in WP1. Due to parameter perturbation, mesopelagic POC distribution will reach a new equilibrium that is expected to be attained after 5-10 years according to our preliminary results (cf. Section 1.1). Following this spin-up (1988-1997), all **param** simulations will be evaluated against bgc-Argo observations (see task 1.4). We will estimate parametric model uncertainty as the maximum range of the anomalies in the 27 **param** runs. All analyses will be done in the same spatio-temporal framework as described in task 2.1. To quantify how much certain combinations of parameters improve or degrade model skill for the proper reasons, we will compare the simulations at the process-level. We will compute the anomalies of sPOC concentration and major sPOC fluxes (identified in task 2.1) with respect to **ref** and we will analyze statistically the relationship between sPOC flux anomalies and the values of the perturbed parameters.

WP3: Impact of horizontal advection on mesopelagic POC budgets
Llort (40%), Galí (15%), Ruprich-Robert (20%), RE1 (20%). Coordinated by Llort.

The ability to simulate realistic mesopelagic sPOC fields with PISCES finally enables examining the role of lateral sPOC transport. Lateral sPOC inputs have been poorly addressed in the past, and could help explain patterns of mesopelagic microbial abundance, activity (growth, respiration) and genetic composition through horizontal connectivity of particle populations. To address Objective 3 and H3, we will perform a detailed analysis of the sPOC mass transports, their contribution to mesopelagic POC stocks and budgets, and their control on sPOC residence times. In addition, we will quantify the impacts of sPOC advection on modelled mesopelagic respiration through idealized experiments.

Task 3.1 - Characterization of advective sPOC transport: fluxes and pathways (led by J. Llort). In a first step, we will analyze major sPOC transport pathways at the basin scale by (a) mapping sPOC mass transports in latitudinal and longitudinal directions and (b) analyzing sPOC mass transports across selected sections. We will then assess the contribution of net sPOC transport to total POC turnover. These analyses will allow us to identify regions where advective processes play a prominent role, either because they are net sPOC exporters or net sPOC importers. In these advection-influenced regions we will conduct a detailed analysis of the contribution of sPOC advection to sPOC turnover along the vertical and temporal (seasonal) axes. We expect the largest horizontal sPOC exports (inputs) to occur within (downstream of) productive surface ecosystems, conveyed by intermediate and mode waters. Candidate source regions include the vicinity of the Newfoundland shelf, where Subarctic Intermediate Water is formed by water-mass mixing and dynamically subducted; the Iceland and Irminger Seas, which export Subpolar Mode Waters formed by atmospheric cooling along the SPG cyclonic circulation; and the Labrador Sea, which exports to the entire basin the water mass formed by deep convection.

Task 3.2 - Impact of horizontal POC advection on other biogeochemical fields (led by J. Llort). To further evaluate the importance of sPOC horizontal advection in the spatio-temporal distribution of mesopelagic POC, we will perform an additional simulation in which horizontal transport of mesopelagic sPOC will be suppressed (**no_adv**; cf Fig. 5). The comparison of **no_adv** with **ref**, by means of anomaly profiles and maps, will reveal the impact of sPOC horizontal transport on both sPOC budgets and bacterial activity. Furthermore, we will evaluate whether the absence of advection affects remineralization rates and other biogeochemical fields. We will put particular attention to nutrients and zooplankton abundance as both have implications on the energy transfers sustaining the trophic chain.

WP4: Estimation of the mesopelagic POC interannual variability
Ruprich-Robert (40%), Galí (20%), Llort (15%), Lapin (20% from his 0.5 EDP), RE1 (30%). Coordinated by Ruprich-Robert.

In OPERA, for the first time, we will investigate the interannual variability of mesopelagic POC, with the main objective of identifying the principal budget terms controlling this variability. This will address Objective 4 (H4). Mesopelagic POC distribution depends on euphotic-layer plankton activity, mesopelagic microorganism activity and remineralization rates (controlled by water mass temperature), zooplankton flux-feeding, and vertical turbulent mixing. Any fluctuation in one of these parameters is expected to lead to mesopelagic POC variations. As the North Atlantic Oscillation (NAO) is the main driver of oceanic temperature, circulation and upper layer mixing in the North Atlantic at interannual timescale, we will particularly focus on the mesopelagic POC response to this atmospheric forcing.

