Convocatoria 2022 - «Proyectos de Generación de Conocimiento»
Formato Memoria Científico-Técnica Proyectos Individuales

1. *PROPOSAL DATA*

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TÍTULO DEL PROYECTO (ACRÓNIMO): ***Respuesta de la BIOgeoquímica oceánica a estimaciones refinadas de deposición de hierro aTmosférico en climA presente y futuro (BIOTA)***
TITLE OF THE PROJECT (ACRONYM): Ocean BIOgeochemistry response To refined Atmospheric iron inputs in present and future climate (BIOTA)

2. *CURRENT STATUS AND JUSTIFICATION OF THE PROPOSAL*

2.1 Adequacy of characteristics and the purpose of selected modality.

2.1.1 Relevance of the atmospheric deposition of soluble iron for the climate.

About a quarter of the emitted CO_2 since the industrial revolution has been uptaken and stored by the ocean (Ciais et al., 2013). Although physical drivers (e.g., warming or wind stress) control the present-day anthropogenic carbon sink, biological processes are responsible for most of the vertical gradient in the ocean's dissolved inorganic carbon. Besides, the biology-mediated vertical transport of carbon into the deep ocean, known as the Biological Carbon Pump (BCP), is an essential mechanism for long-term CO_2 storage (Canadell et al., 2021) and the contribution of biological processes to CO_2 uptake is expected to become more significant with continued climate change (Hauck et al. 2015, Ostle et al., 2022).

Ocean biological processes are sustained by marine primary production (PP), which in turn depends on the availability of light and nutrients like nitrogen (N), phosphorus (P), iron (Fe), and silica (Si) (Moore et al., 2013). In open areas of the ocean, far from the coastal influence and with limited supply from the bottom, atmospheric deposition constitutes the primary source of nutrients (Jickells et al., 2005, Mahowald et al., 2017). Particularly, atmospheric iron deposition controls primary productivity in high nutrient low chlorophyll regions, such as the Southern Ocean, the east equatorial Pacific or the North Pacific. Nitrogen fixers extend this sensitivity to oligotrophic ocean regions (Jickells et al., 2005; Mahowald et al., 2017). As a result, marine PP is under the influence of atmospheric deposition of iron in one-third of the global ocean.

Increasing our knowledge of the present and future evolution of atmospheric iron deposition is fundamental to better understanding the ocean's role in the global carbon cycle and accurately assess the impact of carbon mitigation policies.

2.1.2 Sources and processes that affect the soluble iron deposition in the ocean.

Mineral dust, emitted by wind erosion from arid and semi-arid regions of the world, constitutes the primary source of iron to the atmosphere, contributing more than 90% of the total iron emitted mass at present (Mahowald et al., 2009). Combustion sources, both natural (e.g., forest fires) and anthropogenic (e.g., fossil fuels combustion), emit the remaining ≈10 % (Luo et al., 2008; Bergas-Massó et al., 2022). However, ocean productivity relies specifically on the bioavailable Fe fraction, which is often assimilated to the soluble Fe fraction (i.e., that on Fe(II) oxidation state). While freshly emitted iron from dust sources is highly insoluble, it gets dissolved during transport owed to atmospheric processing (Rodríguez et al., 2021; Shi et al., 2012). On the other hand, Fe from combustion sources presents a higher solubility at emission (Ito et al., 2019; Hamilton et al., 2020), and it is usually co-emitted with other gas-phase and aerosol species that enhance atmospheric dissolution. Atmospheric iron dissolution occurs primarily through acidic (Shi et al., 2011a,b), organic ligand-mediated and photo-reductive dissolution processes (Pehkonen et al., 1993; Paris and Desboeufs, 2013). As a result, the amount of soluble iron deposited in the ocean depends on environmental factors (e.g., humidity, aerosol and cloud droplets acidity, presence of chemical precursors, temperature or sunlight), as well as on characteristics of the iron-containing aerosols (such as particle size, which inherently affects its residence time in the atmosphere), or mineralogical composition.

Relevance of dust mineralogy and size distribution.

Dust aerosols have been traditionally considered a compositionally homogeneous entity. However, they are, in reality, mixtures of minerals which hold different physicochemical properties and that show significant regional variations. These minerals have varying iron content, chemical structure and typical grain sizes, thus affecting the total iron emitted and its susceptibility to dissolve (Journet et al., 2008; Shi et al., 2012). Minerals in dust also contain alkaline elements (e.g., calcium, potassium) that alter aerosols' acidity, hence, the dissolution of iron in the atmosphere.

Early models aimed at representing the contribution of dust sources to the atmospheric iron cycle neglected this complexity, using a constant iron content from dust instead (e.g., Luo et al., 2008). This simplification is still assumed in biogeochemical ocean models, which commonly apply dust climatologies with a fixed iron ratio (e.g., 3.5%; Aumont et al., 2015). Advances have been made in recent years to characterise the mineralogy-dependent iron emissions from dust sources (Scanza et al. 2018; Myriokefalitakis et al. 2015, 2022). However, the mineralogical composition of dust sources at the global scale is still uncertain and derived from a massive extrapolation of a limited set of measurements (Claquin et al., 1999; Journet et al., 2014). As a result, current modelling frameworks poorly represent the airborne dust mineralogy and its size distribution (e.g., Perlwitz et al., 2015b; Li et al., 2021; Gonçalves Ageitos et al., 2022) and the soluble iron coming from dust. New initiatives, such as the ongoing NASA EMIT mission (Green et al., 2020), aim to characterise the mineralogy of dust sources through high-quality hyperspectral spectroscopy techniques. The EMIT sensor was installed in the International Space Station (ISS) in mid-2022, and it is currently providing its first images, which will allow the quantification of 10 different minerals in the soil with an unprecedented level of detail (spatial resolution and geographical coverage), relevant for their climate impacts, among others, the iron cycle.

Particularities of anthropogenic dust sources.

Anthropogenic activities influence dust emissions directly through the disturbance of soils, changes in vegetation cover or water bodies, and indirectly through changes in climate and the hydrological cycle. Currently, 10 to 50% of global dust emissions are attributed to anthropogenic activities (Mahowald and Luo, 2003; Tegen et al., 2004; Ginoux et al., 2012). However, their contribution to the iron cycle has been barely explored. Dust sources affected by humans may present high temporal variability. The underlying soil mineralogy of the agricultural land may have a distinct composition from that of the natural sources. This would be linked to the soil-forming processes that make certain regions more fertile and prone to agricultural activities than others. Furthermore, dust from anthropogenic sources would be more likely to be mixed with other compounds (e.g., ammonia from agricultural activities (Ginoux et al., 2012) and/or acidic species, such as nitrates or sulphates, from combustion sources in their vicinity). The interactions of these compounds with dust particles would result in enhanced iron solubility and a specific impact on ocean biogeochemistry.

The dependency of iron solubility on the relative contribution of sources and processing mechanisms still is largely uncertain (e.g., Myrioketalitakis et al., 2015, 2022; Ito et al., 2019; Hamilton et al., 2020; Bergas-Massó et al., 2022; Fig. 1). This is due to the complexity of the atmospheric iron cycle and the scarcity of available observations to constrain it. Yet, the ground-breaking observations provided by EMIT hold the potential to open a new era on the evaluation and modelling of dust mineralogy.

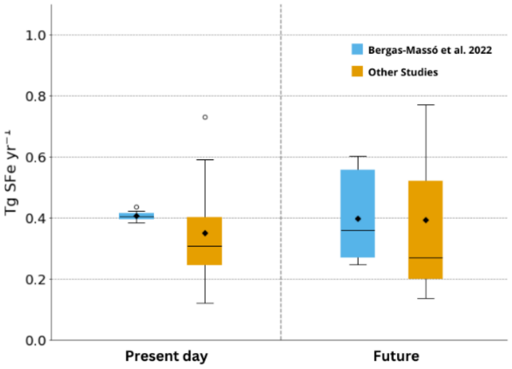

Figure 1. Model estimates of soluble iron deposition in the ocean in present (left) and future climate scenarios (right) as derived from a recent study with the EC-Earth3-Iron model (blue) and other studies from the literature (yellow). Adapted from Bergas-Massó et al. (2022).

BIOTA will timely contribution to this opportunity by bringing together EMIT's soil mineralogical information with a recently developed Earth System Model (ESM), EC-Earth3-Iron that characterises the atmospheric iron cycle at an unprecedented level (Myriokefalitakis et al., 2022). Thanks to these tools and an explicit quantification of anthropogenic dust sources, BIOTA will provide the most accurate quantification to date of the different aeolian iron pathways to the ocean (Obj 1)

2.1.3 Future evolution of the soluble iron deposition in the ocean.

Human activity influences soluble iron and other nutrient deposition in marine ecosystems. Industrial, transport, mining and agricultural activities produce the direct emission of iron, organic compounds and other acid and alkaline species that affect the atmospheric iron dissolution. Human-induced changes in land use and climate affect natural iron sources, such as dust and wildfires. Since the pre-industrial period, there has been an increase in soluble iron deposition in the ocean due to increased anthropogenic activity (Luo et al., 2008; Hamilton et al., 2020; Bergas-Massó et al., 2022). Evidence points to dust loads having increased by 55±30% (Kok et al., 2023), while fire emissions halved (Hamilton et al., 2018). These changes have consequences in the ocean PP regionally. At the global scale, e.g., Mahowald et al. (2010) produced an early estimate of the impact of dust changes over the 20th century, suggesting an increase of 6% in ocean productivity due to doubled dust emissions.

In the future, anthropogenic combustion sources will significantly change depending on the effectiveness of emission mitigation, pollution control policies, and socioeconomic and technological development (Gidden et al., 2019). Dust and biomass burning sources are also expected to change due to direct and indirect human influences. The future evolution of anthropogenic and natural sources of iron, as well as its consequences the soluble iron deposition and the marine carbon cycle, are largely uncertain.

Future dust emissions.

Current models disagree in their projections of future dust sources depending on their formulation (Mahowald and Luo, 2003; Tegen et al., 2004; Kok et al., 2023). Some works reflect the impact of changes in wind speed, with reductions of dust emission in the scenarios with more significant wind reduction (Bergas-Massó et al., 2022). Drier conditions can lead to increased dust emissions by reducing soil moisture, while extreme rainfall events mobilise sediments and increase the matter available for wind erosion. On the other hand, CO_2 fertilisation can expand vegetation to arid regions, reducing active dust sources. Human activities, including land management and irrigation for agriculture, will also impact the location of future dust sources. As a result of the multiple factors involved, our current model estimates range from increased dust emission projections, mostly dominated by increased aridity, to decreases owed to the CO_2 fertilisation effect (Kok et al., 2023).

Future biomass burning emissions.

The present-day patterns of fires are relatively well understood, as they are constrained by satellite data (Van Marle et al., 2017), but their evolution in the future is uncertain. Recent works suggest that, contrary to previously thought, the increased population during the historical period reduced the burned area compared to the pre-industrial era (Hamilton et al., 2018). This reduction is attributed to human-induced changes in land use and fragmentation of ecosystems, as well as to the implementation of fire management practices and air quality mitigation policies in some regions (Andela et al., 2017). However, although these factors will affect fires in the future, their impact will likely be offset by the increased fire activity expected below warmer and drier climates (Pechony and Shindell, 2010). The Coupled Model Intercomparison Project Phase 6 (CMIP6) emission estimates (Gidden et al., 2019) include the effect of anthropogenic-induced fires. Still, they neglect the impact of climate change on fire regimes (Kasoar et al., 2021), leading to the potential underestimation of these sources in the future.

BIOTA will evaluate the impact of future land use, vegetation, and climate changes on the role of dust and biomass-burning aerosols as sources of soluble iron for the ocean (Obj. 2).

2.1.4 Ocean response to aerosol deposition.

Aerosols provide critical nutrients to the global ocean in the contemporaneous ocean, partly sustaining marine primary production and, indirectly, the BCP. Although most research to date has focused on its fertilisation effect, aerosol deposition can also impact the BCP in two other additional ways:

- Community shift: Nutrients supplied by aerosols can alter the phytoplankton community structure (Kramer et al., 2020), shifting it towards species with higher/lower sinking rates, increasing/decreasing the carbon export.

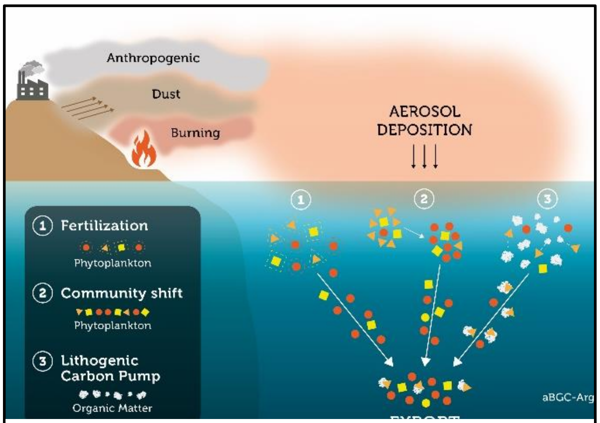

Figure 2. Schematic of the three different biogeochemical mechanisms triggered by aerosol deposition. Credit: J.Llort

- Lithogenic aerosol components can act as ballasts for otherwise buoyant marine organic particles, a mechanism sometimes called the Lithogenic Carbon Pump or the Ballast Effect (Korte et al., 2017.

The three mechanisms (fertilisation, community shift and the lithogenic pump, Fig 2) are entangled, making the link between aerosol deposition and marine primary production much more complex.

The multi-faceted aerosols-ecosystem relationship cannot be isolated from the context of climate change. ESM projections and global observations (Li et al., 2020, Kwiatkowski et al., 2022) agree on drawing an increasingly stratified ocean with oligotrophic gyres extending towards the poles. A more stratified ocean presents shallower turbulent mixing layers decreasing the number of months that phytoplankton growth is light-limited. Although this effect can potentially increase productivity, enhanced stratification reduces the vertical supply of nutrients (Llort et al., 2019). CMIP6 models suggest, with a low inter-model agreement, that the balance between these two opposed effects falls towards a reduction of productivity in most ocean basins (Kwiatkowski et al., 2022). However, the role of aerosols in marine biogeochemistry is not well simulated in CMIP6 models due to strong simplification on aerosols emission, chemical transformation (i.e., solubility) and poor representation of deposition's timing. The latter is critical to capture the response by phytoplankton, which is highly sensitive to the seasonal cycle. Finally, the LCP is currently not represented in any ocean biogeochemical model.

In such an illuminated and nutrient-poor future marine environment, aerosols' (micro-)nutrient supply can become relevant for larger areas of the global ocean. The cutting-edge representation of the atmospheric iron cycle developed in BIOTA will allow the evaluation, with unprecedented accuracy, of the impact of atmospheric iron supply on primary production and the BCP under present and future ocean conditions (Obj 3).

2.2 BIOTA hypothesis and contribution to knowledge generation.

OVERARCHING HYPOTHESIS: The influence of soluble iron deposition on ocean's primary production and carbon export will increase with climate change.

Knowledge generation.

The role of aerosol deposition on the marine carbon cycle has often been approached either by teams of atmospheric composition (Hamilton et al., 2022) or by oceanographers (Guieu et al., 2017). In BIOTA, both expertise will be present, allowing to produce studies with a comprehensive vision, from the mineralogical composition of soil particles to the potential sink of phytoplankton cells and aggregates in the deep ocean. This unique combination will allow taking the most of ground-breaking datasets, such as EMIT observations and advanced climate projections, using new formulations of the emission sources. From the ocean side, BIOTA will use a state-of-the-art biogeochemical model adapted to digest the different sources of dissolved iron. In addition, we will include a parametrisation to simulate the LCP (Fig. 2). The evaluation of aerosols deposition's impact on the BCP at a global scale, at a monthly frequency and with a realistic representation of the atmospheric iron cycle, will be another major innovation. Finally, we will look at these sources and mechanisms in the context of climate change to quantify the importance of the atmospheric iron cycle for the future marine carbon cycle and its feedback on climate (overarching hypothesis).

BIOTA results will also inform the climate modelling community on which sources and processes contributing to soluble iron are critical for the marine carbon cycle. In a moment where ESMs are reaching extremely high complexities, it is crucial to evaluate and identify the dominant processes to ensure that they will not be missed in the future (i.e., CMIP7-8 exercises).

2.3 Justification and expected contribution of the project to solving specific problems linked to Climate Change and Decarbonization.

The research planned within BIOTA belongs to the "*climate, energy and mobility"* strategic area (AE5) defined as a priority in the *IX Plan Estatal de Investigación Científica y Técnica y de Innovación 2021-2023* of the Ministry of Science and Innovation of the Spanish Government. Particularly, BIOTA objectives align with those below the Climate change and decarbonisation topic by improving our estimates of the influence of current and future human activity on a critical parameter for the carbon uptake by the ocean, the soluble iron deposition.

3. OBJECTIVES, METHODOLOGY AND WORK PLAN

3.1. General and specific objectives.

The overarching goal of BIOTA is to improve our understanding of the ocean biogeochemistry response to the varying atmospheric inputs of soluble iron under different climates.

Specific objective 1: Assess the relative contribution of different sources and processes to the soluble iron deposition in the ocean in present climate.

We hypothesise (H1) that the emitted iron from dust sources and its susceptibility to dissolve are tightly linked to the mineralogy of the parent soils. Therefore, the unparalleled knowledge of the soil mineralogy that EMIT will provide (Green et al., 2020) will significantly impact our current estimates of the emitted iron and its regional distribution, as well as the speciation of the iron compounds and the abundance of crustal-alkaline species that influence aerosols acidity.

We hypothesise (H2) that dust sources disturbed by anthropogenic activities constitute a relevant and underrepresented contributor to atmospheric soluble iron deposition. Their distinct composition compared to natural dust sources and distinct temporal variability will likely lead to a specific effect on ocean biogeochemistry.

Specific objective 2: Evaluate the impact of future land use, vegetation and climate changes on soluble iron deposition in the ocean.

We hypothesise (H3) that the future evolution of the soluble iron deposition in the ocean will be affected by the direct and indirect consequences of human activity. Direct consequences such as land use changes and vegetation affecting dust and biomass burning sources are crudely represented or neglected in CMIP6 models. Similarly, the indirect impacts of anthropogenic climate change on the natural iron sources (hydrological cycle, wind stress, warmer conditions) are often not well resolved in current ESMs. Quantifying iron deposition's sensitivity to each of these processes will identify which has the major impact on the future of ocean biogeochemistry.

Specific objective 3: Quantify the response of marine primary production and carbon export to atmospheric iron supply in the present and future climates.

We hypothesise (H4) that the loss of marine productivity associated with stratification can be compensated with a more prominent role of atmospheric nutrient supply in some regions. CMIP6 models show low agreement on marine productivity trends for the future decades in regions such as the North and South-East Pacific, the Atlantic subtropical gyres and the Indian Ocean (Kwiatkowski et al., 2020), all of which regions sensitive to atmospheric iron inputs. The refined iron deposition fields developed in BIOTA will allow quantifying the role that iron deposition plays and will play in the patterns of productivity and carbon export.

3.2. Description of the methodology.

We have organised BIOTA in four work packages (WP) to achieve the proposed objectives. **WP1** will refine current estimates of the contribution of different sources and processes to soluble iron deposition in the ocean in present climate. **WP2** will provide updated estimates of the future evolution of the soluble iron deposition in the ocean, considering the impact of land use and climate change on biomass burning and dust sources. **WP3** will assess the impact of the multiple aeolian pathways towards ocean primary production and the biological carbon pump in present and future climates. **WP4** will ensure the appropriate project management and the dissemination and communication of project results.

BIOTA will fulfil this work plan thanks to a unique combination of observational products and models. We will combine the state-of-the-art ESM EC-Earth3-Iron (Myriokefalitakis et al., 2022) and the ocean biogeochemistry model Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES, Aumont et al., 2015) with cutting-edge satellite observations of dust sources mineralogy (Green et al., 2020), and multiple aerosol observation datasets. This wealth of data will drastically improve our knowledge of the sources and processes that lead to soluble iron deposition and will provide a new perspective on the controls of aerosol deposition on marine primary production and carbon export.

Model Description:

EC-Earth is an ESM collaboratively developed by European research centres from 10 countries, including BSC (Döscher et al., 2022). Its design is based on modules representing different Earth's components (atmosphere, ocean, sea ice, land surface, dynamic vegetation, atmospheric composition, and ocean biogeochemistry), which can be coupled in various model configurations (Fig. 3). The latest version, EC-Earth3, incorporates the Integrated Forecast System (IFS) from the European Center for Medium-Range Weather Forecasts (ECMWF) cycle 36r4 coupled with the general ocean circulation model Nucleus for European Modelling of the Ocean (NEMO version 3.6; Madec 2008). The Tracer Model 5 (TM5) allows for the interactive simulation of atmospheric aerosols and reactive gas species (Van Noije et al., 2021), and PISCES (Aumont et al., 2015), as part of the NEMO system, represents marine biogeochemistry. EC-Earth3 contributed to the CMIP6 and has been extensively used with different configurations to produce climate predictions and projections.

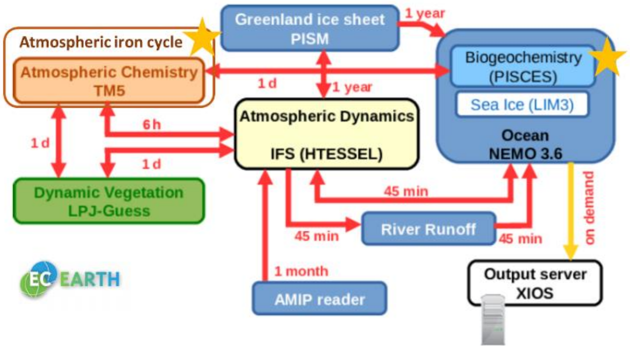

Figure 3. Components of the EC-Earth3 model with red arrows representing the coupling through the OASIS-MTC software. The atmospheric iron cycle has been recently included in the EC-Earth3-Iron version, developed in the NUTRIENT MINECO project (2018-2021). The PISCES biogeochemistry model is embedded in the NEMO ocean model. Adapted from Döscher et al., 2022.