Task 4.1 - Exploring the mesopelagic interannual variability (led by Y. Ruprich-Robert). Based on the mesopelagic POC budget performed in task 2.1, we will quantify the main budget terms controlling interannual variability of mesopelagic POC at the basin, gyre, and local scales in our simulations. We will perform separate composite analysis of the mesopelagic POC budget for NAO+ and NAO- years as case studies for interannual variability. Particularly, we will estimate the rapid effect on mesopelagic POC of the NAO forcing through changes in the mixed layer depth[36] as well as the lag effect of the NAO through its impacts on oceanic circulation and water mass temperature. The simulated composite analyses will be evaluated against similar composites performed from observation estimates. Both reference simulations **ref_default** and **ref_pocrest** (cf. Tasks 1.2 and 1.3) will be evaluated to estimate the impact of model surface POC concentration biases on the representation of mesopelagic POC variability.

Task 4.2 - Simulations with NAO perturbation (led by Y. Ruprich-Robert). To better estimate the mesopelagic POC response to an NAO forcing and the predictability associated with this response, we will perform perturbation experiments with PISCES, named **NAOp_anom** and **NAOn_anom**. Several four-year long simulations will be performed in which additional canonical NAO surface fluxes (heat, freshwater, and momentum) will be added to the JRA-55 historical atmospheric forcing during the first winter and then integrated as for the **ref** simulation. To take into account the internal variability of the climate system dynamics, twenty ensemble members will be performed for both the positive (NAOp_anom) and the negative (NAOn_anom) phases of the NAO. Therefore, although all members will share the same additional NAO forcing anomalies during the first winter, each member will differ by their initial conditions taken from different dates of the **ref** simulation and by their full atmospheric forcing, matching the **ref** simulation period. The ensemble mean of each **NAO_anom** experiments will be compared to the corresponding period's mean of the **ref** simulation. The differences will inform us on the mean mesopelagic POC response following an NAO forcing. The predictability of this response will be estimated using signal to noise ratios.

1.5 Chronogram and risk assessment and contingency plan

Work Packages	Tasks, Milestones and deliverables	Responsible	Year 1												Year 2												Year 3											
			Trim. 1			Trim. 2			Trim. 3			Trim. 4			Trim. 1			Trim. 2			Trim. 3			Trim. 4			Trim. 1			Trim. 2			Trim. 3			Trim. 4		
			1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
WP1	1.1 Budget diagnostics setup	Galí																																				
	1.2 Reference simulation	Ruprich-R.																																				
	1.3 Surf. restoring simulation	Lapin																																				
	1.4 Evaluation tools	Vegas																																				
WP2	2.1 Mesopelagic budget analysis	Galí																																				
	2.2 Parameter perturbations exps.	Galí																																				
WP3	3.1 Advection analysis	Llort																																				
	3.2 Advection perturbation epxs.	Llort																																				
WP4	4.1 Interannual variability analysis	Ruprich-R.																																				
	4.1 NAO perturbation exps.	Ruprich-R.																																				
Diffusion	Synthesis	All																																	D-Final		
	Scientific articles	All*																				D-WP2							D-WP3						D-WP4			
	Milestones	All*			M1			M2			M3			M4																								
	Conferences	All					A				E								A			OS	E								A				E			I
	Workshops	All			S								O	C	T	Co	S									C	T		S									C

Gantt chart of the OPERA project. The chart assumes a start of the project in August 2020.