As a result of the NUTRIENT MINECO project, led and participated by researchers in this proposal, we have recently developed EC-Earth3-Iron (Myriokefalitakis et al., 2021, Bergas-Massó et al., 2022). There, TM5 accounts for a complex aqueous phase chemistry and an interactive calculation of aerosol and in-cloud pH, which allows a representation of the atmospheric iron cycle with an unprecedented level of detail for an ESM. EC-Earth3-Iron explicitly considers the mineralogy of dust sources (Claquin et al., 1999; Journet et al., 2014) to derive iron emissions from arid and semi-arid regions and distinguishes biomass burning and anthropogenic combustion sources of iron. Although a small amount of the soluble iron is directly emitted to the atmosphere with a source-dependent soluble fraction, most soluble iron is produced via atmospheric processing. EC-Earth3-Iron represents solubilisation through acidic attack, organic-ligand-promoted, and photo-reductive iron dissolution. Lithogenic iron is classified in three mineralogy-dependent pools, with different susceptibilities to dissolve. Iron from combustion sources is also subject to dissolution through atmospheric processing and is included in a separate iron pool. The model explicitly calculates the particles and clouds' pH and oxalate formation, both critical for acidic and ligand-mediated iron dissolution.

PISCES, ocean biogeochemical model.

PISCES (Aumont et al., 2015) is a biogeochemical model which simulates the lower trophic levels of marine ecosystems (phytoplankton, microzooplankton and mesozooplankton) and the biogeochemical cycles of carbon and the primary nutrients (P, N, Fe, and Si). It contains 24 prognostic tracers, including two phytoplankton compartments (diatoms and nanophytoplankton), two zooplankton size classes (microzooplankton and mesozooplankton) and a description of the carbonate chemistry. Various parameterisations can be activated in PISCES, setting, for instance, the complexity of iron chemistry.

All simulations will be based on an improved version of the PISCES model developed by the co-PI Joan Llort in the frame of DOMOS and PYROPLANKTON projects. This PISCES version can digest dissolved iron aerosols from four different sources (natural and anthropogenic dust, fossil fuels, and biomass burning), each with its corresponding solubilities (previously calculated in EC-Earth3-Iron).

WP1. The relative contribution of sources and processes contributing to the deposition of soluble iron in the present climate.

To constrain the role of different sources and processes in the atmospheric soluble iron deposition, we will consider the mineralogical composition of dust parent soils as provided by the latest observational evidence of the spaceborne hyperspectral EMIT sensor (Task 1.1), and we will differentiate iron from natural and anthropogenic dust sources (Task 1.2). We will produce a dataset of wet and dry deposition of soluble iron at the global scale with high temporal frequency (**D1**). This information will characterise the temporal variability of soluble iron deposition from different sources and identify the dominant sources in each ocean basin (Task 1.3). The outputs from this WP will feed the ocean biogeochemistry model in WP3.

Task 1.1. Iron from dust sources using EMIT-based soil mineralogy information.

The airborne dust mineralogy depends on the mineralogy of the parent soils. Yet, at present, the knowledge of mineralogy at sources is limited. There are fundamentally two global soil maps that provide geographically distributed information of use in ESMs: Claquin et al., 1999, modified by Nickovic et al., 2012 (referred to as *C1999*); and Journet et al., 2014 (*J2014*). These maps are built by extrapolating to the global scale a limited set of mineralogy measurements, which are particularly scarce in arid and semi-arid regions. *C1999* gives the abundance of 8 minerals relevant for their climate impacts (quartz, feldspars, calcite, gypsum, illite, smectite, kaolinite and hematite), while *J2014* also identifies mica, vermiculite, chlorite and goethite. These maps distinguish two soil size classes clay (up to 2 µm in diameter) and silt (from 2 to 64 µm). Inferring an emitted size distribution for dust minerals from that information is challenging. Soil mineralogy datasets are based on measurements performed after wet sieving, which breaks the aggregates found in the parent soil. Previous works have proposed extensions of the Brittle Fragmentation Theory (BFT) for dust emission (Kok, 2011) which reconstruct the emitted mineral aggregates destroyed by wet sieving (e.g., Perlwitz et al., 2015a). EC-Earth3-Iron follows this approach to estimate the mineralogy-dependent iron from dust (Myriokefalitakis et al., 2022). Despite these efforts, the ability of our models to capture the size-dependent observed fractions of minerals could still be improved (e.g., Perlwitz et al. 2015b, Gonçalves Ageitos et al., 2022), and, along with them, the most relevant source of iron to the atmosphere (Myriokefalitakis et al., 2022).

In this task, we will incorporate NASA EMIT's mineralogy soil map (Green et al., 2020) to EC-Earth3-Iron. EMIT's hyper-spectral imaging will provide quantitative information on the spectral abundance of 10 minerals (those in J2014, except for quartz and feldspars) with an unprecedented spatial resolution ($\lessapprox$100 m). The first maps to be implemented in ESMs (Level 3 data, at 0.5° spatial resolution) will be available by the end of 2023, therefore fitting the timing of this proposal. Dr. María Gonçalves Ageitos participates as a Science Affiliate in EMIT. Several Working Group members (Dr. Ron Miller and Dr. Paul Ginoux) are involved in the project with different roles, hence ensuring early and reliable access to EMIT data.

A significant part of Task 1.1 will be adapting EMIT's soil map to EC-Earth3-Iron's airborne minerals size distribution, which describes the iron species through a fine and a coarse mode. We will investigate alternative methods to derive the size-distributed emission of minerals from the information provided in EMIT, building upon our current framework that relies on the BFT and observational constraints. The compilation of observed mineral fractions in Perlwitz et al. (2015b) constitutes a unique dataset to validate and constrain our developments. To better exploit this information, we plan to develop a test version of EC-Earth3-Iron in which we will trace the 12 minerals present in dust (*EC-Earth3-mine*). This will add 24 new tracers to the model and impact its computational performance; therefore, we will use this version only for EMIT validation purposes. Once the different tests are completed, we will port the optimized approach to derive the size-distributed mineralogy to EC-Earth3-Iron, which exclusively traces iron and alkaline species.

Following current evidence (Shi et al., 2011a,b), EC-Earth3-Iron classifies the lithogenic iron in three mineralogy-dependent dissolution pools (fast, intermediate and slow dissolution). This partition aims to mimic observations that suggest that a small fraction of the iron, in the form of ferrihydrite and nano-iron oxides, is highly reactive (FeF). In contrast, structural iron in the matrix of phyllosilicates and larger crystalline particles of iron oxides are increasingly difficult to dissolve (Shi et al., 2011a, 2012, Ito and Xu, 2014). EMIT will bring information on the abundance of nano-iron oxides in soils, allowing us to transition from a fixed fraction of FeF to the iron content (Ito and Shi, 2016, Myriokefalitakis et al., 2022) to an advanced characterisation of this fast dissolution pool. We will exploit this information and compare our new estimates to observations of total and soluble iron concentration and deposition (as compiled in Ito et al., 2019 and Myriokefalitakis et al., 2022), focusing on those regions where dust sources are dominant.

Experiments design: We will conduct multiple present-day time-slice (5 years) experiments with EC-Earth3 in atmosphere-chemistry mode (i.e., using observed ocean data) and nudging the atmospheric dynamics towards close-to-reality fields from the ERA5 reanalysis (Hersbach et al., 2020). This setup allows for a time and space-collocated evaluation against observations. We will design and run tailored experiments with *EC-Earth3-mine* to assess different approaches to define the minerals' size distribution at emission. Then, we will conduct additional experiments with EC-Earth3-Iron and EMIT-based iron partition in the three solubility pools; we will integrate the new evidence on the abundance of nano-iron oxides, and consider the range of literature values (e.g., Journet et al., 2008; Nickovic et al., 2012) to define the iron content of the minerals to assess the sensitivity to these assumptions.

Evaluation: We will produce a general evaluation of the dust cycle by comparing modelled dust surface concentration and deposition fields against climatological measurements (Prospero et al., 1990, 1996; Marticorena et al., 2010; Albani et al., 2014), and Aerosol Optical Depth (AOD) in locations dominated by dust against Aerosol Robotic Network, AERONET (Holben et al., 1998, Sinyuk et al, 2020) retrievals. Our mineralogical outputs will be assessed with the observations compiled in Perlwitz et al. (2015b), which we will update by looking for new data in the literature. We will also compare our model results with those of other ESMs that currently include mineralogy in their frameworks, e.g., NASA-GISS (Perlwitz et al., 2015a), CESM-CAM (Scanza et al., 2015), GFDL-AM4 (Horowitz et al., 2020) or the IFS-AER (Remy et al., 2022). Our model's soluble and total iron estimates will be assessed against available observations (Ito et al., 2019; Myriokefalitakis et al., 2022), focusing here on those sites and campaigns heavily influenced by dust sources.

Group contributions: M. Costa (evaluation and observations), R. Miller (advice EMIT mineralogy soil maps), PD (definition and validation of approaches to derive size-resolved mineralogy at emission), IT (technical support for implementation in EC-Earth and data treatment).

Task 1.2. Contribution of anthropogenic dust sources to present-day soluble iron deposition.

Within this task, EC-Earth3-Iron will be further developed to explicitly quantify the relevance of anthropogenic dust sources and their contribution to the total emitted iron. Dust emission in EC-Earth3-Iron is calculated online following Tegen et al. (2002), which allows dust emission from bare soils and areas with low vegetation (grass and shrubs) and considers dry paleo-lakes as preferential sources. The annual vegetation cycle is imposed through a fixed climatology of Fraction of Photosynthetically Active Radiation (FPAR), which affects the effective area available for dust emission. Cultivated areas (pasture and rangeland) are identified in the model through a land-use map (HYDE, Klein Goldewijk et al., 2001), and dust emission is enhanced there with respect to natural vegetated areas (Tegen et al., 2004). Currently, these cultivated areas only change with the month of the year. Within the ESA DOMOS project, we have produced a first, conservative approach of their contribution to the total emitted iron, which we plan to improve and refine in BIOTA.

We will account in EC-Earth3-Iron for year-to-year variations in cultivated regions through an updated version of HYDE (v3.2.1), which distinguishes among cropland, pasture and rangeland (Klein Goldewijk et al., 2017). We will assess the relative effect of these three land use categories on the anthropogenic dust sources. We will also review the current model assumptions about enhancing dust emissions from cultivated areas. To that end, we will use high-frequency dust-filtered AOD from AERONET retrievals and the Frequency of Occurrence (FoO) of Dust Optical Depth (DOD) > 0.2 from the Moderate Resolution Imaging Spectroradiometer (MODIS) Deep Blue product (Ginoux et al., 2012; Hsu et al. 2013) to assess our model outputs. The time-and-space collocated evaluation against MODIS requires implementing in EC-Earth3-Iron a diagnostic of the all-sky DOD for the satellite overpass, ideally with a daily frequency, which we will do following Klose et al. (2021). Finally, we will compare our estimates with other approaches currently used to simulate dust from anthropogenic sources (e.g., Ginoux et al., 2012). With these new developments, we will be able to quantify the contribution of the iron from anthropogenic dust sources to the soluble iron deposition in the ocean, identify the atmospheric processing mechanisms that control its dissolution and assess the impact of interannual variability of anthropogenic land-use changes towards dust emission.

Experiments design: The EC-Earth3-Iron setup will be identical to that defined in Task 1.1. We will assess two different factors of our new implementation: (1) the impact of considering as anthropogenic sources different land-uses, namely crops, crops+pasture, crops+pasture+rangeland; through 3 different experiments and an additional one that will take as a reference the current EC-Earth3-Iron definition; (2) for the extreme case (crops+pasture+rangeland), we will conduct a suite of experiments assess the calibration of the dust emission from anthropogenic sources through comparison with observations.

Evaluation: We will thoroughly evaluate the dust and iron cycle (following the same approach and datasets as in Task 1.1). We will additionally assess our new diagnostic of FoO of DOD > 0.2 from EC-Earth3-Iron with the MODIS DB product, following Klose et al. (2021).

Group contributions: M. Costa (evaluation and observations), P. Ginoux (advice on anthropogenic dust source and evaluation), PD (characterisation of the emission of the agricultural dust sources), IT (technical support for model development and data handling).

Task 1.3. Contribution of sources and processes to present-day soluble iron deposition.

We will produce updated estimates of the contribution of different sources and processes to present-day soluble iron deposition in the ocean. Those will account for the latest advances in our knowledge of soil mineralogy (from Task 1.1); they will discriminate between natural and anthropogenic dust sources (from Task 1.2) and use updated anthropogenic emissions (McDuffi et al., 2021).

Iron emissions from anthropogenic combustion sources are commonly diagnosed in models via scaling factors (e.g., Ito et al., 2019) to emissions reported in global inventories (e.g., Hoesly et al., 2018). In EC-Earth3-Iron, iron from anthropogenic combustion sources depends on sectorial emissions of Black Carbon and Organic Carbon. Recent works suggest that the CEDS reference global inventory used in CMIP6 experiments (Hoesly et al. 2018) fails to capture the trends in aerosol emissions during the recent historical period (Wang et al., 2021). Updated inventories (McDuffie et al., 2022) estimate lower particulate matter emissions globally since the 90's than CMIP6, and significant regional differences, which would have a direct effect on modelled primary iron emissions and its dissolution precursors, as well as a distinct impact depending on the sensitivity of marine biota to atmospheric inputs in the ocean regions preferentially affected.

Within this task, we will incorporate the reviewed anthropogenic emissions (McDuffie et al., 2022) in EC-Earth3-Iron and combine them with our model updates (Tasks 1.1, 1.2) to provide improved estimates of soluble iron deposition in the ocean at present. We will investigate the relevance of the size distribution of the iron from the different sources, both in terms of their solubility and the predominant removal process. We will also analyse the relative importance of the dry and wet deposition on the atmospheric inputs over different ocean basins.

Experiments design: The EC-Earth3-Iron setup will be identical to that defined in Task 1.1. The experiment with improved sources will cover the recent historical period (1980 - 2017). It will produce dry and wet soluble iron and dust deposition fields, differentiated by source and consistent nitrogen deposition fields.

Evaluation: We will assess the model's ability to reproduce the dust cycle, soluble and total iron concentration and deposition fields (using the same datasets as in Tasks 1.1 and 1.2). We will also provide a broader assessment of the model's capability to represent gas-phase species and aerosols against measures routinely produced by air quality networks (e.g., AirBase, EMEP, CASTNET, etc.). To that end, we will use a harmonised and quality-assured database developed at the BSC's Earth Sciences Department (GHOST; Bowdalo et al., 2019).

Group contributions: J. Llort (liaison with WP3), M. Costa (evaluation and observations), E. Bergas (support on evaluation), S. Myriokefalitakis (estimates of nitrogen deposition), PD (assessment of the relevance of different sources towards nutrients deposition), IT (data curation).

WP2. Land use and climate change sensitive estimates of future soluble iron deposition.

Future projections of soluble iron deposition in the ocean largely depend on our ability to represent the evolution of the primary iron sources and dissolution precursors. Anthropogenic combustion emissions will change with population growth and socio-economic and technological factors. To deal with a range of potential outcomes, one can make use of emission scenarios (Gidden et al., 2019) associated with different Shared Socio-economic Pathways (SSPs) and future radiative forcing levels (O'Neil et al., 2014). In this WP, we will focus on the evolution of the other two main sources of iron and dissolution precursors, dust (Task 2.1) and forest fires (Task 2.2), poorly represented in our current modelling frameworks.

Task 2.1. Future evolution of dust sources considering land-use and vegetation changes.

Within this task, we will update our EC-Earth3-Iron model, which derives future dust emission changes primarily via changes in atmospheric variables (e.g., wind speed). We aim to account for the effect of land use and vegetation variations in future climate scenarios on dust and iron emissions.

To that end, we will account for the evolution of cultivated dust sources following the work done in Task 1.2. We will consider the transient Land Use and Land Cover Change data from the Land Use Harmonized version 2 (LUH2) CMIP6 projections (Hurtt et al., 2020). This dataset is consistent with the HYDE 3.2 information we propose to use for the historical period and provides information on the fractional cover of 12 land units, amongst which several crop categories, pasture and rangeland, at 0.25º spatial resolution for different CMIP6 SSP scenarios.

Other relevant factors that affect dust emission in EC-Earth3-Iron are the vegetation type (bare soils, areas covered by grass and shrubs are potential dust sources), its structure (the effective area available for emission in the vegetated model cells is calculated as a function of the FPAR) and the surface roughness (z0), which accounts for the effect of non-erodible surface elements (rocks and vegetation) on the wind momentum. Although the EC-Earth3 system counts on a dynamic vegetation module, LPJ-Guess (Smith et al., 2001), it is currently not coupled online to the dust emission module in TM5. To undertake this coupling entails structural changes in the code that would not be feasible within the time frame of this proposal. Instead, we propose to take advantage of the recently published EC-Earth3-Veg (Döscher et al., 2021) vegetation projections available in the CMIP6 archive (https://esgf-node.llnl.gov/projects/cmip6/) to provide off-line estimates of monthly variations of the vegetation cover, structure and roughness in future climate scenarios. Currently, the vegetation distribution (fractional area cover of shrubs and grass) is updated through a diagnostic that considers EC-Earth3-Veg outputs for historical and SSP scenarios. However, this has a minimal impact on the dust emission, as the other two vegetation-dependent parameters (FPAR and z0) remain unchanged. We will infer changes in FPAR through variations in the published Leaf Area Index (LAI) outputs, following Bondeau et al. (1999). To derive consistent changes in z0, one will have to disentangle the effect of the static (rocks) and dynamic (vegetation) roughness elements, a problem that is not easy to solve. We will explore the proposed approaches of Klose et al. (2021) and Leung et al. (2022) to infer a dynamic z0 consistent with the modelled LAI estimates. We will assess and calibrate the dust emission in the present day and produce a simulation over the historical period that will serve as a reference for our future climate projections. Our future estimates will rely on projections of EC-Earth3-Veg for the SSP1-2.6 and SSP5-8.5 scenarios, which represent futures of strong economic growth but with sustainable and fossil fuels pathways, respectively.

Experiments design: First, we will use the present-day EC-Earth3-Iron model setup (same as in Task 1.1) to assess the impact of varying the z0 formulation on dust emission and the proposed changes against collocated observations. Then, we will conduct a present-day (*HIST*) and two future (SSP1-2.6 and SSP5-8.5) experiments in climate mode (without nudging) for a period of at least 30 years. The ocean variables (sea surface temperature and sea ice concentration) will be obtained from EC-Earth3 atmosphere-ocean experiments available in the CMIP6 archive and corresponding to the historical period and the three SSPs. The SSP1-2.6 with the non-updated model version from Bergas-Massó et al. (2022), *SSP1-2.6-CTRL* will serve as a basis to determine the impact of the updated vegetation and land-use changes in dust emission. We will conduct an equivalent 30-year experiment for the *SSP5-8.5* (*CTRL*), to assess these differences in the most extreme future scenario.

Assessment: We will assess the impact of the land use and vegetation changes in dust and iron fields by comparing them (1) with experiments that neglect these variations (*SSP1-2.6-CTRL, SSP5-8.5-CTRL*), and (2) results from other models that provide dust and iron projections from the literature (e.g., Hamilton et al., 2020).

Group contributions: J. Llort (liaison with WP3), M. Costa (experiments), P. Ginoux (advice on the vegetation impact in dust sources), PD (dust sources).

Task 2.2. Impact of biomass burning in the atmospheric soluble iron deposition in the future.

Within this task, we will consider climate-sensitive biomass burning emission projections in EC-Earth3-Iron. These new emission datasets are derived by one of our collaborators (Dr. D. Hamilton) and his group. They rely on estimates from four independent fire models (CLM5, JSBACH3.2, LPJ-GUESS, and ISBA-CTRIP) used in CMIP6 (Rabin et al., 2016). First, they use these models in the present time to derive bias correction factors, which are then applied with machine learning approaches to provide biomass burning emission estimates for the SSP1-2.6 and SSP5-8.5 scenarios (Kasoar et al., 2021). We will adapt EC-Earth3-Iron to read the new emission datasets and assess their impact on our estimates of nutrient deposition on the ocean in future climates.

Experiments design: We will follow a similar experimental setup as in Task 2.1. We will conduct three 30-year-long time-slice experiments in atmosphere-only mode using the new emission datasets for the SSP1-2.6 and SSP5-8.5. Both experiments, SSP1-2.6 and SSP5-8.5, will consider the updates in the dust emission introduced in Task 2.1. The outputs of these experiments will feed the ocean biogeochemistry model in WP3 and constitute **D2**.

Assessment: We will conduct an assessment equivalent to Task 2.1. We will produce estimates of future vs present changes by comparing the outputs of these experiments with the *HIST* (Task 2.1). We will also compare the new outcomes with the previous model version (*SSP1-2.6-CTRL* and *SSP5-8.5-CTRL*).

Group contributions: J. Llort (liaison with WP3), D. Hamilton (emissions), E. Bergas (experiments).

WP3. Contribution of sources and processes deriving in the deposition of soluble iron to ocean primary productivity and the Biological Carbon Pump.

WP3 will focus on the fate of iron-bearing aerosols deposited over the ocean. In it, we will analyse the response of phytoplankton to aeolian iron inputs and how this response translates into carbon export at depth through the biological carbon pump. Following WP1 and WP2 work with the atmospheric iron fields, we will divide the analyses into two tasks (present and future) plus an additional task focused on the changes in the biological carbon pump.

Task 3.1 Impact of improved dust-iron deposition on marine PP.