Milestone (M). Over the first year, we fix as objective to reach a milestone every 3 months that correspond to the finalization of the 4 technical tasks of WP1

Deliverable (D). Over the remaining 2 years of the project, each deliverable corresponds to the submission of a scientific article, one per WP as described in Section 2.3. The final deliverable corresponds to a high level OPERA synthesis article. (*): activity led by WP leader.
Conferences. **A**: Amercian Geophysical Union, San Francisco; **E**: European Geophysical Union, Vienna; **OS**: Ocean Sciences, Hawaii; **I**: International Union of Geodesy and Geophysics, Berlin.
Workshops. **O**: OPERA workshop, Barcelona; **S**: SUMMER workshop, Derio, Spain; **T**: TRIATLAS workshop, Cape Verde; **C**: CCICC workshop, Brussels; **Co**: COMICS workshop, London.

Risk assessment and contingency plan: The NEMO4 model, which includes PISCES, has recently been ported on MN4 and is being currently used in the project ORCAS (Dr. Galí). This is a major guarantee to produce the project simulations in a timely fashion and without critical delays that would compromise the successful completion of OPERA. Similarly, the data storage infrastructures and most of the initial processing steps for bgc-Argo and satellite data are already setup at ES-BSC. Task 1.3 proposes a technical development (surface POC restoring) that has never been tested for this variable; yet, this task relies on the confirmed expertise of our team members Dr. Lapin and Dr. Ruprich-Robert. Task 1.4 consists mainly in the adaptation of tools and workflows that are currently being tested for other model setups and observational datasets in ES-BSC by our team member Javier Vegas-Regidor. Task 4.2 requires the implementation of a new code subroutine. This will be implemented by Dr. Ruprich-Robert who has already proven his excellent skill in modifying the NEMO code. Therefore, the overall technical risk in our proposal is low. However, in the case that one task doesn't get achieved, the others would be investigated more thoroughly.

1.6 Technical resources

Since its creation in 2006, the BSC has hosted outstanding high-performance computing facilities, which are made available to all its research groups through a bag of non-competitive computing time. These internal resources are a solid basis to support the execution of the experiments envisaged in OPERA if application for other resources do not prove successful. For the main bulk of the experiments, we will demand computing time to the competitive programs from the Red Española de Supercomputación (RES) and the Partnership for Advanced Computing in Europe (PRACE), submissions with which the ES-BSC has had a high success rate.

The current supercomputer, MareNostrum 4 (MN4), was installed in 2017 and is one of the 7 Tier-0 Systems currently available through PRACE. Technical features of MN4 to highlight are: a peak power of 11.15 Petaflops, that enables it to perform more than eleven thousand trillion operations per second (ten times more than its predecessor MN3); a disk storage capacity of 14 Petabytes that is connected to the Big Data infrastructures of BSC-CNS, with a total capacity of 24.6 Petabytes. Current MN4 is expected to be replaced by MN5 in 2021. MN5 will have a peak performance of 200 Petaflops, being one of the 3 pre-exascale supercomputers in Europe.

All BSC scientists have desktops with multi-core processors that are available through the local network and share exactly the same software stack and modules. The available infrastructure and technical expertise offer a seamless environment to perform research in a reproducible way. Reproducibility builds on version control of scientific code through common repositories (BSC-Earth-Gitlab) and access to common data repositories to ensure that the research carried out makes use of the latest, highest quality observational datasets. To facilitate an efficient development of the activities within the BSC and during missions outside the BSC (attendance to meetings and visits to our collaborators), we have budgeted two workstations (PCs) and two laptops with an UNIX-based OS, covering the needs of the Research Engineer and the PhD student we plan to incorporate. To store the simulation outputs and processed satellite datasets produced during OPERA, we requested hardware to expand the storage system of the Department (1 disk cabinet and 5 disks).

1.7 Human resources

The OPERA project will be carried out within the Climate Prediction (CP) and the Computational Earth Sciences (CES) groups of the ES-BSC. Thanks to the tight collaboration between researchers and computing engineers, OPERA can count on a unique combination of human resources to secure essential technical developments that will enable forefront scientific results. Members of CES are highly qualified to deal with complex parallelized codes such as the ones that will be used in OPERA, and also provide IT support and maintain common repositories. CP and CES members benefit from frequent training events offered by BSC. BSC also has dedicated Communication and Project dissemination units (10 staff members) that will provide assistance with outreach activities, publications and transfer of knowledge.