The first task will quantify the relative contribution of each aerosol source (natural and anthropogenic dust, biomass burning and anthropogenic combustion) and the improvement of mineralogy to changes in marine primary production over the global ocean. The deposition fields generated in WP1 (D1) will be used as forcing for four different ocean-only configurations covering 1980 - 2017. Aerosol inputs will be read monthly to consider the seasonal variability of aerosol deposition and phytoplankton.

Experiments design: We will run two 30 years of experiments using the new aerosol deposition fields developed in WP1. One experiment (*oBGC_EMIT*) will use the projections for dust (based on EMIT data, Task 1.3) and biomass-burning as input for PISCES iron aeolian supply. The outputs of this experiment will be compared to the reference simulation based on the mineralogy of *C1999* (Bergas-Massó et al, 2022), named here *oBGC-C1999*.

For the second experiment, we will use the same inputs without considering the contribution of natural dust (oBGC-EMITant)

Assessment: Configuration *oBGC-C1999* will be used as a reference run and compared to *oBGC-EMIT*. We will compare surface chlorophyll (a standard proxy for phytoplankton accumulation), the phytoplankton community (i.e., the dominance of diatoms or nanophytoplankton), and the depth-integrated primary production. Analyses will be done for averaged (10 years) seasonal cycles to identify regions and the months when the aerosol influence is the strongest. We will also evaluate the potential subsurface dissolved iron concentration changes associated with long-term (30 years) trends in aeolian inputs. Further analyses might be needed to understand some of the patterns observed. In particular, analyses of the surface concentration of nutrients (N, P, Si) and dissolved iron relative portioning (e.g., N:P) can provide insightful information on how the ecosystems respond to changes in iron supply. Surface chlorophyll concentration in the first three configurations will also be compared to observations. In particular, we will use the ESA-CCI Ocean Colour dataset that provides climate estimates of surface chlorophyll from 1998 to the present. C. Guieu will advise in these diagnostics and interpretation while providing other sources of observations (cruises or mooring data) that can be compared with models.

Additional diagnostics will focus on quantifying the importance of anthropogenic dust on the ocean response by comparing *oBGC-EMIT* against *oBGC-EMITant*. We will also quantify the changes in primary production and phytoplankton community in regions with strong anthropogenic input to define the importance of natural inputs.

Group contributions: Y. Ruprich (run experiments and interpretation), M. Gonçalves (liaison with WP1), C. Guieu (outputs assessment and interpretation).

Task 3.2 Future trends in primary production using refined aerosol projections.

The second task of this work package will deal with the future changes in marine primary production associated with changes in aerosol deposition. The new deposition fields developed in WP2 (D2) will be critical to evaluate the role that aerosol deposition will play in an ocean impacted by Climate Change with unprecedented accuracy.

Experiments design: We will run three 30 years of experiments using the new aerosol deposition projections developed in WP2. A historical period reference (*oBGC_HIST*) will use the atmospheric inputs from Task 2.1. One future experiment (*oBGC_S85_DBB*) will use the projections for both dust and biomass-burning as input for PISCES iron aeolian supply. For the second future experiment (*oBGC_S85_D*), we will turn off biomass-burning aerosol input to quantify its relative contribution and compare it to the contribution by dust. All three simulations will be compared to the present reference simulation (*oBGC_HIST*) to quantify the changes in primary production associated to changes in the ocean dynamics or changes in aerosol deposition. An additional simulation (*oBGC_S85_CTRL*) will run for 30 years with the non-updated emission fields. For all of them, we will nudge the ocean dynamics towards EC-Earth3 atmosphere-ocean experiments available at the CMIP6 archive (the same ones used to obtain the new emission fields in WP2) corresponding to the most extreme scenario, SSP5-8.5.

Assessment: We will compare the two simulations with new emission fields with the *oBGC_S85_CTRL* to quantify the contribution of each source and the impact of improving its representation. We will also compare our outputs with published primary production CMIP6 projections (Kwiatkowski et al., 2020).

Group contributions Y.Ruprich (run experiments and interpretation), M.Gonçalves (liaison with WP2)

Task 3.3. The role of aerosol deposition on the biological carbon pump, now and in the future

One of the least studied impacts of aerosol deposition on marine biogeochemistry is how changes in primary production and/or phytoplankton community shifts can impact the biological carbon pump. We will also consider the potential export enhancement by the lithogenic carbon pump. C. Guieu (BIOTA's working group) collaborates with the leading developer of PISCES (O. Aumont) to incorporate the lithogenic carbon pump into the model. Thanks to her contribution to BIOTA, we will use the new parametrisation in all WP3 simulations.

Experiments design: For this task, we will further exploit the simulations produced in Task 3.1 and 3.2.

Assessment: Simulation *oBGC-C1999* will be used as a reference to be compared with the present-day simulation with EMIT (*oBGC_EMIT*) sources, and *oBGC_HIST* with the future simulation (*oBGC_S85_DBB*). The assessment of changes in the BCP will be done at two different timescales. First, we will identify strong deposition events to statistically quantify the relative contribution of each of the three BCP mechanisms (fertilisation, community shift or LCP, Fig 2). We will specifically look at the seasonal and regional variability of the relative contribution. Comparing the future and present simulations, we will explore the marine carbon cycle's future sensitivity and quantify if this sensitivity is indeed expected to increase (BIOTA's overarching hypothesis).

A second diagnosis in this task will be to study the impact of 30-years-long aerosol deposition on the subsurface stocks of dissolved iron and other elements such as Carbon, Nitrate, Silicate and Phosphate.

Group contributions: Y. Ruprich, M. Gonçalves (liaison with WP1-2), C. Guieu.

WP4. Project management and dissemination.

WP4 is devoted to project management and dissemination tasks. The project PIs, with the support of the management team of the host institution (BSC) and the communication team of the Earth System Services group of the Earth Sciences Department (ES-BSC), will ensure the successful completion of the project objectives and the appropriate dissemination of its results. We will monitor the progress of the different tasks, verify the completion of the milestones and deliverables planned (see schedule below), and act appropriately in case of unforeseen circumstances (see the contingency plan below). We will promote the communication and dissemination of results through the preparation of scientific reports, publications, and communications at international conferences, as well as the development of outreach activities (see section 4.4). This WP will facilitate communication among the Research and Working Group members' institutions (BSC, NASA, NOA, NOAA GFDL, North Carolina State University, and Sorbonne Université). We will organise online coordination meetings with the Working Group members every 3 months. There will be several 1-week visits by the members of the Working Group to discuss the progress on WPs 1 to 3.

3.3. *Work plan and schedule.*

List of milestones:

M1. Kick-off.
M2. Completion of present-day experiments with EC-Earth3-Iron.
M3. Mid-term report to the ministry.
M4. Completion of future scenario experiments with EC-Earth3-Iron.
M5. Completion of the PISCES suite of experiments.
M6. Final report to the ministry.

List of deliverables:

D1. Present-day estimates of soluble iron, total iron, dust and nitrogen generated by EC-Earth3-Iron.
D2. Future projections of soluble iron, total iron, dust and nitrogen generated by EC-Earth3-Iron.
D3. Mid-term report to the Ministry.

D4. Final report to the Ministry.

Schedule:

				Year 1				Year 2				Year 3			
	Res. Group	**Work Group**	**Hired**	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**	**Q11**	**Q12**
WP1	MG			🟨	🟨	🟨	🟨	🟨	🟨						
T1.1	MG, MC	RM	PD, IT	🟦	🟦	🟦	🟦								
T1.2	MG, MC	PG	PD, IT	🟦	🟦										
T1.3	MG, JLl, MC	SM, EB	PD, IT			🟦	🟦	🟦	🟦						
WP2	MG							🟨	🟨	🟨	🟨				
T2.1	MG, MC	PG	PD							🟦	🟦				
T2.2	MG, JLl	DH, EB							🟦	🟦					
WP3	JLl					🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
T3.1	JLl, YR, MG	CG				🟦	🟦	🟦	🟦						
T3.2	JLl, YR, MG								🟦	🟦	🟦	🟦			
T3.3	JLl, YR, MG	CG										🟦	🟦	🟦	🟦
WP4	MG, JLl														
Comm.	All			🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Dissem.	All						DIS1		DIS2		DIS3		DIS4		DIS5
Milestones	All			M1			M2		M3, M4		M5				M7
Deliverables	MG, JLl						D1		D2, D3						D4
Meetings	All	All	All	KO, PM	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM	PM

MG: Dr. María Gonçalves Ageitos (PI1), JLl: Dr. Joan Llort (PI2), MC: Dr. Montse Costa Surós, YR: Dr. Yohan Ruprich Robert, RM: Dr. Ron L. Miller (NASA), SM: Dr. Stelios Myriokefalitakis (NOA), PG: Dr. Paul Ginoux (GFDL), EB: Elisa Bergas (BSC), DH: Dr. Douglas Hamilton (NCSU), CG: Cècile Guieu (USorbonne). PD: Requested post-doctoral researcher. IT: Requested computational support engineer. All: all members of the respective group.

3.4. *Identification of critical points and contingency plan.*

BIOTA is an ambitious proposal to advance our knowledge in an existing research area. The definition of the appropriate tools and methods, as well as the estimates of the duration and resources required for the completion of the tasks, are based on the PIs and research team's experience, and, if the resources are granted, they will allow the successful completion of the project objectives.

We have not identified substantial risks within BIOTA besides occasional potential delays in milestones/deliverables. To prevent them, we have conducted a thorough screening of the potentially critical points and established a contingency plan in case of occurrence (see list below). Progress will be tracked through the project meetings and the achievement of milestones. If any task is delayed because of unexpected setbacks, the PIs of BIOTA will take appropriate actions to ensure that the specific delay in one task does not compromise other tasks.

- Risk 1: The substitution of Marenostrum4 (the current High Performance Computing, HPC, machine installed at BSC) for Marenostrum5 planned for summer 2023 impacts the EC-Earth3-Iron model performance. Probability: Low. Impact: Low (delay in experiments). Contingency: The research team has broad experience in applying for the Spanish Supercomputing Network (RES) projects, and alternative HPC machines could be requested and used.
- Risk 2: Some of the vegetation variables needed for Task 2.1 are unavailable in the CMP6 repository for all the desired scenarios. Probability: Low. Impact: Low (delay in experiments). Contingency: The variables needed would be obtained from available alternative models (e.g., GFDL-LM4 from our collaborator PG's group).
- Risk 3: The desired profile for the post-doctoral researcher is not timely found to fit in the proposed schedule. Probability: Medium. Impact: Medium. Contingency: The profile will be broadened to include post-doctoral researchers' from other associated disciplines or with less experience.