Requested human resources: To achieve the ambitious objectives of OPERA, its team would need to contract a Junior Research Engineer (RE1) for 3 years. He/she will join the CES group under the advice of Martí Galí, co-PI of OPERA. The RE1 will be involved in all phases of the project, particularly in the generation and post-processing of PISCES simulations. The RE1 will (i) carry out most of the simulations of WP2-4 under the supervision of the researchers responsible for each task; (ii) perform computationally demanding post-processing of simulations produced in tasks 2.2 and 4.2; (iii) perform model evaluation tasks using ESMValTool under the supervision of Javier Vegas-Regidor; and (iv) maintain code repositories. The profile of the RE1 should fulfill these characteristics: having a Master's degree in Computer Science, Mathematics or Physics; excellent development skills in Python (knowledge of R will be an asset); experience with UNIX/LINUX environments and scripting languages (bash); experience of version control in a distributed team (SVN or Git); experience in HPC architectures and parallel programming; previous experience in climate or ocean modeling; and overarching competencies including good communication skills, fluent English, team-work skills and individual initiative. The employment offer will be posted on BSC's Job Opportunities portal and advertised through appropriate channels as soon as the project is granted.

2. IMPACTO ESPERADO DE LOS RESULTADOS - *EXPECTED RESULTS IMPACT*

2.1 Scientific and technical impact

Advancing knowledge: The improvement of our understanding of mesopelagic carbon budget will translate into a better representation of ocean carbon cycle in Earth System Models. The total ocean carbon storage can be considered as the sum of a fraction of the extra carbon emitted by human activities (anthropogenic carbon) and the carbon that was already stored in the ocean in preindustrial times (natural carbon). Both carbon fractions are continuously exchanged with the atmosphere but although we can only measure their sum, model estimates show that the natural component of the air-sea flux dominates the total, being the net anthropogenic flux only a small residual (IPCC-AR5). The ocean takes up anthropogenic carbon through physical processes while biogeochemistry acts mostly on the natural carbon. Both components are highly uncertain, especially when considered regionally, yet the natural carbon flux has received far less attention because it is believed to be in a global steady-state. However, our limited knowledge of the mechanisms regulating the mesopelagic carbon budget does not justify this assumption. The knowledge generated with OPERA will tackle this issue and will reduce the uncertainties in the estimates of future ocean carbon uptake.

Understanding the fate and residence times of mesopelagic organic particles is also crucial for predicting ocean carbon storage and the dynamics of mesopelagic food webs. Failing to do so will perpetuate the current uncertainties in the carbon budgets hindering our understanding of one of the vastest and still untamed (yet threatened[44]) ecosystems on the planet. The results of OPERA will directly be used to improve higher level trophic web models, as direct estimates of mesozooplankton secondary production can be diagnosed in PISCES, and the potential transfer of biomass to higher trophic levels can be estimated from the mesozooplankton mortality closure term[19].

Developing synergies: OPERA is highly complementary to ongoing initiatives at international level. Good examples are the EU-funded projects SUMMER, MEESO, TRIATLAS, INADEC and CCICC, all of which include members of the OPERA working team as coordinators or work package leaders. This provides a clear opportunity to optimize research efforts and budgets, which will be accomplished through organization of the OPERA workshop and attendance to workshops of the projects led by our external collaborators. These activities have the potential to be the seed for future Horizon Europe proposals, aligned with the objectives of both the EU's Blue Growth Strategy and Spain's Strategy for Science, Technology and Innovation.