3.5. *Previous results of the team in the theme of the proposal.*

Principal Investigator 1: Dr María Gonçalves Ageitos brings in her strong background on aerosols, focusing on mineral dust and their interactions with the Earth system. She has wide experience in defining and assessing new processes in emission, atmospheric composition (e.g., Gonçalves et al., 2008a,b; 2012; 2022; Klose et al., 2021) and ESMs, e.g., Li et al. (2021); Chatziparaschos et al. (2022). She has produced open access climate projections at the regional and global scale, including for the MedCORDEX (Rutti et al.,2013) and CMIP6 AerChemMIP (van Noije et al., 2022) initiatives or the ESCAT project (Gonçalves Ageitos et al., 2013, 2014, Barrera et al., 2013). She recently co-lead the Spanish project NUTRIENT, which aimed at constraining the atmospheric iron cycle (Myriokefalitakis et al, 2022, Bergas-Massó et al., 2022) and resulted in an improved ESM and new estimates of past, present and future soluble iron deposition in the ocean. At present, she contributes to a variety of projects, among others the ESA-funded 4DAtlantic Dust Observational and Modelling Study (DOMOS), which aims at assessing the impact of dust (and iron deposition) on biogeochemistry in the Atlantic Ocean, or the NASA EMIT project, which will advance our knowledge of the mineralogy of dust sources worldwide through high quality spaceborne hyperspectral imagery. Dr María Gonçalves will act as co-PI in BIOTA and be in charge of WP1 and WP2.

Principal Investigator 2: Dr Joan Llort is a biogeochemical oceanographer specialising in the influence of atmospheric aerosols and ocean dynamics on marine biogeochemistry. He obtained a PhD from 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 modelling using PISCES (Llort et al., 2015, 2019) and demonstrated expertise working with remote sensing observations (Llort et al., 2018, Tang and Llort et al., 2021). His current research is focused on the impact of dust and biomass-burning aerosols on phytoplankton. In this line, he has led a ground-breaking study (published in Nature as co-first author) that demonstrated the fertilisation of ocean waters with aerosols issued from the 2019/20 Australian wildfires. He is now leading the project PYROPLANKTON, funded by ESA and the BSC, to characterise the dissolution and influence of wildfire ash on marine primary production using remote sensing and experimental approaches. Joan is also involved in the DOMOS consortium. Finally, he is deeply engaged with SOLAS (Surface Ocean Lower Atmosphere Survey), an international research network on ocean-atmosphere exchanges. Dr Joan Llort will act as co-PI in BIOTA and will be in charge of WP3.

Dr Montserrat Costa Surós is an experienced researcher in analysing the aerosol impacts on climate. BIOTA will benefit from her wide experience in observational analysis and remote sensing techniques to characterise aerosols and clouds (Costa-Surós et al., 2013; 2014; 2016a,b). That, combined with her numerical modelling skills (e.g., Costa-Surós et al., 2020; Stevens et al., 2020), make her a valuable team member for achieving this proposal’s objectives. She has recently joined the BSC team, where she has made sound contributions in the field of climate data analysis (Lacagnina et al., 2022) and to the EC-Earth3 Earth System Model developments (Chatziparaschos et al., 2022). She has participated in the past in Spanish National projects (NUBESOL-2) and is actively involved at present in the European Horizon 2020 project FORCeS (Constrained aerosol forcing for improved climate projections). Dr Montse Costá-Surós is part of the research team in BIOTA, and she will contribute to tasks in WP1 and WP2, particularly on the experiment configuration, monitoring and evaluation.

Dr Yohan Ruprich Robert is an expert in climate variability and predictability. He started investigating these subjects in 2010 during a PhD project at Cerfacs (Toulouse, France). He is recognised in the climate community for pioneering studies assessing the effects of the North Atlantic ocean variability on regional climate conditions. He received a European Marie-Curie individual fellowship and a LaCaixa Junior Leader Fellowship to work on the coupling between the atmosphere and the ocean at decadal scales. He was also co-PI of the OPERA project to understand the marine carbon cycle better, with the main objective of improve our ability to predict the global climate of the next decades. His expertise in atmosphere-ocean coupling will be key to developing WP3 approaches and analysing the results considering the internal ocean variability.

In addition to the Research Group, BIOTA will benefit from the contribution and expertise of the members of the Working Group, who are internationally recognised scientists in the field of climate and mineral dust modelling (Dr Ron Miller, NASA, US; Dr Paul Ginoux, NOAA-GFDL, US) and atmospheric and ocean biogeochemical cycles (Dr Cécile Guieu, U. Sorbonne, France; Dr Stelios Myriokfalitakis, NOA, Greece; Dr Douglas Hamilton, North Carolina University, US). Furthermore, we will incorporate into the Working Team a 2nd year PhD student working with us at BSC who has wide experience with the EC-Earth3-Iron Earth System Model (Elisa Bergas-Massó, BSC, Spain).

3.6. *Human, material and equipment resources available for the execution of the Project.*

Human resources:

BIOTA will be developed by researchers in the Atmospheric Composition (AC) and Climate Variability and Change (CVC) groups of the ES-BSC. The tight collaboration between the two teams allows tackling cross-cutting science questions for both disciplines. Furthermore, BIOTA researchers will count on the external support of the Computational Earth Sciences group, formed by experienced researchers and technicians in HPC computing, development of tools to manage experiments and to apply standardised procedures to model evaluation that bring in quality assurance and control. BIOTA will also benefit from the advice of the Earth System Services group, which counts on experts on science transfer and communication.

The contribution of the Research and Working Group members' contribution to each task is highlighted in the methodology section. To achieve the ambitious objectives of BIOTA, we ask for the incorporation to the team of an experienced Post-doctoral researcher (PD) for 2 years and a computational support engineer (IT) for 18 months. PD will ensure the successful development of tasks related to the improvement of dust mineralogy (Task 1.1) and the definition of dust sources in the present (Task 1.2, 1.3) and future climates (Task 2.1). Dust is a key player in the Earth System, and the characterisation of dust mineralogy will bring advances in the assessment of its impacts. Having a post-doctoral researcher focused on improving dust and dust mineralogy in a state-of-the-art ESM will timely advance our knowledge and provide relevant outcomes for the scientific and modelling community. Furthermore, through the framework of BIOTA, she/he will be able to assess the impact of dust mineralogy on the iron cycle and, ultimately, the carbon cycle. The desired profile will hold a PhD in Atmospheric Sciences or a related discipline and proven experience in Earth System Modelling (R2).

BIOTA requires handling large amounts of data (e.g., EMIT maps, information on vegetation masks, model outputs at high resolution), treating them, archiving them and sharing them properly (see section 4.5). For that reason, to produce quality-assured outputs, we request the support of an IT engineer that would support us in WP1 and would be entirely devoted to BIOTA tasks. The desired profile would be that of a junior research engineer (RE1: Master's degree or equivalent, preferably in computational sciences).

Infrastructure:

BIOTA will count on the HPC facilities available at the host centre, the BSC, which has been a reference centre nationally and internationally since its creation in 2005. At present, the BSC hosts the 4th version of the MareNostrum Supercomputer, and it is in the process of installing the 5th version, which will be operational in summer 2023. Marenostrum5 is a pre-exascale machine with a peak performance of 314 PFlops (i.e., 314 billion operations per second), more than 200 PB of storage and 400 PB of archive, which makes it one of the top supercomputers in Europe. The ES-BSC is porting the EC-Earth3 code to other EuroHPC machines in Europe (e.g., LUMI or MeluXina, in Finland and Luxembourg), which have a similar infrastructure and will timely install all codes and packages in the Marenostrum5 machine. In Marenostrum4, an EC-Earth3-Iron atmosphere-chemistry simulation, with prescribed ocean variables at standard resolution (T255L91 for IFS, 3ºx2º for TM5) has an average performance of 1.4 simulated years per day (using 326 cpu). The model performance is expected to remain the same or improve in the new Marenostrum5 supercomputer. The research team is part of the EC-Earth consortium. As such, it has access to the code developments shared by the community and the necessary data for initial and boundary conditions.

4. EXPECTED IMPACT OF THE RESULTS.

4.1. *Expected impact on the generation of scientific-technical knowledge in the thematic area of the proposal*.

The improved estimates and tools arising from BIOTA will contribute to addressing the challenge of Climate Change and Decarbonization identified below the strategic area 5, "Energy and Climate" of the *IX Plan Estatal de Investigación Científica y Técnica y de Innovación* of the Ministry of Science and Innovation. In particular, they will impact the definition of decarbonisation strategies (i.e., those defined in the *Estrategia de Descarbonización a largo plazo 2050*), which necessarily have to account for natural carbon sinks and the potential influence of human activities on them. BIOTA's outcomes will also contribute to the climate assessments used for the definition of adaptation and climate resilience strategies (e.g., those included in the *Plan Nacional Integrado de Energía y Clima 2021-2030*).

BIOTA will contribute to two Earth Sciences disciplines: atmospheric composition and the marine carbon cycle. A major contribution to the former will be the data treatment and model ingestion of ground-breaking observations acquired by EMIT. These observations come from a test sensor onboard the ISS installed less than one year ago. Hence, EMIT data is a highly new product that requires a major work investment by the community to transform it into relevant insights. BIOTA is positioned to be one of the first projects to apply EMIT data to ESM. Our project will also contribute to understanding atmospheric aerosols' link to the marine carbon cycle. The main novelty of this goal will be the comprehensive analysis that will evaluate not only the fertilisation effect but also the potential changes in the phytoplankton community and the boost of export associated with the LCP. Previous modelling efforts have purely focused on the fertilisation effect.

The advances planned within BIOTA also target specific scientific needs identified by the Intergovernmental Panel on Climate Change (IPCC). First, they contribute to improving our understanding of the processes affecting the efficiency, climate sensitivity and emerging feedback in the ocean carbon cycle via the BCP, and second, they will provide new insights through observationally-constrained estimates of the variability of air-sea fluxes. In addition, BIOTA contributes to the World Climate Research Programme Grand Challenge in Carbon Feedbacks in the Climate System, which points to the identification of biological processes that drive and control the ocean carbon sink and the impact of climate-carbon feedback on climate change as urgent questions to be answered.

BIOTA will follow an open data policy, and all the research results will be published with open access. This project will provide to the scientific community (e.g., GEOTRACES) new estimates of aeolian nutrient deposition in present-day and future climate scenarios, valid for the ocean biogeochemistry and Earth System modelling community to improve their estimates of carbon-climate feedbacks. Furthermore, the assessment of the ocean responses to different atmospheric sources of nutrients will inform the scientific community on the key sources and processes to be included in the new generation of ESM being developed for CMIP7.

Introducing the observation-constrained mineralogy maps of EMIT in EC-Earth3 will bring benefits beyond ocean biogeochemistry. In particular, it will help constrain the impact of dust mineralogy in other relevant climate features, such as the formation of mixed-phase clouds (e.g., Chatziparaschos et al., 2022) or the direct radiative effect (e.g., Li et al., 2021), which ultimately will improve current estimates of the aerosols' radiative forcing.

4.2. *Social and economic impact of the expected results*.

To estimate the global carbon budget, a better representation of the marine carbon cycle is essential. BIOTA's results will be of interest to the annual report issued by the Global Carbon Project (Friedlingstein et al., 2022), which sets the basis for mitigation policies and decarbonisation strategies around the globe. Indirectly, through the improvement in the representation of dust in ESMs, BIOTA will also impact other socio-economic sectors affected by this ubiquitous aerosol, which impacts air quality and health, visibility, aviation, or solar energy production, among others.