Leveraging Earth Observation (EO) programs: OPERA objectives support the continued investment in long-term EO programs and data access platforms. Commitment of ES-BSC members to EO is currently being channeled through CMUG (Climate modeling User Group; with Dr. Pablo Ortega acting as PI at BSC) an ESA Climate Change Initiative promoting the use of community datasets (e.g. CMIP6). Other prominent examples of synergies with ongoing EO programs are:

- GlobColour and CCI, initiatives sponsored by the European Space Agency aiming to provide end users with consistent multiyear datasets of ocean colour satellite data.
- REFINE (Robots Explore plankton-driven Fluxes in the marine twIlight zone), an ERC-funded project led by Hervé Claustre, collaborator of the ORCAS project (Galí).
- EXPORTS (Export Processes in the Ocean from Remote Sensing), an ambitious project funded by NASA to estimate POC export and sequestration.
- SOCCOM, a project sponsored by US' NSF that makes extensive use of bgc-Argo floats and models to understand Southern Ocean biogeochemistry.
- PACE, NASA's ocean color flagship initiative that will enhance the retrieval of DOM and POM concentrations and properties from space using hyperspectral sensors.

Potential for technological transfer. Thanks to their moderate computational cost, intermediate complexity models like PISCES are the workhorse for global biogeochemistry studies, high-resolution simulations and operational applications. To strengthen the efficiency and community impact of our work, all the numerical tools and scripts developed within OPERA will be openly shared through a GitHub platform under GNU licenses, and original simulation data will be publicly shared through Pangaea. These practices promote research reproducibility and transparency.

2.2 Social and economic impact

The mesopelagic ocean is currently one of the main knowledge frontiers in marine biogeochemistry. Understanding the mesopelagic carbon budget is crucial for representing correctly (1) the ocean carbon cycle and (2) the dynamics of mesopelagic food webs. The former will benefit society directly by reducing the uncertainties in the estimate of future ocean carbon uptake as well as to better evaluate current emissions with respect to the Paris Agreement. By better representing carbon supplies to mesopelagic small fish, the latter will support improved estimates of the productivity of species with commercial and strategic value[45].

The longevity of North Atlantic commercial fisheries and of the research devoted to this region has allowed to identify clear correlations between the basin-wide abundance of fish and the NAO. Less clear are the associated mechanisms that cascade the environmental alterations from the bottom up to the top of the trophic chain. Mesopelagic POC is expected to play a fundamental role as it is the source of food for detritivorous zooplankton, which in turn sustains small commercial fish (sardine, herring, squid) and, indirectly, large species. A better understanding of mesopelagic POC dynamics will help teasing apart the drivers of changes in fish stocks and point out which processes need to be included in future models to successfully predict changes in marine resources.

The Earth System Services group at ES-BSC will interact with the OPERA team to explore possible outlets of results outside the scientific community. Collaboration with Dr. Irigoien, Scientific Director at AZTI-Tecnalia, ensures that any finding of relevance for the sustainable management of ocean resources will be transferred to marine ecosystem stakeholders. AZTI Foundation is a public-private partnership with the mission of promoting technological transfer to develop sustainable products, services and business initiatives aimed at preserving natural resources.

2.3 Dissemination plan

Peer-reviewed publications and conferences: The OPERA research results will be disseminated to the scientific community through publications in international peer-reviewed journals, aiming at high-impact journals such as Science, Nature group or PNAS whenever appropriate. To guarantee open access to all peer-reviewed scientific publications related to the project, BSC will provide open access, and will deposit all the articles in the institutional repository UPCommons to ensure they are preserved in the long term. At least 4 research articles are foreseen, 3 articles dedicated to the outputs of WP2-4 and a fourth article that will synthesize the full outcomes of the project:

1. WP2: *Biogeochemical processes driving mesopelagic POC budgets across North Atlantic biomes*
2. WP3: *The Role of advection in mesopelagic POC distribution and budgets in the North Atlantic*
3. WP4: *Role of the NAO in the interannual variability of mesopelagic POC dynamics*
4. Synthesis article: *Drivers and variability of North Atlantic mesopelagic POC budgets*

At least 3 additional articles will result from research carried out by the PhD student. The specific content of these articles will depend on the research path designed jointly by the PhD student and the co-supervisors Dr. Galí and Dr. Ruprich-Robert (Section 3). In addition to peer-reviewed articles, the researchers involved in OPERA will attend international conferences to present the results of the project (8 presentations planned). In particular, they will attend to the American and European Geophysical Union General Assemblies, the Ocean Sciences conference, and workshops focusing more specifically on ocean biogeochemistry (cf. Gantt chart in Section 1.5). OPERA members will also use visits to the institutions of the external collaborators as opportunities to present the OPERA research results to an aimed research community.

Outreach and dissemination through the Earth System Services group. One of the priorities of the project will be to seek public engagement through the active and effective communication of results to the non-specialized audience and to students. OPERA will have the support of the BSC Communication Department and the Earth System Services group of ES-BSC for the following planned activities:

- Inclusions of the project information, progress and results in several dissemination activities of BSC (e.g., website, presentations, leaflets, brochures, videos),
- Participation in MareNostrum open day events for high school, graduate students, and general public.
- Organization and participation as teachers in the “Crazy about Supercomputing” event, an annual hands-on course directed toward first-year high-school students with a special interest in the multidisciplinary research that uses the MareNostrum supercomputer (CP group and OPERA members participated in previous editions).

3. CAPACIDAD FORMATIVA - *TRAINING CAPACITY*

Aligned with this project, we will offer training to one PhD student, providing her/him the opportunity to work in a highly international and multidisciplinary scientific environment in the ES-BSC. We will recruit and enroll a PhD student in the doctoral program in Marine Sciences of the Polytechnical University of Catalonia (UPC), which was recognized with MEC Excellence Mention from 2003 to 2013 (MCD2004-00394, MEE2011-0335). The PhD offer will be advertised through institutional platforms and using the extensive international network of collaborators of the OPERA team members.

Proposed training program: The proposed PhD project aims at furthering our understanding of mesopelagic carbon budgets, their drivers and controlling factors, exploiting the comprehensive sets of simulations that OPERA will produce and performing additional experiments if required. Under the co-supervision of Dr. Galí and Dr. Ruprich-Robert, experts in biogeochemistry and ocean dynamics, the PhD student will have the opportunity to shape her/his very own project depending on her/his affinity with the following proposed tasks:

1. An integral approach toward quantifying mesopelagic POC budgets, using both satellite-based empirical models and numerical models. This work would benefit from collaboration with Dr. Henson (NOC) and Dr. Aumont (LOCEAN), and would tackle regions other than that investigated in OPERA, for example the Southern Ocean (a highly relevant region for global ocean functioning and climate).
2. Investigating the variability of mesopelagic biogeochemistry at longer timescales, e.g. through persistent (multiyear) NAO forcing experiments, or by introducing other modes of atmospheric forcing variability like ENSO or volcanic eruptions. By focusing on sources of variability, this approach would pave the way toward seasonal to decadal prediction of mesopelagic biogeochemical cycles and biological resources, relying on collaboration between BSC’s ocean modellers and the AZTI-Irigoien group.
3. Exploring the impacts of multiple stressors (e.g. temperature, deoxygenation and ocean acidification) on mesopelagic biogeochemistry under a number of future global change scenarios. This pathway is well aligned with research conducted by our external collaborators Dr. Henson and Dr. Aumont.
4. Exploring, from the physical dynamics point of view, the links between POC transformations and transport and water-mass formation processes, focusing on changes driven by the NAO. This

pathway could include studying the impacts of model resolution, by comparing selected OPERA simulations at standard 1-degree resolution to 1/4 and 1/12 degree resolution.

Our flexible approach to supervision will ensure that the trainee develops his/her own research path and skills. All the topics proposed above are very timely and interdisciplinary, and can guarantee the future employability of the PhD student in- or outside academia.

The PhD student will count on the direct supervision and advice of the co-PIs of the project, Dr. Martí Galí and Dr. Yohan Ruprich-Robert. They will guide him/her to develop a Research and Training Plan within the first academic year, considering both the training goals and the student needs. The training plan will be oriented towards the acquisition of competences in biogeochemical modeling, ocean dynamics, and analysis of climate-forced interannual variability. The student will be involved in the research group activities, including periodical internal and external seminars and invited speaker conferences held at BSC. In addition, he/she will be strongly encouraged to share the results of her/his research in different national and international scientific forums, will be guided in the publication of her/his original work in high impact scientific journals, and will also have the opportunity to co-author scientific articles.