4.3. *Plan for scientific communication and internationalization of the results (indicate the forecast of open access publications)*.

BIOTA will make available new knowledge to the scientific community by publishing 5 open-access articles in high-impact journals (DIS1 to 5 in the schedule). The research team will actively participate in international conferences (EGU General Assembly, Ocean Sciences, SOLAS open conference) and specialised workshops (AeroCOM, Iron at the Air-Sea interactions) with the twofold objective of sharing the project findings and receiving feedback from other experts in the field. The active involvement of team members in national and international scientific committees (EC-Earth community, SOLAS) will further enable the projection of BIOTA's results.

The project will also bring attention towards the capacity of BSC's Earth Sciences Department to develop research on the ocean-atmosphere interface. In this regard, BIOTA's research team is contacting SOLAS executive directors to organise the first SOLAS workshop on modelling ocean-atmosphere processes. This workshop will trigger a new international modelling initiative within SOLAS and will give exposure to the BSC Earth Sciences Department and the Spanish research community.

Furthermore, we will foster collaboration with international researchers that conduct research in Earth System or Atmospheric modelling (T. Van Noije, KNMI; A. Benedetti, ECMWF; S. Remy, HYGEOS), biogeochemical cycles (N. Mahowald, Cornell U.; A. Ito, Japan Agency for Marine-Earth Science and Tech.; M. Kanakidou, U. of Crete), or dust observations (V. Amiridis, NOA), among others. These constitute top-leading researchers in their field, and many of them are already collaborators of our team in other proposals. We intend to scan opportunities to present project proposals (under the framework of the EC H2020 programme or ESA funded contracts, for instance) to further advance the knowledge on aerosol-ocean interactions and their impacts on climate.

Finally, within BIOTA, we plan to openly distribute the new data generated in our EC-Earth3-Iron experiments (D1, D2) to increase the project's impact in different sectors and of particular relevance for ocean biogeochemistry modellers and experimentalists. Furthermore, the EC-Earth3-Iron code developments will be committed to the EC-Earth development portal and shared with the community.

4.4. *Plan for dissemination of the results to the most relevant groups for the theme of the project and to society in general.*

The ES-BSC is a recognised centre in dust research, at present, hosts the WMO regional centre on Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS), the Barcelona Dust Forecast Center, and the AXA Chair on Sand and Dust Storms (led by the Atmospheric Group leader, Dr C. Pérez García-Pando). As a result, the Department routinely organises training courses and seminars that target meteorologists from Northern Africa and the Middle East, but are open to researchers and the general public. BIOTA's results will interest this forum, mainly on dust mineralogy, dust-related iron and future evolution of dust sources.

Outreach activities are crucial to increase public awareness and understanding of science, and, simultaneously, to show the payback of national investment in I+D+i. BIOTA will target the general public by preparing specific materials that will use a language understandable by non-specialists and with an appealing format. To this end, we foresee the creation of a wiki page with a team-restricted access area and an open access area to publish: main project results (open access articles, presentations, reports, and other project deliverables), dissemination materials and general public tailored products (i.e. leaflets, videos, press releases, etc.). The project will also take advantage of the BSC presence in social media (Facebook and Twitter account with more than 2500 followers) to spread further the project results. BSC has a media communication manager, a communication team, and an in-house designer. Within the ES-BSC, the Earth System Services group has a team specifically devoted to communicating scientific results to the broad public. BIOTA will benefit from their expertise and advice.

4.5. *Summary´s management plan of the planned data*

BIOTA requires handling numerous datasets. We will acquire and process data from different models (CMIP6 and biomass burning emission datasets, vegetation fields from ESM realisations) and reanalysis (ERA5), satellite data (EMIT, MODIS Deep Blue), as well as observational information from ground stations (AERONET retrievals, datasets from air quality station networks) and specific campaigns (data on dust mineralogy and iron observations). They will be archived following the ES-BSC conventions, ensuring traceability in data sources and characteristics. When processed (e.g., time-averaged), we keep the original data and the scripts used to treat them in our archive to ensure reproducibility. The 2D or 3D structured data will be stored in netCDF format (CF compliant), when possible. Most of our model outputs follow the CMOR conventions, a well-known standard in the climate modelling community, ensuring traceability and making our results easy to share and use by external researchers. The new variables included in our model (e.g., new iron or dust tracers) will mimic these conventions in the output formatting. Our D1 and D2 correspond to netCDF datasets that will be openly shared with the community (after being scientifically exploited in the corresponding BIOTA publications). We will store them in open repositories such as ZENODO, which provides a DOI to refer to the specific dataset. All the data related to BIOTA will be stored for at least 5 years after the project completion in our local archive, and the public data will be permanently archived. The contribution of the requested IT will be fundamental to addressing all the aspects of this data plan properly.

4.6. *Effects of gender inclusion in the content of the proposal*

The BSC is committed to gender equity, as demonstrated by the recently approved Gender and Diversity Equality Plan approved in 2022 and co-created with representatives of all staff members. The strategy in this plan oversees all the activities run at the BSC and covers the broad spectrum of issues related to gender inequalities. Of particular application for BIOTA will be the measures proposed for ensuring a fair and unbiased recruitment process, for instance, taking into consideration the job offer's wording and the selection committee's composition. In addition, all staff, including the two new positions associated with BIOTA, is encouraged to follow training activities on Equity, Gender Perspective and Leadership.

5. *JUSTIFICATION OF THE REQUESTED BUDGET*

The requested budget for BIOTA will cover the contracts of the R2 post-doctoral researcher for 2 years and the RE1 support engineer for 18 months. The need for these resources has been justified in **section 3.6** about the resources needed to develop this proposal. Furthermore, we request a PhD student fellowship that will conduct her/his research the framework of WP3 (ocean biogeochemistry) through this call.

Associated with the new personnel, we need to purchase the necessary equipment for them to develop their job. Therefore, we request three personal equipment suites (including a UNIX laptop, keyboard, mouse, screen, headphones and connectivity cables) to provide them.

To maintain effective communication with BIOTA Working Group members, we will organise quarterly online meetings (regularly) as well as specific teleconferences when needed. However, to create an environment for deeper discussion and facilitate the progress on some tasks, we plan to organise 1-week visits of the external working group members to our centre, and also to send 1 person from the research team for 1 week to visit our collaborators in France/Greece and the US.

BIOTA dissemination plan envisages the publication of 5 open access articles in journals of the geosciences area. The results will also be shared with the scientific community in specialised conferences and workshops. We plan to attend at least two editions of the EGU General Assembly (Austria) and one of the Ocean Sciences conference (US), the SOLAS open conference (India) and the AEROCOM workshop (location changes with the edition). We also aim to share the results of our project in the Iron at the air-sea interface workshop (hybrid/US). To reduce the environmental footprint, our team will send one representative in person, but we plan to send at least two contributions to maximise the reach of our project results. Therefore, the budget should cover the travel and accommodation costs for 1 person but the registry for at least 2.

Finally, we are in contact with SOLAS executive directors to host in 2024 the first ocean-atmosphere modelling initiative workshop in Barcelona, which is expected to trigger a long-term international effort on modelling the ocean-atmosphere processes. The cost estimate (25,000€) includes the catering/coffee for around 40 participants during 3 days (7000€), 3 travel+accomodation grants for Global South and Early Career researchers (9000€), travel support for SOLAS executive directors (6000€) and support towards dissemination and open access publication (i.e., white paper, 3000€).

6. TRAINING CAPACITY

6.1. *Training program planned in the context of the requested project*

The ES-BSC offers the opportunity for PhD students to work in an international multidisciplinary scientific environment. In the context of this project, we would like to recruit and enrol a PhD student in the Environmental Engineering doctoral program (https://doctorat.upc.edu/ca/programes/enginyeria-ambiental) of the Universitat Politècnica de Catalunya (UPC), which is registered in the Spanish Register of Universities and Degrees (RUCT: 5600080) and has been verified by the ANECA (in 2019).

The PhD student will count on the direct supervision and advice of the PIs of BIOTA, who will guide him/her to develop a Research and Training Plan within the first academic year, considering both the training goals and the student's needs. The training plan will be oriented towards acquiring competencies in ocean biogeochemistry and Earth System Modelling. The student will be involved in the research group activities, including periodical internal and external seminars, journal clubs, and invited speaker conferences held at BSC. In addition, she/he will have the opportunity to share the results of her/his research in different national and international scientific forums, and he/she will be encouraged to co-author scientific research articles of high impact. Complementary skills required for efficient research execution and communication will be fostered through student participation in multiple training activities offered by BSC and the UPC libraries.

The Earth Sciences Department has a long record of supervising PhD theses in the Environmental Engineering program of the UPC. Dr María Gonçalves Ageitos is part of the faculty of that PhD program, and she has been the academic tutor of 4 students in the last 10 years. At present, only in the Atmospheric Composition group are there 8 theses under development. María is the tutor for 6 of them and currently supervises 2 PhD students within the Department. Additionally, BSC has a specialized Education and Training Team, dedicated to establishing a curriculum based on cutting-edge scientific research on software tools for HPC and application areas. BSC offers a personalized professional development plan to each member, according to their profile and objectives. Thanks to this approach, BSC has been awarded with the *Human Resources Excellence in Research*, recognising the alignment of its human resources policies to the principles set out in the EU Charter and Code for Research. BIOTA's PhD will benefit from all these resources and the experience of the IPs and the group in supervising students and defining research objectives and training plans. We will additionally plan for the student's stay in international research centres (e.g., in our collaborators' groups) for at least during 3 months throughout the PhD so that she/he would opt for the PhD's International Mention.

6.2. *Theses completed or in progress within the scope of the research team (last 10 years).*

The number of theses developed at the ES-BSC in the last 10 years is 14. Below we list exclusively those in which María Gonçalves Ageitos acted as an academic tutor.

Balakrishnan Solaraju Murali. "*On the use of Decadal predictions for agricultural climate services: bridging the gap between service providers and users*". 26/01/2023. Publications: Solaraju-Murali et al. (2022, Clim. Services), Solaraju-Murali et al. (2021,npj Clim. Atmos. Science), Solaraju-Murali et al. (2019, Env. Res. Letters).

Daniel Rodríguez Rey. "*Evaluating the impact of urban mobility policies on the air quality levels of Barcelona by means of an integrated modelling system*". 21/03/2022. Publications: Rodríguez Rey et al. (2022, Sci.Tot. Env), Rodríguez Rey et al. (2021, Transp. Res. D).

Jaime Benavides. "*Development and evaluation of a street-scale air quality modelling system for the city of Barcelona*". 18/02/2020. Publications: Benavides et al. (2019, Geophys. Mod. Dev), Benavides et al. (2021, Env. Res. Lett.).

Rubén Cruz García. "*Seasonal Arctic Sea Ice predictability and prediction*". 01/07/2020. Publications: Cruz García et al. (2019, 2021, Clim. Dyn.).