Training environment and career trajectories at the ES-BSC: The Earth Sciences Department has a long record of supervising PhD theses in doctoral programs of the UPC. Since the ES-BSC has been established in its current form in 2014, 8 PhD theses were completed and 10 are currently ongoing within the Department. In addition, the BSC has a dedicated Education and Training Team, offering tailored training activities to develop and strengthen important skills for a scientific career. These training activities cover technical, research and soft skills, and cover a wide range of topics from specific programming techniques or HPC skills, to project management and leadership training, for example. These training opportunities are available not only to the PhD student, but to all BSC staff including all members of the research team. BSC offers a personalized professional development plan to all staff, according to their profile and objectives. Thanks to this approach, BSC has been awarded with the Human Resources Excellence in Research, recognizing the alignment of its human resources policies to the principles set out in the EU Charter and Code for Research. The excellence of the BSC training environment is attested by the success of doctors and postdocs trained in the Department, both in academia (Dr. Carlos Pérez García-Pando, Dr. Kaarsten Haustein, Dr. Martin Ménegoz, Dr. Rachel White) and in the private sector (Dr. Matthias Piot, Dr. Omar Bellprat).

Training capacity of the OPERA research and working teams: The co-supervisors, Dr. Galí and Dr. Ruprich-Robert, are outstanding early-career scientists and acquired experience in student mentoring through their successive doctoral and postdoctoral positions in top research groups and institutions worldwide. During his PhD at ICM-CSIC (Barcelona), Dr. Galí closely supervised the work of Sarah-Jeanne Royer, and remained highly involved with her research until her PhD graduation (2015) as attested by 3 co-authored publications (Environ Chem, GRL, Scientific Reports; 2 of which as second author). Since 2016 Dr. Galí has been co-supervising Pablo Rodríguez-Ros, a visiting PhD student from ICM, after hosting him for 3 months at Laval University. Since December 2018, Dr. Galí has been supervising Marcus Falls, a Research Engineer dedicated full time to the project ORCAS led by Martí Galí. The co-supervisor Dr. Ruprich-Robert acquired training experience during his postdoc at Princeton University / GFDL, where he co-supervised the work of Irene Mavilia, a PhD student from the University of Bologna, during her 4-month visit at GFDL. This research was published in Climate Dynamics. At BSC, he co-supervised in 2018 the work of Miquel Canal, a summer undergraduate student. Since October 2019, Dr. Ruprich-Robert is co-supervising the work of Paloma Trascasa, who is doing her PhD at the University of Leeds (UK) and BSC.

Complementary skills required for efficient research execution and communication will be fostered through the student participation on multiple training activities offered by BSC. Thanks to her/his strong involvement in OPERA, the PhD student will collaborate with scientists from four European institutes. In this context, several-months-length visits will be organised for her/him at LOCEAN, NOC or AZTI depending on the pathway he/she prioritizes. The PhD student will take part in the OPERA workshop and its organization and will be invited to participate in European project workshops in which the OPERA team is involved. The foreseen scientific visits and the participation to project workshops will open career opportunities for the PhD student. In addition to his/her direct supervisors, the PhD will also benefit from the vibrant research atmosphere at BSC and the specific guidance from members of the OPERA research and working teams at BSC (Llort, Bernardello) and abroad (Henson, Aumont, Irigoien).

Additional training opportunities: In addition to successful formation of PhDs, the Department has a long history of hosting Master or intern students during their Master or end-of-degree research projects. In this context, we will offer research work aligned with the OPERA objectives for Master thesis projects or summer internships to interested students, building on the well established participation of ES-BSC in UPC degrees and Masters' programs.

4. CONDICIONES ESPECÍFICAS PARA LA EJECUCIÓN DE DETERMINADOS PROYECTOS - *SPECIFIC CONDITIONS FOR THE EXECUTION OF CERTAIN PROJECTS*

Not applicable.

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SUPPORT LETTERS

We include here two support letters to our project OPERA from Dr. Josep Gasol (CSIC, Spain) and Dr. Hervé Claustre (CNRS / Sorbonne Université, France). The online version of these letters can be found here (Gasol) and here (Claustre).

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
INSTITUT DE CIÈNCIES DEL MAR (ICM)

Barcelona, 12 October 2019

To whom it may concern:

This is a support letter to project **OPERA (Organic Particle Export, Respiration and Advection in the North Atlantic mesopelagic layer),** submitted by **Dr. Martí Galí** to the Convocatoria 2019 de Proyectos de I+D+i del Plan Estatal de Investigación Científica y Técnica y de Innovación del Ministerio de Ciencia, Innovación y Universidades. I know Dr Galí from his PhD work when we collaborated in some studies, and as a microbial oceanographer that has extensively worked on the microbial ecology and biogeochemistry of the dark ocean, I support the project because:

- This is an extremely relevant subject, as our understanding of the capacity of the ocean to sequester atmospheric carbon relies on what actually occurs with sedimenting particles in the mesopelagic regions of the ocean. We can hardly measure, model or predict the role of this ocean layer because of our lack of understanding of its biogechemical functioning.
- This is a timely project because of our recent identification of the role that small particles and their transformations play in this layer, and the recent availability of models and measurement devices that account for these particles.
- Throughout his education, and in particular during the time he has worked in Canada, Dr. Galí has mastered a strong portfolio of methodologies, that includes biogeochemistry, microbial ecology, satellite oceanography and ecosystem modelling. He is in a perfect position to address the challenges posed in the project, and I am certainly sure he will suceed.

Josep M. Gasol
CSIC Research Professor
Departament of Marine Biology and Oceanography
Institut de Ciències del Mar, CSIC

email: pepgasol@icm.csic.es

Pg. Marítim de la Barceloneta, 37-49
08003 Barcelona, Catalunya, Spain
TEL.: +34 93 230 95 00

CNRS — SCIENCES SORBONNE UNIVERSITÉ

Observatoire Océanologique de Villefranche-sur-Mer
LABORATOIRE D'OCÉANOGRAPHIE DE VILLEFRANCHE - LOV

Hervé Claustre
CNRS Research Director
claustre@obs-vlfr.fr

Villefranche-sur-mer, October 13, 2019

Attn: Support letter for the research proposal OPERA, "Organic Particle Export, Remineralization and Advection in the North Atlantic mesopelagic layer"

With this letter I would like to express the excellent impression I have of the research proposal being submitted by Dr. Martí Galí and Dr. Yohan Ruprich-Robert (co-PIs). The proposal aims at a highly relevant topic and is very important for our understanding of ocean biogeochemistry. In my view, the major strength of the proposal is the tight combination of observations from autonomous platforms (biogeochemical-Argo floats and satellites) and modeling (with the PISCES biogeochemical model). Autonomous platforms are revolutionizing the observation of underexplored deep ocean ecosystems, and are poised to play a central role in ocean discovery in the next decades. As a promoter of the biogeochemical-Argo program through the ERC-funded RemOcean and REFINE projects, I can state without hesitation that modeling is an essential part of the deployment strategy of biogeochemical-Argo floats.

The OPERA project brings together expertise from various disciplines, an approach that is essential to deal with the complex Ocean system. In recent years I have established collaboration with Dr. Martí Galí and Dr. Joan Llort (member of the OPERA research team). With this perspective, I am confident that the complementary profiles of these researchers will be a major asset to achieve the ambitious goals of the OPERA proposal. I sincerely hope that this excellent project will receive funding.

Sincerely yours,

Hervé Claustre

Poste
LOV – UMR7093
181 chemin du Lazaret
06230 Villefranche-sur-Mer Cedex
France

Livraisons
LOV, Station Zoologique
181 chemin du Lazaret
06230 Villefranche-sur-Mer
France

Téléphone/email
Secrétariat : +33 (0)4 93 76 38 16 T
Administration : +33 (0)4 93 76 38 03 T
Télécopie : +33 (0)4 93 76 38 34 T
email : lov@obs-vlfr.fr