6.3. *Scientific or professional development of graduate doctors from the group.*

Pedro Jiménez - Full professor at Universidad de Murcia (Departamento de Física); María Teresa Pay - Assistant professor at Universitat de Barcelona (Departamento de Genética, Microbiología y Estadística), Visiting professor - Posdoc researcher at U. Toronto (Chemical Engineering and Applied Chemistry); Karsten Haustein - Researcher at University of Oxford (School of Geography and the Environment); Simone Marras - Associate Researcher at US Naval Research Laboratory (Monterey), Associate Researcher at Stanford University (Department of Geophysics); Angel Alberto Rincón - Associate professor at Universidad del Pacífico Paraguay (Facultad de Ingeniería); Alba Badia - Researcher at the Autonomous University of Barcelona (Institute of Environmental Sciences and Technologies); Victor Valverde - Researcher at Joint Research Center, Vincenzo Obiso - Researcher at NASA-GISS; Jaime Benavides - Researcher at Columbia University.

REFERENCES

Albani, S. et al. (2014). J. Adv. Modeling Earth Systems, 6, 541–570, doi:10.1002/2013MS000279.
Andela, N. et al. (2017). Science. 356, 1356–1362, doi:10.1126/science.aal4108.
Aumont, O. et al. (2015). Geosci. Model Dev., 8, 2465–2513, doi:10.5194/gmd-8-2465-2015.
Bergas-Massó et al. (2022). Earth Future (submitted), preprint, doi: 10.1002/essoar.10512902.1.
Bondeau et al. (1999). Global Change Biology, 5(S1), 35-45.
Bowdalo, D. (2019). 20th EMEP Task Force on Measurement and Modelling Meeting, Madrid.
Canadell, J.G. et al. (2021). Climate Change 2021. IPCC. AR6, doi:10.1017/9781009157896.007.
Chatziparaschos, M. et al. (2022). Atmos. Chem. Phys. Discuss. 1–27, doi: 10.5194/acp-2022-551.
Ciais, P. et al. (2013). Climate Change 2013. IPCC. AR5.
Claquin, T. et al. (1999). J. Geophys. Res. 104256(27):243-22, doi: 10.1029/1999JD900416.
Döscher, R. et al. (2022). Geosci. Model Dev. 15, 2973–3020, doi: 10.5194/gmd-15-2973-2022.
Friedlingstein, P. et al. (2022). ESS Data 14, 4811–4900, doi: 10.5194/essd-14-4811-2022
Gidden, M. J. et al. (2019). Geosci. Model Dev. 12, 1443–1475, doi: /10.5194/gmd-12-1443-2019.
Ginoux, P. et al. (2012). Rev. Geophys. 50(3), 1–36, doi: 10.1029/2012RG000388.
Gonçalves Ageitos, M. et al. (2022) [submitted to Atmos. Chem. Phys, 6 Dec. 2022].
Green, R. O. et al. (2020). IEEE Aerospace Conference (2020), 0.1109/AERO47225.2020.9172731.
Hamilton, D. S. et al. (2018). Nat. Commun. 9, 3182, doi:10.1038/s41467-018-05592-9.
Hamilton, D. S. et al. (2020). Global Biogeochem. Cycles 34, doi 10.1029/2019GB006448.
Hauck, J. et al. (2015). Global Biogeochem. Cycles 29, 1451–1470, doi:10.1002/2015GB005140.
Hersbach, H. et al. (2020). Q. J. R. Meteorol. Soc. 146, 1999–2049, doi: 10.1002/qj.3803.
Hoesly, R. M et al. (2018). Geosci. Model Dev. 11, 369–408, doi:10.5194/gmd-11-369-2018.
Holben, B. N et al. (1998). Remote Sens. Environ, 66, 1–16, doi:10.1016/S0034-4257(98)00031-5.
Horowitz, L. W. et al. (2020). J. Adv. Model. Earth Syst. 12, doi: 10.1029/2019MS002032.
Hsu, N. C et al. (2013). J. Geophys. Res.-Atmos. 118, 9296–9315, doi: 10.1002/jgrd.50712.
Hurtt, G. C. et al (2020). Geosci. Model Dev. 13, doi: 10.5194/gmd-13-5425-2020.
Ito, A. & Xu, L. (2014). Atmos. Chem. Phys. 14, 3441–3459, doi: 10.5194/acp-14-3441-2014.
Ito, A. & Shi, Z. (2016). Atmos. Chem. Phys. 16, 85–99, doi: 10.5194/acp-16-85-2016.
Ito, A. et al. (2019). Sci. Adv. 5, doi:10.1126/sciadv.aau7671.

Jickells, T. D. (2005). Science 308(5718), 67–71, doi: 10.1126/science.1105959.
Journet, E. et al. (2008). Geophys. Res. Lett. 35, 3–7, doi: 10.1029/2007GL031589.
Journet, E. et al. (2014) Atm. Chem. Phys. 14, 3801–3816, doi: 10.5194/acp-14-3801-2014.
Kasoar, M. et al. (2021) EGU GA 2021, EGU21-13822, doi:10.5194/egusphere-egu21-13822.
Klein Goldewijk, K. (2001) Global Biogeochem. Cycles 15(2), 417– 433, 10.1029/1999GB001232.
Klein Goldewijk, K. et al. (2017). Earth Syst. Sci. Data 9, 927–953, doi:10.5194/essd-9-927-2017.
Klose, M. et al. (2021). Geosci. Model Dev. 14, 6403–6444, doi: 10.5194/gmd-14-6403-2021.
Kok, J.F. (2011) Proc. Natl. Acad. Sci. U. S. A., 108, 1016–21.
Kok, J.F. et al. (2023). Nat. Rev. Earth Environ., doi: 10.1038/s43017-022-00379-5.
Korte, L.F. et al. (2017). Atmospheric Chem. Phys., 17(9), doi: 10.5194/acp-17-6023-2017.
Kramer, S. et al. (2020), J. Geophys. Res. Oceans, 125(12), doi: 10.1029/2020JC016851
Kwiatkowski, L. (2020). Biogeosciences 17, doi: 10.5194/bg-17-3439-2020
Leung, D. M. et al. (2022). Atmos. Chem. Phys. Discuss. [preprint], doi: 10.5194/acp-2022-719.
Li, G. et al. (2020). Nat. Clim. Change 10(12), doi: 10.1038/s41558-020-00918-2.
Li, L. et al. (2021). Atmos. Chem. Phys. 21, 3973–4005. doi: 10.5194/acp-21-3973-2021.
Luo, C. et al. (2008). Global Biogeochem. Cycles 22(1). doi:10.1029/2007GB002964.
Madec, G. (2008) NEMO ocean engine Note du Pôle de modélisation, France.
Mahowald, N. M. et al. (2010). Atmos. Chem. Phys. 10, 10875–10893,10.5194/acp-10-10875-2010.
Mahowald, N. M. and Luo, C. (2003). Geophys. Res. Lett. 30, doi: 10.1029/2003GL017880
Mahowald, N. M. et al. (2009). Ann.Rev.Mar.Sci. 1, 245–278, doi: 10.1146/annurev.marine.010908.163727.
Mahowald, N. M. et al. (2017). Current Clim. Change Reports, 1–16, doi: 10.1007/s40641-017-0056-z
Marticorena, B et al. (2010). Atmos. Chem. Phys. 10, 8899–8915, doi: 10.5194/acp-10-8899-2010.
McDuffie, E. E. et al. (2020). Earth Syst. Sci. Data12(4), 3413–3442, 10.5194/essd-12-3413-2020.
Moore et al., 2013. Nature Geoscience 6, 701–710, doi:10.1038/ngeo1765.
Myriokefalitakis, S. et al. (2015). Biogeosciences 12, 3973–3992, doi: 10.5194/bg-12-3973-2015.
Myriokefalitakis, S. et al. (2022). Geosci. Model Dev. 3079–3120, doi:10.5194/gmd-15-3079-2022.
Nickovic, S. et al. (2012). Atmos. Chem. Phys.,12(2):845-855, doi:10.5194/acp-12-845-2012.
O'Neill, B.C. et al. (2014).Clim. Change 122, 387–400, doi:10.1007/s10584-013-0905-2
Ostle C. et al (2022). Environ. Res. Lett. 17 114056, 10.1088/1748-9326/ac9ecf.
Paris, R. & Desboeufs, K.V. (2013). Atmos. Chem. Phys., 13(9), 4895–4905, doi: 10.5194/acp-13-4895-2013.
Pechony, O. & Shindell, D. T. (2010). Proc. Natl. Acad. Sci. U. S. A. 107, 19167–19170, doi: 10.1073/pnas.100366910.
Pehkonen et al. (1993) Environ. Sci. Technol., 27, 2056–2062, doi: 10.1021/es00033a003.
Perlwitz, J. P. et al. (2015a). Atmos. Chem. Phys. 15, 11593–11627, doi: 10.5194/acp-15-11593-2015.
Perlwitz, J. P et al. (2015b) Atmos. Chem. Phys. 15, 11629–11652, doi: 10.5194/acp-15-11629-2015.
Prospero, J. M (1990). pp. 59–86, Springer Netherlands. doi: 10.1007/978-94-009-0503-0_4.
Prospero, J. M. (1996). The Atmospheric Transport of Particles to the Ocean, Wiley, New York, 1996.
Rabin, S. S. et al. (2017). Geosci. Model Dev. 10, 1175–1197, doi: 10.5194/gmd-10-1175-2017 .
Rodríguez, S. et al. (2021). Atmos. Environ., 246. doi: 10.1016/j.atmosenv.2020.118092.
Rémy, S et al. (2022). Geosci. Model Dev., 15, 4881–4912, doi: 10.5194/gmd-15-4881-2022.
Scanza, R. A. et al. (2015). Atmos. Chem. Phys. 15, 537–561, doi: 10.5194/acp-15-537-2015.
Scanza, R. A. et al. (2018). Atmos. Chem. Phys. 18, 14175–14196.
Shi, Z. et al. (2011a). Global Biogeochemical Cycles, 25(2), 1–14. 10.1029/2010GB003837
Shi, Z. et al. (2011b). Atmos. Chem. Phys., 11(3), 995–1007. 10.5194/acp-11-995-2011
Shi, Z. et al. (2012). Aeolian Research, 5, 21–42. doi:10.1016/j.aeolia.2012.03.001
Sinyuk, A. et al. (2020). Atmos. Meas. Tech. 13, 3375–3411, doi:10.5194/amt-13-3375-2020.
Smith, B. et al. (2001). Glob. Ecol. Biogeogr. 10, 621–637.
Tegen, I. et al. (2002). J. Geophys. Res. A. 107(21), doi: 10.1029/2001JD000963.
Tegen, I. et al. (2004). Geophys. Res. Let. 31(5), doi:10.1029/2003GL019216.
Van Marle, M. J. E. et al. (2017). Geosci. Model Dev. 10, 3329–3357.
Wang, Z. et al. (2021). Npj Clim. Atmos. Sci. 4(1), 1–8, doi:10.1038/s41612-020-00159-2.